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Systematic Review

Design-to-Manufacturing Integration for Prefabricated Timber Construction in Australia: A Systematic Review and Conceptual Framework Linking BIM, CAD/CAM and CNC Workflows

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Abstract

The growing adoption of prefabricated timber construction in Australia has highlighted persistent difficulties in integrating digital workflows between architectural design, structural engineering, and manufacturing. Although Building Information Modelling (BIM), Computer-Aided Design and Manufacturing (CAD/CAM), and Computer Numerical Control (CNC) technologies are increasingly used, fragmented software environments, inconsistent data exchange, and limited early manufacturer involvement continue to cause information loss, manual rework, and design-to-manufacturing workflow gaps. This study provides a PRISMA-informed structured review of design-to-manufacturing integration in prefabricated timber construction, focusing on workflow stages, software ecosystems, interoperability issues, and manufacturer-ready data requirements. Following PRISMA 2020 guidelines, 588 records from ScienceDirect and Web of Science were screened, resulting in 60 peer-reviewed studies. These were supplemented by 32 practice-based technical sources, including industry reports, software manuals, user guides, CNC/machinery manuals, and interface documents. The review maps current workflows for timber frames, trusses, and mass timber components, identifying recurring challenges such as fragmented responsibilities, insufficient data detail, incompatible software, repeated remodelling, and weak design-production continuity. Based on these findings, the paper proposes a conceptual digital integration framework emphasising early collaboration, shared parametric logic, and clearer manufacturer-ready data to support more reliable, resource-efficient, and sustainable design-to-manufacturing workflows in Australian prefabricated timber construction.

Keywords: prefabricated timber construction; design-to-manufacturing; BIM-CAD-CAM interoperability; CNC systems; digital workflow; software integration; Australia

Academic Editor: Giouli Mihalakakou

Received: 24 April 2026
Revised: 28 June 2026
Accepted: 30 June 2026
Published: 3 July 2026

1. Introduction

The construction industry is one of the main sectors of the global economy, significantly contributing to gross domestic product (GDP), employment, and infrastructure development [1]. Despite its economic importance, the sector persists in demonstrating low

https://doi.org/10.3390/su18136790

productivity growth relative to manufacturing and other industrial sectors [2]. Over the past few decades, construction has remained characterised by fragmented supply chains, project-based production models, and labour-intensive methods, resulting in inefficiencies, rework, and cost overruns [3]. Unlike manufacturing, which has achieved significant productivity gains through process standardisation, automation, and digitalisation, construction has been slow to adopt systematic innovation in both process and production technologies.

This stagnation is increasingly unsustainable given current demographic and environmental pressures. The expansion of the global population, rapid urbanisation, and increasing living standards persist in fuelling the need for housing and infrastructure [2]. Conversely, the industry concerns increasing material and energy limitations, labour shortages, and rising expenses [4]. Australia is expected to need more than 1.2 million additional dwellings by 2030 to accommodate population growth, and housing affordability demands.

Traditional on-site construction methods are unable to meet this demand, as they heavily depend on skilled labour and sequential processes that are progressively limited by workforce availability and declining productivity. The rising costs of materials, logistics, and labour intensify the gap between supply and demand, underscoring the necessity for a fundamental change in construction planning and execution [3].

Industrialised and off-site construction have gained prominence internationally as effective strategies for addressing these systemic challenges. Prefabrication transfers production from variable site conditions to controlled factory environments as a key component of industrialised construction [5]. This shift facilitates process standardisation, quality assurance, and the concurrent execution of tasks, thereby improving project efficiency and reducing waste [1,6].

Prefabrication also provides a foundation for automation and digital integration, enabling the use of robotics, computer-numerically controlled (CNC) machinery, and model-driven manufacturing workflows [7,8]. These advancements align closely with the principles of Design for Manufacturing and Assembly (DfMA) and Design for Disassembly (DfD), which promote constructability, efficiency, and lifecycle sustainability through early design integration and modular production [9–12].

Automation plays a central role in enhancing productivity within prefabrication workflows. The integration of digital design tools, parametric modelling, and automated fabrication systems supports greater precision and consistency while minimising manual intervention and human error [13,14]. Automated production not only mitigates the effects of skilled labour shortages but also enables predictable output, scalability, and continuous improvement through data feedback [15]. The construction sector's transition towards automation thus mirrors broader industrial transformations under Industry 4.0, where interoperability, data exchange, and cyber–physical integration are key enablers of performance improvement [10,16].

Within this context, prefabricated timber construction has emerged as a promising pathway towards sustainable and industrialised building practices. Engineered timber products such as cross-laminated timber (CLT), glue-laminated timber (GLT), and laminated veneer lumber (LVL) exhibit high strength-to-weight ratios, dimensional stability, and compatibility with digital fabrication [10,17,18]. Their renewable properties and ability to store carbon led to substantial decreases in embodied emissions relative to traditional concrete and steel structures. These attributes correspond with Australia's decarbonisation goals and circular economy initiatives, which increasingly prioritise low-carbon materials and waste minimisation throughout the construction lifespan.

Despite these benefits, the implementation of prefabrication and automation in the Australian construction industry is still restricted. Industry fragmentation, inconsistent regulatory frameworks, and insufficient integration between the design and manufacturing processes continuously limit scalability and performance outcomes [4,6,13]. One of the most critical challenges lies in the weak digital connection between architectural, structural, and manufacturing models [3,19].

In current practice, design intent rarely translates directly into manufacturer-ready information, resulting in data loss, redundant modelling, and frequent design revisions. The absence of interoperability among software platforms constrains automation potential and undermines the benefits of DfMA and DfD [9,10]. Consequently, the transition from design to manufacturing remains a major bottleneck to achieving efficiency, cost predictability, and sustainability within Australia's prefabricated timber industry [20].

Building Information Modelling (BIM) has been widely investigated in prefabricated and off-site construction as a means of improving multidisciplinary coordination, clash detection, documentation, quantity extraction, component planning, assembly sequencing, and stakeholder communication [21–25]. These studies demonstrate the value of BIM for improving coordination and information management in prefabricated construction. However, the use of BIM for coordination does not automatically ensure that design models contain the fabrication-level information required for CAD/CAM modelling and CNC-based timber manufacturing.

While previous research has explored BIM-enabled prefabrication, digital fabrication, DfMA, robotics, and timber manufacturing workflows, the design-to-manufacturing interface in prefabricated timber construction remains insufficiently synthesised as a distinct integration challenge. Existing studies often discuss digital tools broadly or focus on isolated stages such as design coordination, fabrication automation, or manufacturability assessment.

There has been less emphasis on the workflow gaps that arise between architectural models, structural models, and manufacturer-specific CAD/CAM and CNC systems, especially concerning manufacturer-ready information requirements and the issues caused by fragmented software ecosystems. This issue is particularly important in Australia, where prefabricated timber delivery is limited by uneven industrial maturity, diverse software practices, and minimal early collaboration between design and manufacturing stakeholders.

This paper explores the gap in integrating design and manufacturing in prefabricated timber construction, focusing specifically on the Australian context. Instead of proposing a validated implementation model, it offers a structured review and synthesis of current workflows, stakeholder interactions, software ecosystems, and common interoperability issues at the design–manufacture boundary.

The contributions include: (i) mapping the existing design-to-manufacturing workflow for prefabricated timber systems; (ii) identifying recurring fragmentation points in software, data, and processes across BIM, CAD/CAM, and CNC environments; (iii) clarifying the information requirements needed for manufacturers that are often absent from initial design models; and (iv) proposing a conceptual framework for digital integration based on reviewed evidence. In this way, the study aims to position the digital integration challenge not only as a software compatibility challenge but also to address issues related to information maturity, workflow management, and early cross-disciplinary coordination.

2. Methodology

This study employed a structured document-based review methodology to examine design-to-manufacturing integration in prefabricated timber construction. The review integrated peer-reviewed academic literature with selected industry and technical documentation to capture both scholarly perspectives and practice-based evidence on software ecosystems, BIM, CAD/CAM, CNC workflows, interoperability issues, and manufacturer-ready information requirements.

The review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [26]. A PRISMA 2020 flow diagram was used to document the identification, screening, eligibility assessment, and inclusion of peer-reviewed studies and relevant industry/technical sources. The completed PRISMA 2020 checklist is provided as Supplementary Material [26]. The review protocol was not formally registered, and no separate protocol document was prepared.

2.1. Literature Identification and Search Strategy

Peer-reviewed studies were identified through systematic searches in ScienceDirect and Web of Science, covering publications from 2015 to 2025. These databases were selected because they provide broad coverage of construction management, architectural engineering, digital construction, timber engineering, automation, and manufacturing-related research.

As shown in Figure 1, the database search identified 588 records, including 489 records from ScienceDirect and 99 records from Web of Science. After removing 110 duplicate and non-peer-reviewed records, 478 records remained for title screening.

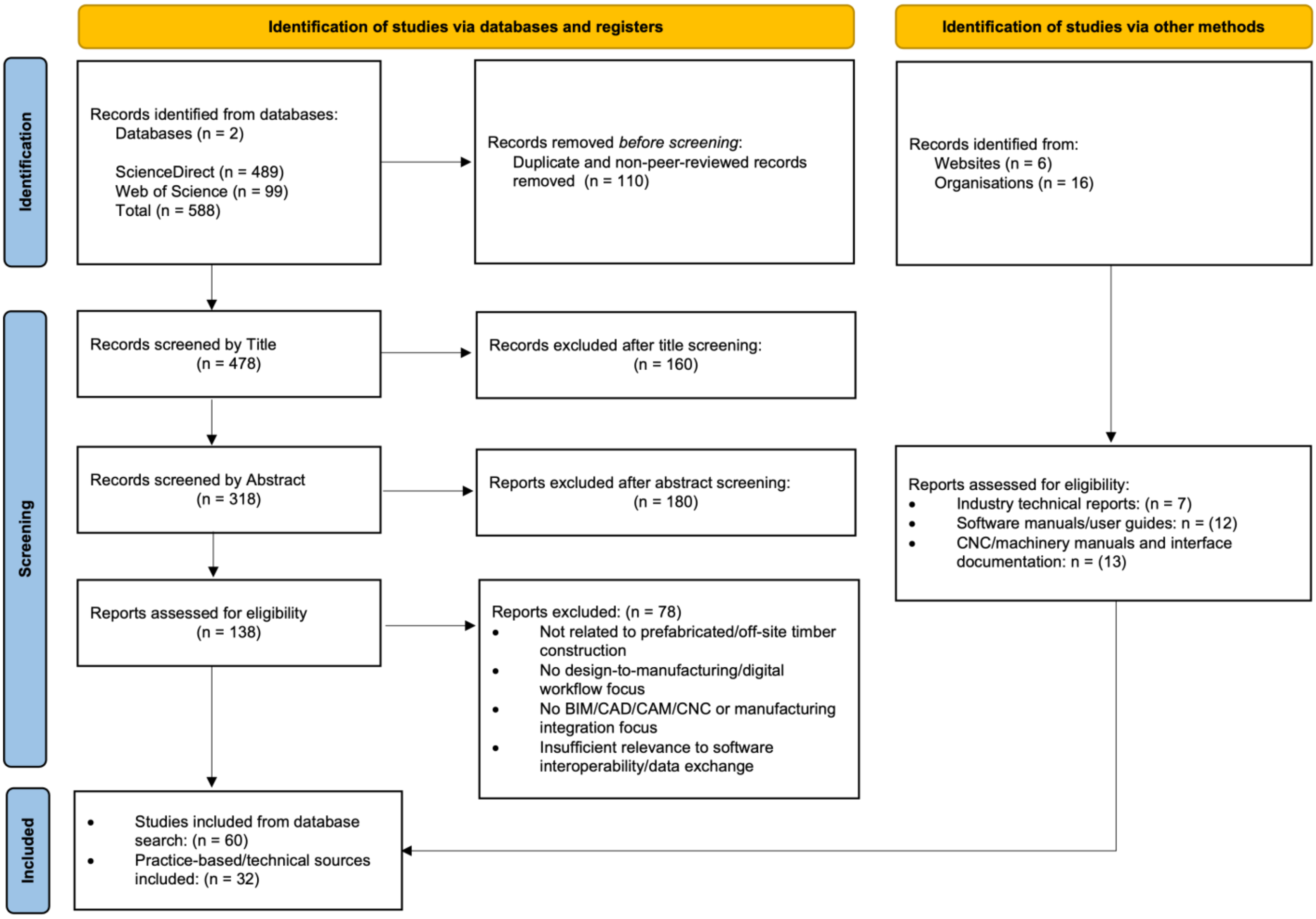

Figure 1. PRISMA-informed database search and literature screening process.

The search strategy was designed to identify studies addressing the digital transition from design to manufacturing in prefabricated timber construction. Search terms combined concepts related to prefabricated timber, off-site construction, mass timber, BIM, digital modelling, CAD/CAM, CNC manufacturing, workflow integration, automation, interoperability, and design-to-manufacturing coordination. The search strategy used in each database is summarised in Table 1.

Table 1. Search strategy used for database identification.

Database	Search Terms/Search String
ScienceDirect	(“timber”) AND (“CAD model” OR “CAM model” OR “CNC”) AND (“digital workflow” OR “integration” OR “BIM-to-fabrication” OR “design-to-manufacturing”)
Web of Science	(“mass timber” OR “prefabricated timber” OR “timber manufacturing” OR “offsite manufacturing”) AND (“CAD” OR “CAM” OR “CNC” OR “digital modelling” OR “fabrication” OR “manufacturing model”) AND (“digital workflow” OR “automation” OR “integration” OR “BIM-to-fabrication” OR “design-to-manufacturing”)

2.2. Eligibility Criteria and Study Selection

Studies were selected using predefined inclusion and exclusion criteria. The criteria were developed to ensure that the selected literature specifically addressed design-to-manufacturing integration rather than timber construction more broadly. The inclusion and exclusion criteria are summarised in Table 2.

Table 2. Inclusion and exclusion criteria used for study selection.

Category	Inclusion Criteria	Exclusion Criteria
Publication period	Studies published between 2015 and 2025	Studies published outside the selected period
Language	English-language publications	Non-English publications
Publication type	Peer-reviewed journal articles and conference papers identified through academic databases	Non-peer-reviewed academic records during database screening
Construction context	Studies focused on prefabricated, off-site, industrialised, engineered, or mass timber construction	Studies focused only on conventional timber construction without prefabrication or manufacturing workflow relevance
Digital workflow focus	Studies involving BIM, advanced 3D modelling, parametric modelling, computational design, CAD/CAM, CNC, digital fabrication, or manufacturing modelling	Studies with no clear digital workflow, software, interoperability, automation, or manufacturing link
Design-to-manufacturing relevance	Studies addressing design-to-manufacturing integration, data exchange, workflow coordination, manufacturer-ready information, model transfer, or software interoperability	Studies focused only on structural performance, fire, acoustics, material behaviour, or sustainability without workflow integration relevance
Practical/technical sources	Industry reports, software manuals, machinery manuals, user guides, and interface documentation relevant to prefabricated timber design-to-manufacturing workflows	Marketing-only sources, general webpages, or documents without sufficient technical detail

The selection process followed a staged PRISMA-based screening procedure. First, titles were screened to remove studies outside the scope of prefabricated/off-site timber construction and digital workflow integration. This resulted in the exclusion of 160 records, leaving 318 records for abstract screening. Abstract screening then excluded a further 180 records that did not sufficiently address design-to-manufacturing integration, software interoperability, or manufacturing-related workflows. The remaining 138 reports were assessed in full text for eligibility.

During full-text assessment, 78 reports were excluded because they were not sufficiently related to prefabricated/off-site timber construction, did not focus on design-to-manufacturing or digital workflow integration, did not address BIM/CAD/CAM/CNC or manufacturing integration, or lacked relevance to software interoperability and data exchange. A final set of 60 peer-reviewed studies was included from the database search, and a summary of these studies is provided in Supplementary Table S1.

The initial screening and data extraction were conducted by the first author. The inclusion logic, selected studies, and synthesis structure were reviewed through discussion with the co-author team to improve consistency and reduce interpretive bias. No automation tools were used to make inclusion or exclusion decisions.

2.3. Industry Reports and Technical Documentation

Since many software compatibility issues, machine-specific data requirements, fabrication workflows, and model-to-machine processes are not fully documented in peer-reviewed academic publications, the review was further supported by selected industry and technical sources. These sources were used to capture practice-based information on real-world design-to-manufacturing workflows, especially where academic literature provided limited detail.

The main purpose of including these documents was to identify and report current practice within the Australian prefabricated timber industry. Peer-reviewed studies provide important academic evidence, but they often do not describe the detailed software configurations, shop detailing practices, CNC data preparation steps, machine-interface requirements, and model handover problems encountered in day-to-day industry workflows. Therefore, technical documents from major Australian prefabricated timber manufacturers, software providers, and CNC machinery suppliers were reviewed to better understand the real-world workflow conditions, practical constraints, and integration challenges currently faced by industry practitioners.

Industry and technical sources were identified from publicly available websites, organisational reports, technical guides, software documentation, user manuals, machinery manuals, and interface documents relevant to prefabricated timber construction, timber manufacturing, specialist CAD/CAM platforms, CNC machinery, and digital fabrication systems. As shown in Figure 1, documents were sourced from 6 websites and 16 organisations. The practice-based source pathway included 7 industry technical reports, 12 software manuals/user guides, and 13 CNC/machinery manuals and interface documents, resulting in 32 practice-based and technical sources.

The industry and technical sources were selected purposively rather than through extensive organisational sampling. The aim was not to represent every prefabricated timber manufacturer, software provider, or CNC machinery supplier, but to capture technically relevant evidence from documents that reflect current Australian prefabricated timber practice. Sources were prioritised when they provided direct information on BIM/CAD/CAM interoperability, timber detailing, shop drawing workflows, CNC data preparation, machine-readable file formats, production planning, and model-to-machine transfer.

Therefore, sources were prioritised when they provided direct technical relevance to BIM/CAD/CAM interoperability, timber detailing, CNC data preparation, machine-readable file formats, production planning, and model-to-machine transfer. This approach was appropriate because many practical workflow and machine-interface details are documented in software manuals, machinery guides, implementation documents, and manufacturer-facing technical resources rather than peer-reviewed literature.

These sources were not treated as equivalent to peer-reviewed empirical studies. Instead, they were used as practice-based technical evidence to contextualise current industry workflows, software environments, production constraints, data exchange formats, and manufacturing information requirements that are frequently underrepresented in academic literature. This distinction was maintained during synthesis, with peer-reviewed studies forming the core academic evidence base and industry documents supporting the interpretation of current practice and practical workflow challenges.

2.4. Data Extraction and Synthesis

Relevant information was extracted from both peer-reviewed studies and practice-based technical sources. The extracted data focused on software ecosystems, workflow stages, file exchange formats, manufacturing outputs, CNC-related requirements, and recurring issues such as information loss, remodelling, version-control problems, and coordination gaps between design and production. The data extraction and synthesis framework is summarised in Table 3.

Table 3. Data extraction and synthesis framework.

Review Focus	Data Extracted	Purpose of Extraction	Contribution to Synthesis
Software ecosystems	BIM, CAD, CAM, CNC, structural modelling, detailing, and manufacturing software platforms	To identify the tools used across design, engineering, detailing, and production stages	Supported the software comparison and discussion of fragmented toolchains
Data exchange formats	IFC, DWG, BTL, BVX, NC files, proprietary formats, and other machine-readable outputs	To understand how information is transferred between design and manufacturing environments	Informed the analysis of interoperability issues and information loss
Workflow stages	Architectural modelling, structural modelling, fabrication review, manufacturing modelling, shop detailing, nesting, CNC file generation, production planning, and installation outputs	To map the design-to-manufacturing process in prefabricated timber construction	Supported the development of workflow diagrams
Manufacturer-ready information	Tolerances, material specifications, connection details, machining requirements, part identifiers, sequencing logic, and production constraints	To identify information required for reliable manufacturing and CNC-enabled production	Informed the discussion of manufacturer-ready data requirements
Integration challenges	Remodelling, metadata loss, geometric inaccuracies, file-based handovers, late manufacturer involvement, role ambiguity, and version drift	To identify recurring causes of workflow fragmentation	Supported the thematic discussion of design-to-manufacturing integration challenges
Practice-based constraints	CNC machine requirements, software configuration needs, post-processing workflows, machine interfaces, and factory-specific constraints	To capture technical details often absent from academic literature	Strengthened the practical relevance of the conceptual framework
Feedback mechanisms	Design-to-factory feedback, detailing revisions, quality checks, production feedback, and site/factory coordination	To understand whether information flows back from manufacturing to design teams	Supported the discussion of bidirectional feedback and digital continuity

The extracted information was analysed through qualitative narrative synthesis supported by structured manual categorisation. This approach was appropriate because the review did not aim to calculate effect sizes or conduct statistical meta-analysis. Instead, the purpose was to synthesise evidence from heterogeneous academic and technical sources to understand how design-to-manufacturing workflows are currently structured, where integration problems occur, and what information is required to improve digital continuity in prefabricated timber construction.

The synthesis involved three main steps. First, included studies and technical sources were grouped according to their relevance to key workflow stages, including architectural modelling, structural modelling, fabrication review, manufacturing modelling, CAD/CAM processing, CNC file generation, production planning, and factory/site feedback. Second, recurring integration issues were compared across source types, with attention to software interoperability, information loss, remodelling, file-based handovers, and late manufacturer involvement. Third, the synthesised findings were used to develop workflow diagrams, software comparison tables, discussions on current integration challenges, and the proposed conceptual digital integration framework.

Particular attention was given to CAD/CAM modelling practices for timber components, BIM-to-fabrication data transfer, CNC file generation, machine-specific constraints, software interoperability, workflow fragmentation, manufacturer-ready information requirements, and feedback mechanisms between design, detailing, and factory environments.

No statistical synthesis or meta-analysis was conducted because the reviewed sources were heterogeneous in scope, method, and evidence type. The findings are therefore presented through narrative synthesis, workflow mapping, comparative tables, and conceptual framework development.

2.5. Methodological Limitations

Several methodological limitations should be acknowledged. The academic database search was limited to ScienceDirect and Web of Science, and only English-language publications from 2015 to 2025 were considered. Although these databases provide broad coverage of construction, engineering, and digital technology research, relevant studies indexed elsewhere may have been missed.

The industry and technical documentation were also selected purposively and may not capture every software platform, machinery vendor, or manufacturing workflow used across the prefabricated timber sector. However, the selected sources were considered sufficient for the purpose of this review because they covered the main categories of information required to examine design-to-manufacturing integration, including BIM/CAD/CAM workflows, CNC data preparation, software interoperability, machine-readable file formats, and production-level constraints.

These sources also varied in scope, detail, and level of technical transparency, as some were prepared for software support, product guidance, or machinery implementation rather than academic reporting. Therefore, they were used to supplement the peer-reviewed literature with technically relevant practice-based evidence, rather than to conduct a complete market survey of all available organisations or technologies.

Despite these limitations, combining academic literature with selected industry and technical sources provided a more comprehensive basis for analysing design-to-manufacturing integration in prefabricated timber construction. This combined approach was necessary because many practical issues related to software compatibility, CNC data preparation, machine-specific constraints, and fabrication-level information requirements are not fully captured in academic publications alone.

3. Findings

3.1. Prefabricated Timber Construction

Prefabricated timber construction has become an important component of industrialised building systems, facilitating the shift towards more efficient and sustainable production methods [27]. The construction industry worldwide is increasingly transitioning from fragmented, site-specific activities to integrated, factory-based procedures [16]. Timber is essential to this transformation because of its renewable characteristics, versatility, and suitability for modular and automated fabrication methods [15]. Prefabrication improves accuracy, minimises waste, and accelerates project timelines, while also supporting decarbonisation goals through the utilisation of renewable materials and regulated manufacturing environments [7,16,28].

Across many developed regions, prefabricated timber has reached a level of industrial maturity underpinned by integrated supply chains, regulatory support, and strong market acceptance [4]. Many Countries have demonstrated that industrialised timber construction can achieve high levels of productivity, consistency, and quality while meeting diverse architectural and structural demands [17,29]. These contexts illustrate the potential of prefabrication to deliver large-scale, sustainable construction outcomes when design, manufacturing, and assembly processes are effectively aligned through early collaboration and digital integration [5].

The Australian timber construction industry is still in the early stages of industrialisation. Despite the nation’s substantial forest resources and increasing engineered timber manufacturing capabilities, the widespread implementation of prefabricated construction techniques remains in its early stages [30–32]. The industry faces multiple structural challenges, such as fragmented supply chains, insufficient regulatory coordination, and an absence of early collaboration between design and manufacturing sectors. Labour constraints, increasing expenses, and inconsistent implementation of digital workflows further limit the sector’s ability to expand prefabricated manufacturing [33]. Despite these limitations, prefabricated timber construction offers considerable possibilities for enhancing productivity, enhancing safety outcomes, reducing site disruption, and advancing national sustainability and housing objectives.

3.1.1. DfMA and DfD in Prefabricated Timber Construction

Design for Manufacture and Assembly (DfMA) and Design for Disassembly (DfD) are complementary strategies that support the efficiency and sustainability of prefabricated construction [10]. DfMA focuses on optimising components for ease of fabrication, transportation, and assembly, while DfD emphasises adaptability, reusability, and material recovery at the end of a building’s life cycle [11,19]. Together, these principles aim to reduce waste, improve productivity, and extend the lifecycle value of timber systems.

Despite conceptual consistency between DfMA and DfD, implementation is still fragmented throughout practice. During the early stages of design stages, architects and engineers rationalise layouts and simplify parts from their perspective [32]. Since manufacturers often participate after approval or procurement of designs, manufacturing constraints are not fully embedded into the early stages of design decision-making [19]. Therefore, when the manufacturers later review the project, fabrications that are incompatible or less efficient have arisen, necessitating changes. As a result, DfMA and DfD are applied in isolation by different stakeholders rather than through an integrated workflow that systematically aligns design intent with manufacturing capability, allowing inefficiencies and lost optimisation opportunities to persist [20,34].

The application of Design for Disassembly (DfD) in prefabricated timber construction remains extremely limited in Australia. Although its principles, such as modularity, reversible connections, and material reuse, are well established in academic research and pilot projects, they are rarely adopted in mainstream practice [9,11]. Barriers, including regulatory constraints, cost pressures, the absence of shared standards, and weak collaboration between architects, engineers, and manufacturers, further limit the adoption [11]. Consequently, only a small number of pilot buildings have incorporated disassembly-ready detailing, and DfD continues to be more aspirational than operational in the current industry context [10,35].

The systematic use of DfMA and DfD can support improved coordination, fewer design changes, and more consistent delivery outcomes [36]. It facilitates efficient manufacture through precise modelling, material optimisation, and waste minimisation, enhances site safety and assembly efficiency, and promotes long-term reuse and recycling, therefore strengthening circular economy and sustainability outcomes for prefabricated timber construction systems [31,32,34].

3.1.2. End-to-End Workflow in Prefabricated Timber Construction

Prefabricated timber construction follows a systematic and connected series of processes from project initiation to completion, with every phase having different deliverables and different levels of stakeholder engagement. During the inception and feasibility phase, the client and project team define the project brief, budget, site limitations, and delivery expectations. Initial evaluations of prefabrication applicability are conducted by architects and engineers, focusing on spatial, engineering, and regulatory feasibility [29,37].

Figure 2 shows the traditional design-to-manufacturing timeline, where architects and engineers control initial decision-making, whereas manufacturers are generally involved at later stages. In the conceptual and schematic design phases, design teams translate client requirements into spatial configurations, preliminary structural frameworks, and initial budget estimates [1]. While DfMA ideas like standardisation, modularity, and simplified geometry may be considered at this stage, they are frequently implemented without direct input from manufacturers. Therefore, critical decisions primarily depend on expert judgement instead of manufacturing-based standards, potentially limiting downstream manufacturability [19].

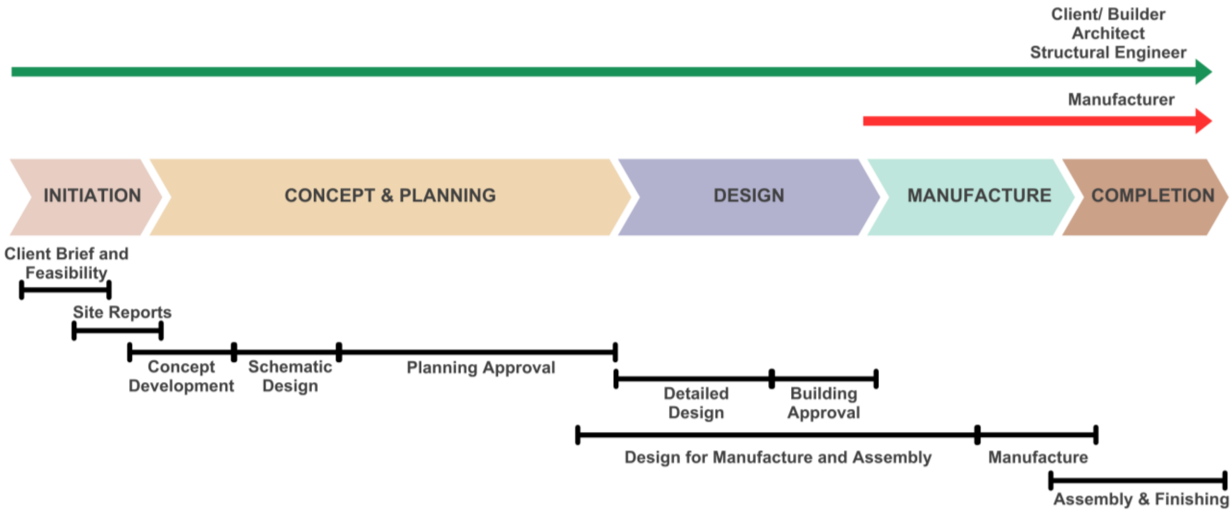

Figure 2. Conventional stakeholder involvement across the design-to-manufacturing timeline in prefabricated timber construction.

In the design development and detailed design stages, architectural, structural, and services information is integrated into coordinated documentation needed for regulatory approval. Manufacturer involvement often occurs upon building approval, as suppliers examine the approved design to assess production feasibility [38]. Collaborative discussions are then held with architects and engineers to address constraints relating to manufacturing attributes [32]. However, the ability to implement substantial adjustments is often limited by prior design approvals, which constrain opportunities for early optimisation [20].

Following approval, manufacturers transform the coordinated design into production-ready shop drawings and fabrication models, specifying tolerances, nesting methods, and CNC instructions [31]. Manufacturing includes machining, assembly, and quality assurance, followed by the labelling, packaging, and preparation of components for site installation. Construction thereafter emphasises logistical coordination, assembly, inspection, and final documentation [30].

Although this workflow appears linear, in practice it remains iterative and partially fragmented. Delayed manufacturer involvement and limited interoperability between software environments create a disconnect between design intent and production feasibility, often leading to redesigns, duplicated effort, and inefficient coordination [32,35,37]. This highlights the importance of earlier collaboration and more structured digital continuity across the design-to-manufacturing process [10,19].

3.2. Software Ecosystems and Digital Workflows in Prefabricated Timber

3.2.1. Architectural Design and Modelling

Architects are typically responsible for developing the building's spatial layout, envelope, and regulatory compliance documentation [38]. They are generally sufficient for coordination with engineers and for obtaining planning and building approvals [14,39]. Many architects also incorporate aspects of DfMA and DfD principles at this stage, such as rationalised grids, repetitive layouts, modularity, and transport constraints, drawing on their professional experience [10,19]. However, these early design decisions are not always aligned with downstream manufacturing requirements [20,34].

3.2.2. Structural Analysis and Detailing

Structural engineers are responsible for developing the building's primary structural system, establishing load paths, and designing connections to ensure structural performance and compliance. In the design and approval process, structural models mainly focus on performance, code compliance, and coordination. Engineers also provide critical inputs such as member size, structural tolerance, service penetrations, fire tolerance, vibration, and indicative connection type [38].

At this stage, many engineers also consider inputs from DfMA, such as rationalisation of spans based on standard panel widths, matching structural grids to modular solution layouts, and conceptual connection design that can accommodate buildability and assembly requirements [13]. However, similar to the architectural phase, these efforts occur largely in isolation from manufacturers, resulting in designs not fully optimised for manufacturing [37].

3.2.3. Fabrication Review and Manufacturability Assessment

Once building approvals are secured, manufacturers and builders are formally engaged, and the project enters the transition from design to fabrication. At this stage, the approved architectural and structural documentation is reviewed against fabrication capabilities, transport constraints, and site logistics [37]. This review frequently identifies the need for adjustments such as modifying panel or member dimensions to suit CNC machining limits, altering joint details to align with production lines, revising tolerances to match factory precision, splitting or merging elements to accommodate transport and handling constraints, or refining connection details to support faster installation [20].

Architects and structural engineers continue to play a critical coordinating role during this phase with manufacturers, ensuring that changes remain consistent with the original design intent, regulatory approvals, and performance requirements [31,32]. However, because manufacturers typically become involved only after design development and approvals are completed, many fabrication-related considerations are addressed late in the process [21,40]. This late-stage refinement approach will result in missed opportunities to improve the design structure for manufacturing and assembly, and any significant structural modifications identified at this stage might require alterations to permits, which will raise the complexity of the delivery timeline [26].

3.2.4. Manufacturing Modelling and Digital-to-Factory Integration

Manufacturing represents a critical phase in prefabricated timber construction, marking the transition from digital design to physical production [41]. At this stage, architectural and engineering concepts are converted into precise, data-driven instructions that guide automated and semi-automated manufacturing systems [13,14,42]. This transformation requires high levels of technical accuracy and close coordination among architects, structural engineers, and manufacturing specialists, as the effectiveness of this phase directly influences the quality, precision, and efficiency of prefabricated components delivered to the site [31].

In modern prefabrication workflows, manufacturing relies heavily on digital modelling as the foundation for production [41]. Unlike conventional construction, where much of the decision-making occurs on-site, prefabrication demands that all geometric, structural, and connection details be resolved in the digital environment before fabrication begins [19]. The manufacturing model, often referred to as the fabrication model, extends beyond design representation to include the exact dimensions, cutting paths, and material properties that guide machinery operations [39].

Digital-to-factory integration ensures that these models can be directly translated into manufacturing processes with minimal manual intervention. It connects CAD-based design platforms with CAM systems that control machining and assembly, creating a continuous digital thread from design to production [6,8,43,44]. The outcome is a manufacturing-ready digital twin that mirrors the physical product and embeds key parameters such as tolerances, material grades, and assembly logic [45,46].

The degree of digital integration varies widely across the industry. Advanced facilities operate fully automated production lines where design models feed directly into CNC routers, saws, or press machines, while smaller or hybrid operations still rely on partial manual input and layered approval stages [33,47]. Regardless of the level of automation, the main objective is to ensure seamless and accurate transition from design intent to manufacturing [37,48]. This often requires manufacturers to redraw or remodel received design data within specialised platforms, ensuring compatibility with production systems and fabrication workflows [21,31].

Therefore, the manufacturing modelling and digital-to-factory integration form the backbone of industrialised timber construction. They connect design intelligence with production capability, enabling prefabricated systems to achieve the high levels of quality, repeatability, and efficiency required for modern construction [34,49]. As digitalisation continues to advance, this integration will increasingly depend on interoperable data environments, smart manufacturing technologies, and adaptive workflows that bridge design, engineering, and fabrication in real time [14].

(a) CNC systems in the timber prefabrication industry

Prefabricated timber manufacturing in Australia involves a range of CNC machine types and associated control environments, each with different capabilities, data requirements, and implications for the transition from design models to fabricated components [30,31,33]. The reviewed industry and technical sources indicate that machine selection is closely related to product type, production workflow, and factory configuration. Table 4 summarises the main CNC machine categories and vendor platforms identified through the reviewed Australian industry documentation and associated technical references.

The data pathways from the model to these machines vary greatly between the different manufacturing facilities. In some cases, an open manufacturing format like BVX, BTL, or NC is used by multi-axis beam and panel processing machines, while in other cases, a suite-specific format from the machinery vendor is required [50]. IFC and DWG formats are mainly used for reference and coordination, as CNC machines require optimised job files that have been post-processed for toolpath generation [13,31,51].

To ensure the production is reliable, strict revision control is followed by the manufacturing plants, treating the manufacturing model as the single source of truth during the entire fabricating process. Comprehensive validation checks are performed to ensure that the model information, part names, and geometry are consistent to mitigate the risk of version drift and support traceability from design to final installation [20,31].

Table 4. CNC systems used in the Australian prefab timber industry.

Machine	Main Use/Application	Machine Capabilities	References
Hundegger	CLT, GLT, LVL beams, wall frames, floor cassettes, trusses	Multi-axis milling, sawing, drilling, notching, trenching; panel and beam machining	[52,53]
Essetre	CLT and engineered timber panels	5-axis profiling, joinery detailing, openings	[54,55]
Ledinek	CLT and GLT panel processing lines	Profiling, trimming, finishing, press integration	[56,57]
Kallesoe	Glulam beam shaping and profiling	Beam profiling, taper cuts	[58,59]
Randek	Wall frames, cassettes, trusses, volumetric modules	Framing line automation, cutting, nailing, nesting	[60]
Weinmann (Homag)	Panelised wall, floor, roof systems	Routing, nailing, sheathing, integrated panel lines	[61]
MiTek	Roof trusses and wall frames	Linear saws, truss jigs, automated fabrication	[62–64]
Pryda	Roof trusses and wall frames	Nailplate truss systems, framing line automation	[65–67]
Multinail	Wall frames and trusses	Linear saws, AutoFramer, truss lines	[68–70]
Vekta	Linear cutting and handling for frame and truss components	High-speed linear saw, automated infeed, labelling	[71]

Overall, these CNC machines specify the information requirements needed during digital design. While mass timber manufacturers rely on multi-axis and simulation-driven systems that demand precise data-rich models, the residential factories depend on streamlined, proprietary ecosystems optimised for repetitive workflows [45]. This diversity in machinery types contributes to the broader lack of interoperability and standardisation, reinforcing the need for digital data exchange protocols between design and manufacturing stages.

(b) Design and CAD modelling

The development of a specialised CAD/CAM model is an essential stage in the digital processing of prefabricated timber construction [44,72]. This model serves as the principal interface between design intent and physical production, converting approved architectural and structural information into manufacturing-ready data [43,73]. Architectural and engineering models primarily emphasise coordination, compliance, and structural performance, whereas the manufacturing model prioritises geometric integrity and production logic to ensure compatibility with CNC-driven operations, including cutting, drilling, routing, and assembly [21,73].

Compared to architectural and structural design models, usually produced at LOD 200–300, manufacturing demands significantly more information levels (LOD 350–500) [34,74,75]. Manufacturing operations need precise instructions for joinery, fastener positioning, machining allowances, sequencing logic, grain orientation, lifting points, assembly sequence, and machine-specific tolerances [19,31,49].

This fabrication-critical information is rarely incorporated carefully within architectural or structural models. Therefore, the direct use of design models for CNC-enabled manufacturing is inconsistent. As a result, manufacturers develop an independent CAD/CAM model that incorporates both the approved design and the practicalities of factory production [38]. This model facilitates the development of shop drawings, cutting lists, nesting plans, and machine-readable files, including BVX, BTL, or NC codes [13,30,31].

The manufacturing modelling process typically begins following the completion and approval of architectural and structural documentation. Manufacturers receive a set of project files typically including IFC, DWG, and PDF mark-ups, that must be analysed and reconstructed within proprietary CAD/CAM systems [31,34]. Re-modelling has become widely utilised in the industry due to the limited interoperability across design and manufacturing tools [14,19].

Despite IFCs being recognised as a neutral exchange format, the integration of these files into manufacturing tools often results in geometric imperfections, positional discrepancies, metadata loss, and incorrect connection definitions [34,51]. Even small changes could lead to significant implications during automated CNC processes. As a result, many manufacturers choose to reconstruct models utilising 2D/3D references instead of rectifying defective imports [20].

Figure 3 represents the current industry workflow for design-to-manufacturing in prefabricated timber construction, highlighting the reliance on manual re-modelling and multi-format data handovers between design and factory environments. In Australia, prefabricated timber manufacturers utilise a range of specialised software platforms selected primarily based on product type, factory workflow requirements, and compatibility with existing CNC machinery. Software choices are typically shaped by operational capability, in-house expertise, and machine integration needs rather than industry-wide interoperability considerations.

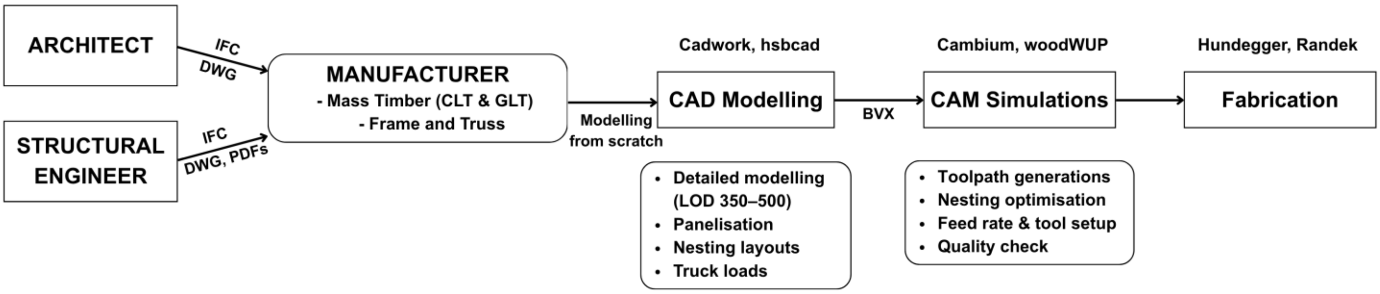

Figure 3. Overview of the current industry workflow for design-to-manufacturing in prefabricated timber construction.

Table 5 summarises the main software tools identified across the reviewed Australian timber manufacturing and technical sources, together with their typical functions, strengths, and commonly reported limitations.

Table 5. Software tools currently used in the Australian prefab timber industry.

Software	Primary Function	Typical Use	Key Strengths	Limitations/Challenges
Cadwork [76,77]	3D modelling, Detailing, CAD/CAM export for timber systems	CLT, GLT, wall & floor panels, light-frame timber construction	Modular architecture; strong CNC/fabrication-data export capability.	IFC/BIM workflows less emphasised; potential metadata loss when interfacing with broad BIM platforms
HsbDesign (hsbcad) [78]	BIM-based design + manufacturing data export for off-site timber	Panelised walls/floors/roofs, CLT/SIP, light-frame factories	Compatible with AutoCAD/Revit; export to major CNC machines.	As with many design-to-manufacture tools, full parametric flexibility and machine-specific export may require configuration
MiTek Sapphire [62–64]	Whole-house 3D model, design & production workflow for timber/framing	Residential wall & roof framing, trusses, panelised timber systems	3D digital model of entire structure; supports manufacturing output.	Ecosystem is relatively closed; interoperability with non-MiTek production systems may be limited
Pryda Build [65–67]	Truss and frame design software + production automation	Roof trusses, floor trusses, light-frame components	Australian-fabricator focus; training/support ecosystem.	Primarily focused on truss/frame rather than large panels; export/coordination across diverse machines may be less developed
Vertex BD [79]	BIM software for wood & cold-formed steel framing	Modular & panelised housing, timber framing factories	Automates drawing sets, material scheduling, manufacturing data.	CNC export capability may be less well documented; IFC property mapping may vary
Cornerstone (Multinail) [68]	Detailing + workflow coordination + manufacturing data export for truss/frames	Off-site timber module producers, truss & wall framing plants	Designed for the Australian timber industry; direct export to manufacturing machines.	Not always as deep in upstream BIM/design coordination for prefabricated panels; machine-specific export may require extra work
HOMAG woodWOP [61,80]	CAM/CNC programming software for machining centres	Downstream cutting, routing, machining of panels/beams	High-precision machine control; supports 3–5 axis CAM programming.	Requires fully modelled upstream data; less emphasis on design/BIM integration
Hundegger Cambium [52,53]	Production/CAM control platform for Hundegger machines	Large-format engineered timber: CLT, GLT, beam/kit-of-parts lines	Native machine-manufacturer platform; integrates design to machining for Hundegger equipment.	Specific to Hundegger machines; interfacing with non-Hundegger systems may require custom files or translation

These software platforms can be categorised into timber-specific 3D modelling and detailing environments for developing manufacturing models for production, vertically integrated 3D truss and frame systems offering a combination of engineering and production outputs, and machine-based CAM/control environments used to execute manufacturing data [31,34]. Although some platforms offer some level of similarity to one another, the choice of a platform is often based on various factors such as product type, compatibility with a CNC machine, licensing, and technical support, among others, and not on the level of industry-wide integration [19].

(c) Manufacturing planning, documentation, and quality control

Following the internal verification of the manufacturing model and consultant approvals, the production process begins, including nesting, documentation, coordination of the logistics, and quality assurance [34,81]. The nesting in mass timber manufacturing includes optimising the positioning of panels and machining processes on billets to improve material efficiency [15]. In lightweight framing and truss manufacturing, optimising similarly emphasises saw-cutting patterns to reduce waste and assembly time while maintaining structural integrity and connection effectiveness [33].

Machine-readable files generated by CAD/CAM platforms, such as BVX, BTL, or NC formats, are transferred to specialised CAM environments compatible with specific CNC machines [31,50]. These systems function as the final digital interface between modelling and fabrication, where imported data is verified, optimised, and transformed into executable toolpaths [15,30]. Simulation and validation processes are executed to evaluate tool accessibility, collision risks, fastening methods, and tolerance compliance, functioning as the final digital verification before machining [31,53,80].

Manufacturing documentation is thereafter produced to facilitate coordinated manufacturing and installation [31,32]. Outputs typically include CNC job files, component labels, cutting lists, quality assurance diagrams, inspection checklists, loading plans, and installation drawings. These documents ensure the alignment of machining logic, packaging order, and site sequencing, thereby maintaining the efficiencies achieved throughout digital production [30,33].

Quality assurance procedures are integrated throughout the workflow. Throughout the design phase, the model's compliance with specifications and interface requirements is evaluated. Post-machining measurement checks ensure tolerance accuracy, while dispatch inspections ensure completeness, accurate labelling, and compliance with loading plans [31]. This comprehensive traceability across the modelling, machining, and dispatch phases improves responsibility, ensures quality compliance, and reduces conflicts arising from late design modifications or site-level inconsistencies.

3.3. Challenges and Limitations in Design-to-Manufacturing Integration

A major inefficiency in Australia's prefabricated timber sector is the repeated necessity to remodelling or reinterpretation of design data during the transition from design to manufacturing [21]. This problem extends beyond project miscommunication and indicates fundamental fragmentation within organisational structures, information management methods, and digital technology ecosystems. The absence of continuous integration between design and manufacturing reduces the key advantages such as speed, precision, and material efficiency of industrialised construction, and shows the lack of a unified digital framework for model development, exchange, and validation across disciplines [13,14,44].

3.3.1. Organisational and Procedural Fragmentation

Manufacturers are mostly involved only after the design approvals and procurement phases are finalised, limiting significant early-stage manufacturability contributions [14]. While engineers and architects consider Design for Manufacturing and Assembly (DfMA) concepts, they are rarely integrated at a level needed for direct production. Delayed involvement of manufacturers limits design optimisation possibilities and leads to models that frequently lack compatibility with manufacturing software environments or machine-specific data requirements [34,37]. As a result, manufacturers must reinterpret approved models within their systems, which causes duplicated modelling efforts, data loss, and an increased chance of interpretive errors [38,49].

3.3.2. Information Granularity and Model Incompatibility

The transition from design models to manufacturing-ready data is limited by varying degrees of information granularity among disciplines. Models designed for coordination and regulatory approval generally lack manufacturing-level attributes, as the inputs change depending on a variety of product types, production workflows, and CNC platforms [31,34]. In practice, this creates uncertainty about what information is reliable, what is missing, and who is responsible for defining it during the handover from design to manufacturing [19,37].

Manufacturers rarely depend on the incoming design models and proceed with remodelling the design within proprietary CAD/CAM environments, which satisfy the machine constraints, internal production standards, and sequencing requirements [30]. This translation stage presents risk, as assumptions may be established and design intent may diverge when parameters are poorly specified [38]. File-based exchanges increase these issues, as IFC and DWG formats sometimes do not maintain parametric and semantic integrity, resulting in metadata loss and dependence on 2D drawing checks or PDF remarks. The lack of unified information requirements and model governance breaks digital continuity between design and manufacture [31,74].

3.3.3. Software Fragmentation and Interoperability Challenges

The Australian prefabricated timber industry operates within a very diverse software ecosystem that goes from architectural modelling to structural analysis, detailing, and manufacturing-specific CAD/CAM. These systems are optimised for specific lifecycle stages and usually rely on different data schemas, file standards, and, in many cases, proprietary formats. As a result, the digital continuity between design and production environments is still limited [14,19].

Although IFC and DWG are neutral exchange formats commonly used for coordination, they are insufficient to communicate the detailed parametric and machining information necessary for fabrication [51,74]. As a result, information that is technically accurate in a design stage becomes incomplete or unreliable in manufacturing contexts and requires model remodelling to ensure compatibility with CNC machines [82].

3.3.4. IFC and Timber-Specific Manufacturing Data Formats

A further interoperability issue relates to the different purposes of general BIM exchange formats and timber-specific manufacturing data formats. Industry Foundation Classes (IFC) is widely used as an openBIM format for multidisciplinary coordination, object-based information exchange, and model sharing between design and engineering platforms [31,51]. In prefabricated timber projects, IFC can support the transfer of building elements, geometric relationships, spatial information, and selected object properties between software environments.

However, IFC-based exchange is generally more suitable for coordination and information transfer than for direct CNC production. Manufacturing requires a higher level of fabrication-specific information, including machining operations, connection processing, production tolerances, part identifiers, sequencing logic, and machine-specific parameters [13,21,31]. These requirements are not consistently embedded in coordination-stage BIM models, which can lead to information loss, remodelling, or additional checking before fabrication [51].

Timber-specific manufacturing formats, including BTL, BTLx, BVX, and NC-type outputs, are more directly associated with CAD/CAM and CNC production workflows. These formats can transfer fabrication-level operations such as cutting, drilling, milling, notching, profiling, and component identification to machine-control environments

[13,31,50]. These formats are therefore important for converting manufacturing models into machine-readable data required for CNC-based production.

Nevertheless, these manufacturing formats do not automatically resolve the design-to-manufacturing integration problem. Their reliability depends on the quality, completeness, and governance of the upstream model from which they are exported. If design intent, tolerances, material specifications, connection logic, or element definitions are incomplete, the exported manufacturing data may still require manual correction, remodelling, or validation before CNC execution [21,50].

Therefore, the integration challenge should not be understood as a simple choice between IFC and BTL/BTLx. IFC remains important for openBIM coordination and multidisciplinary exchange, while BTL/BTLx and related outputs are more relevant to fabrication and CNC execution. The key requirement is a governed workflow in which information progressively matures from design coordination to manufacturer-ready production data through early manufacturer involvement, agreed information requirements, model validation, and structured handover processes [13,31,51].

3.3.5. Role Ambiguity and Lack of Defined Frameworks

A continuous challenge in design-to-manufacturing integration originates from the lack of well-defined frameworks defining stakeholder roles, responsibilities, and data ownership. Many projects lack a formal agreement defining accountability for tolerances, datums, or interface geometry throughout the transition from design to manufacture [39]. Architects define dimensional intent, engineers assess structural limitations, and manufacturers modify tolerances according to production capabilities, often in isolation from each other [37]. This misalignment results in differences in shop modelling, iterative defining processes, and late-stage design modifications, hence increasing both technical and coordination risks [14,34].

3.3.6. Insufficient Standardisation and Data Governance

Despite model-based standards like IFC supporting design-stage coordination, they are insufficient for providing the manufacturing-specific interpretation necessary for prefabrication. Existing exchange formats generally communicate geometry and fundamental properties but lack fabrication-critical information. This lack of common standards also creates problems in governance. There is no clear guideline available on the ownership of data, transfer of liabilities, or certification between design consultants and manufacturers.

As a result, the process of verifying model accuracy and approving shop-level modifications often occurs informally, relying on unstructured communication and personal relationships rather than regulated workflows [30,31,34]. As a result, the absence of established information maturity standards, defined handover requirements, and validated exchange of information methods increases dependence on manual coordination.

4. Discussion

The findings indicate that the design-to-manufacturing gap in prefabricated timber construction is not simply a software issue, but a broader systems-level problem involving workflow fragmentation, uneven information maturity, and weak governance across the transition from design to production [83]. Rather than supporting continuous model-based integration, current practice remains characterised by staged handovers and discipline-specific reinterpretation, which limit the effective use of digital tools across the full delivery process.

Improving integration does not necessarily require replacing current specialised software platforms. It necessitates process-oriented coordination methods that coordinate architectural, structural, and manufacturing knowledge at an earlier stage to maintain this alignment throughout the design-to-delivery lifecycle [50]. Parametric and computational modelling platforms can function as a foundational intermediary, facilitating the representation and stabilisation of design intent, manufacturing limitations, and assembly logic before discipline-specific detailing begins.

The effectiveness of this technique depends on well-defined decision gates, clear information ownership, and common definitions of manufacture-ready data. In the absence of defined governance, established data requirements, and defined responsibilities, digital tools alone are insufficient to prevent downstream rework. The following sections provide structured recommendations to assess the advantages and implementation challenges of a unified digital framework for prefabricated timber buildings.

4.1. Recommendations for Improving Design-to-Manufacturing Integration

Addressing the design-to-manufacturing gap in Australia's prefabricated timber sector requires more than software adoption alone. The following recommendations focus on strengthening collaboration, information continuity, manufacturer-ready deliverables, and governance across specialised digital platforms [6,84].

4.1.1. Integrating Manufacturers into Early Design Decision-Making

Manufacturer engagement at later project stages remains a major contributor to rework, information loss, and production delays [31,32,34,85]. Engaging manufacturers at the early design phases enables manufacturability constraints, tolerance techniques, and machine capabilities to influence geometry while maintaining adaptability [1,21,49,86].

To encourage early manufacturer engagement, the project needs to incorporate established decision gates associated with information maturity. At each phase, essential geometric and manufacturability criteria should be assessed and confirmed before progressing. After approval, these features become fixed to prevent uncontrolled downstream changes, thereby minimising late-stage rework and defining responsibility across disciplines [44]. This method defines clear standards among architects, engineers, and manufacturers by defining which information is modifiable and which parameters have been formally established.

4.1.2. Establishing a Shared Parametric Geometry Framework

A shared parametric geometry framework facilitates the integration of architectural, structural, and manufacturing expertise while allowing stakeholders to maintain their preferred specialised tools [14,49]. This framework serves as a reliable and verifiable reference model that incorporates important project concepts, including grids, interface requirements, modular regulations, segmentation techniques, and essential manufacturing limitations. In this role, the parametric backbone functions as the digital point of alignment across architectural, structural, and manufacturing workflows. Figure 4 shows the proposed shared parametric geometry framework linking architectural, structural, and manufacturing models through a central computational backbone.

Parametric and computational modelling environments, such as Rhinoceros with Grasshopper or Revit with Dynamo, are particularly well-suited for this purpose as they facilitate rule-based modelling instead of static geometry [14,38,87,88]. Design intent can be formally integrated through parametric relationships that define tolerances, modular coordination, and assembly logic. These regulations remain flexible in the initial phases, allowing controlled iteration while maintaining consistency among downstream models [89]. Each discipline can thereafter produce comprehensive documentation, analysis, or manufacturing outputs within its specialist platform while maintaining alignment with the common geometric framework [83,86]. Connecting parametric logic to decision gates enhances the management of information maturity, differentiating between adaptable design variables and stable, production-ready parameters.

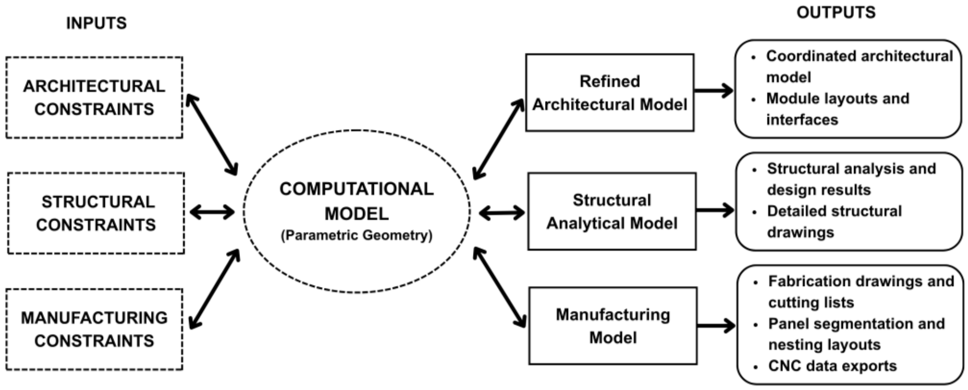

Figure 4. Shared geometry framework linking architectural, structural and manufacturing models through a central computational backbone.

4.1.3. Standardising the Manufacturer-Ready Dataset

A significant weakness in the present practice is the lack of a distinctly established foundation for "manufacturer-ready" data. In the absence of established minimum information requirements, deliverables often remain incomplete or inconsistent, requiring manufacturers to reinterpret design implications. A standardised, manufacturer-ready dataset must include confirmed geometric definitions, material specifications, tolerances, interface conditions, and sequencing information necessary before the initiation of production [16]. Implementing these needs into contractual agreements formalises accountability and illustrates the transition from design responsibilities to manufacturing execution. This standardisation enhances trust in digital outputs and facilitates more reliable downstream automation.

In addition to geometric and production information, the manufacturer-ready dataset should incorporate relevant timber design standards, building code requirements, and project-specific technical criteria. These requirements may include timber product specifications, material grades, member sizes, connection requirements, fabrication tolerances, fire and acoustic requirements where relevant, durability considerations, serviceability limits, and inspection or certification requirements.

Within an integrated workflow, these standard-based requirements should be translated into explicit model parameters, decision-gate checks, and information handover requirements rather than remaining only in separate drawings, specifications, or manual review processes. This ensures that the transition from BIM coordination models to CAD/CAM and CNC-ready manufacturing data is governed not only by software compatibility, but also by compliance, constructability, and production reliability.

4.1.4. Role Definition, Training, and Collaborative Protocols

Effective digital integration exceeds modelling techniques and requires organisational integrity. Roles and responsibilities regarding tolerances, interface geometry, revision control, and data validation must be clearly defined from the beginning of the project. Implementing organised governance tools, such as a RACI framework, helps minimise redundancy, improve decision-making, and promote transparent data exchanges [34].

Additionally, continuous investment in training and multidisciplinary development of skills is essential. Parametric and data-driven processes require knowledge of both specialised software tools and the associated platform logic and manufacturing limitations [46,89]. Pilot projects serve as controlled settings for evaluating integration strategies, documenting lessons learned, and developing repeatable templates. Overall, these initiatives can enhance a comprehensive knowledge base within the industry, enabling consistent, model-based collaboration throughout the prefabricated timber supply chain [3].

4.2. Comparison with Existing BIM, Digital Twin, and Collaborative Delivery Approaches

BIM workflows, digital twin approaches, and Integrated Project Delivery (IPD) each contribute to digital and organisational integration in construction, but they address different dimensions of the problem. BIM mainly supports design coordination, documentation, clash detection, and information sharing [23–25]. Digital twins focus on lifecycle data linkage, simulation, monitoring, and feedback between physical and digital assets [90–92].

IPD promotes earlier collaboration, shared decision-making, and improved alignment between project stakeholders [93,94]. However, these approaches do not, by themselves, fully define the manufacturer-ready data structures, CAD/CAM translation logic, CNC requirements, and fabrication-level governance needed for prefabricated timber design-to-manufacturing integration [13,50].

As shown in Table 6, existing BIM, digital twin, and IPD approaches provide important support for coordination, information continuity, and collaboration. However, their focus is broader than the specific design-to-manufacturing transition addressed in this study.

Table 6. Comparison of the proposed framework with existing digital integration approaches.

Approach	Main Focus	Strengths	Limitations for Design-to-Manufacturing Timber Integration	Relevance to This Study
Conventional BIM workflows [22–25]	Design coordination, documentation, clash detection, multidisciplinary model sharing	Supports model-based coordination, information exchange and approval-stage integration	Often insufficient for fabrication-level data exchange; manufacturer-ready information and CNC-specific requirements are not consistently embedded	Provides an important upstream environment, but does not resolve the downstream design-to-manufacturing gap
Digital twin approaches [90–92]	Lifecycle data linkage, monitoring, and feedback between digital and physical systems	Supports data continuity, performance monitoring, simulation, and lifecycle feedback	Often focuses on operational monitoring or lifecycle feedback rather than early-stage manufacturing model structuring and fabrication handover	Relevant as an enabling concept, but not sufficient alone for the manufacturer-ready timber production workflows
Integrated Project Delivery (IPD) [93,94]	Early stakeholder collaboration, shared decision-making, and coordinated project delivery	Improves communication, early involvement, shared risk, and cross-disciplinary alignment	A delivery and governance approach rather than a model structure; does not itself define CAD/CAM translation, CNC data requirements, or fabrication-level information standards	Supports the collaborative conditions required for integration, but requires supporting digital workflow and data-governance mechanisms
Proposed conceptual framework	Design-to-manufacturing integration through shared parametric logic and manufacturer-ready information, and structured handover	Directly focuses on continuity between architectural, structural, CAD/CAM, and CNC-oriented manufacturing environments	Still conceptual and requires future validation through proof-of-concept workflows, case studies, or industry implementation	Addresses the specific software, data, and workflow fragmentation problem identified in this review

The proposed framework is therefore positioned as a complementary integration approach rather than a replacement for these existing methods. Its purpose is to clarify how shared parametric logic, manufacturer-ready information requirements, and structured handover processes can support better continuity between BIM coordination, CAD/CAM modelling, and CNC-oriented timber manufacturing.

4.3. Potential Benefits and Limitations of an Integrated Digital Framework

4.3.1. Benefits of an Integrated Digital Framework

The following benefits are based on the reviewed literature and workflow synthesis, rather than on empirically validated results of the present study. In this context, an integrated parametric and computational framework could serve as a useful basis for enhancing the connection between design, coordination, and manufacturing processes in prefabricated timber construction.

A unified parametric and computational framework may provide a useful basis for improving continuity between design and manufacturing stages in prefabricated timber construction [43,82]. Instead of replacing existing specialised tools, platforms like Rhinoceros with Grasshopper and Revit with Dynamo can serve as intermediary coordination layers linking architectural, structural, and manufacturing processes [27,38,73]. These platforms enable structured data sharing with BIM and CAD/CAM systems through open APIs and flexible plugin ecosystems, allowing stakeholders to operate from a common geometric and parametric baseline while maintaining discipline-specific modelling environments [14,19,73,84].

Figure 5 highlights the integrated digital framework adopted in this study, showing how structural geometry generation, BIM coordination, and manufacturing information are derived from a shared parametric backbone.

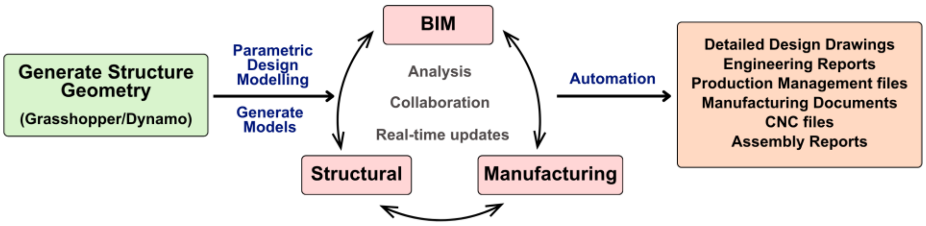

Figure 5. Integrated digital framework showing generation of structural geometry, BIM coordination, and manufacturing information from a shared backbone.

A key potential benefit of this framework is its capacity to stabilise fundamental project concepts earlier in the project lifecycle. By defining geometry, interfaces, modular rules, and tolerances as parametric relationships instead of static elements, teams can investigate various configurations while maintaining manufacturability limitations. This rule-based modelling approach may support more controlled iteration and reduce the likelihood of downstream reinterpretation [3,95]. Optimisation methods may be used to evaluate material efficiency, structural performance, cost considerations, and production feasibility, potentially supporting more customised outcomes while maintaining fabrication requirements [89,96].

The computational environment may also support preliminary structural reasoning during early design decision-making. While initially introduced as a neutral geometry backbone, Rhino/Grasshopper possesses capabilities far beyond geometric modelling [38,73,97,98]. Through an extensive ecosystem of plugins, it can perform structural analysis, environmental simulations, and performance-based optimisation at the early design stage, allowing designers and engineers to perform generative design optimisations [8,27,83,87]. The Figure 6 presents the role of the computational platform in enabling early optimisation, decision-making, analysis, and the automated generation of manufacturing-ready outputs.

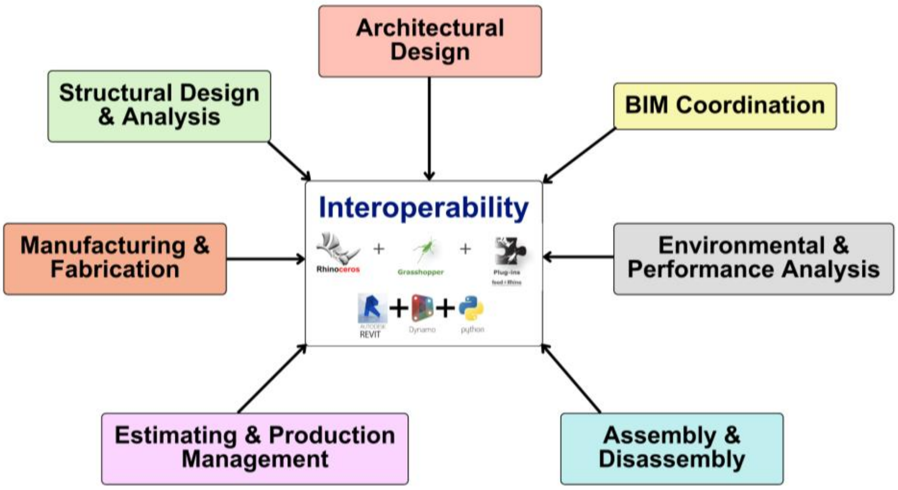

Figure 6. Computational platform for early optimisation, decision making, analysis and automated production outputs.

Beyond design and analysis, the framework supports the consolidation of tasks that are traditionally fragmented across multiple tools and document-based workflows. These computational tools may also support the generation of manufacturing-relevant outputs such as component schedules, identifiers, cutting lists, and structured shop-level information. Where manufacturer-specific constraints are defined, the same logic can support nesting and cutting pattern optimisation, and basic production planning [38,99].

Figure 7 highlights how an integrated digital framework could support a clearer distribution of information and responsibilities across the prefabricated timber design-to-delivery workflow, with potential benefits for coordination, resource use, and process efficiency.

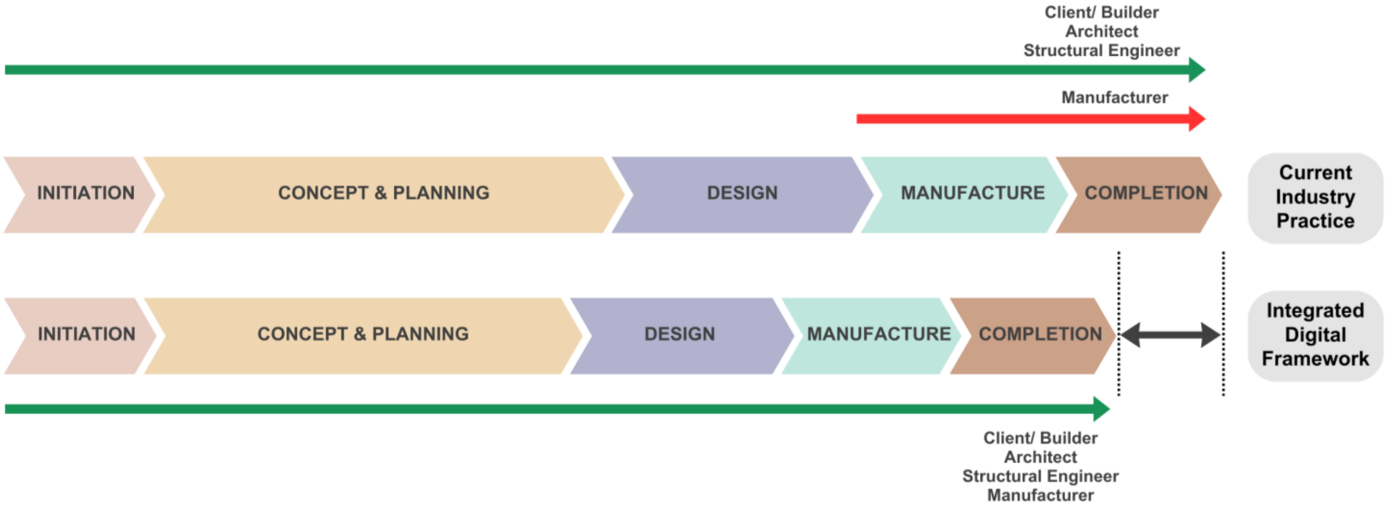

Figure 7. Current practice and integrated digital framework across the prefabricated timber design-to-delivery workflow.

An integrated digital framework may offer several potential benefits across the design-to-delivery lifecycle by supporting a shared geometric reference that could reduce design rework, limit unnecessary data translation, and minimise downstream production errors. Improved continuity between design, detailing, and manufacturing environments may support more manufacturing-aware decision-making, helping align architectural intent and structural performance with fabrication and assembly constraints.

Additionally, it enhances the coordination between stakeholders, increasing predictability in logistics, site operations, and installation processes. At the same time, improved material utilisation and reduced waste support more resource-efficient and sustainable construction outcomes. These potential benefits suggest that prefabricated timber systems could move toward more integrated digital workflows, with possible improvements in coordination, accuracy, and resource efficiency if implemented effectively.

4.3.2. Limitations and Implementation Constraints

Despite the significant potential of the proposed approach, several constraints continue to impede its full implementation within the prefabricated timber industry. One of the most fundamental challenges lies in the existing procurement and contractual structures. Traditional project delivery models rarely accommodate early-stage collaboration or the technical integration necessary for shared digital environments. Manufacturers are commonly engaged only after the design has reached approval or tender stages, which limits early involvement opportunities and minimises the impact of manufacturability considerations. As a result, late-stage adjustments often occur under compressed timeframes, leading to inefficiencies and coordination issues across disciplines.

A second constraint relates to limited digital proficiency and technical capacity in the industry [1,14,38]. The adoption of parametric modelling, computational design, and data governance requires specialised knowledge that remains underdeveloped in much of the Australian construction industry [15,82,97]. Without systematic investment in education, training, and cross-disciplinary skill development, implementation will remain limited to technologically advanced organisations and academic-industry collaborations [46]. The absence of a skilled workforce also increases the risk of inconsistent data management and fragmented model ownership, both of which undermine the reliability of digital workflows [14,39].

Technological fragmentation remains another significant constraint, as manufacturers continue to depend on diverse proprietary CAD/CAM tools, even when operating within a shared geometric backbone. This diverse ecosystem complicates interoperability and prevents the seamless transfer of data from design to CNC production. Consequently, complete automation of the design-to-manufacturing workflow remains an aspirational objective rather than an achievable standard.

The construction industry has historically been resistant to the adoption of new digital processes due to perceived risks, upfront investment costs, and uncertainty regarding long-term benefits [16]. Many organisations are reluctant to alter established workflows due to concerns about productivity disruption and loss of control over proprietary data [14]. These cultural and organisational factors reinforce fragmented practices and slow the transition toward collaborative, data-driven project delivery models [38].

The success of digital integration depends on coordinated alignment across the supply chain. Inconsistent stakeholder participation disrupts data continuity and reintroduces manual interventions. Overcoming these challenges requires systemic change beyond technological solutions, supported by structured governance, collaborative frameworks, and policy mechanisms that promote shared accountability and sustained digital maturity within the prefabricated timber sector.

As this study is a systematic review and conceptual framework, the proposed integration framework has not been implemented as a software prototype or validated through a live industry case study. Future research should test the framework using representative prefabricated timber projects and assess practical indicators such as remodelling effort, information loss, manufacturer-ready data completeness, software interoperability, and design-to-manufacturing continuity.

In addition to these implementation constraints, several methodological limitations should be noted. The academic database search was limited to ScienceDirect and Web of Science, and only English-language publications from 2015 to 2025 were considered. Although these databases provide broad coverage of construction, engineering, and digital technology research, relevant studies indexed in other databases may not have been captured.

The industry and technical documentation were also selected purposively to supplement the academic literature and may not capture every software platform, machinery vendor, or manufacturing workflow used across the prefabricated timber sector. These documents varied in scope, technical depth, transparency, and purpose, as some were prepared for software support, product guidance, or machinery implementation rather than academic reporting. Therefore, they were not treated as equivalent to peer-reviewed empirical studies but were used to provide practice-based evidence on software environments, CNC data preparation, machine-readable formats, and production-level constraints.

5. Conclusions

This study reviewed the challenges of integrating design and manufacturing in prefabricated timber construction, focusing on the Australian context and the interface among BIM, CAD/CAM, and CNC-based systems. The analysis reveals that frequent remodelling, fragmented software ecosystems, inconsistent information maturity, and late-stage manufacturer involvement are key obstacles to achieving reliable digital continuity from design to fabrication. These challenges indicate that the integration gap extends beyond technical file exchange, encompassing broader concerns related to workflow coordination, information governance, and clearly defined manufacturer-focused data requirements.

Based on these findings, the paper proposed a conceptual framework for digital integration focusing on earlier collaboration, shared parametric logic, and more structured handover processes between design and manufacturing stakeholders. This framework aims to serve as a structured foundation for future practical use, rather than offering a fully validated solution. Its main contribution is in identifying key areas of fragmentation and suggesting how a more coordinated digital workflow could be developed across prefabricated timber delivery procedures.

The review emphasises that the Australian prefabricated timber sector needs better interoperability practices, more initial collaboration, and clearer alignment between design and fabrication. Future research should test and refine the proposed framework using applied case studies, prototype workflows, or industry-based implementations. Such validation should assess whether the framework can reduce remodelling, improve manufacturer-ready data completeness, strengthen software interoperability, and support more reliable design-to-manufacturing continuity in prefabricated timber projects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18136790/s1, PRISMA 2020 Checklist; Supplementary Table S1: Summary of the 60 peer-reviewed studies included in the systematic review.

Author Contributions: Conceptualization, S.S. and T.G.; methodology, S.S. and T.G.; software, S.S.; validation, S.S.; formal analysis, S.S.; investigation, S.S. and T.G.; data curation, S.S.; writing—original draft preparation, S.S.; writing—review and editing, S.S., T.G., P.M. and D.W.B.; visualization, S.S.; supervision, T.G., P.M. and D.W.B.; project administration, T.G. and P.M.; funding acquisition, T.G., P.M. and D.W.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the University of Melbourne Research Scholarship and the Australian Research Council Industrial Transformation Research Program (ITRP)—Research Hub IH220100016: ARC Research Hub to Advance Timber for Australia's Future Built Environment.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: All data are contained within the article and Supplementary Materials.

Acknowledgments: The authors gratefully acknowledge the Department of Infrastructure Engineering at the University of Melbourne and the School of Architecture and Urban Design at RMIT University for their valuable support, resources, and academic environment. The authors also thank colleagues and collaborators for their constructive feedback throughout the development of this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modelling
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
DfMA	Design for Manufacture and Assembly
DfD	Design for Disassembly
GDP	Gross Domestic Product
CLT	Cross Laminated Timber
GLT	Glued Laminated Timber
LVL	Laminated Veneer Lumber
LOD	Level of Detail
IFC	Industry Foundation Classes

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