building 4.0 crc

#15:USING THE WHOLE TREE FOR FUTURE TIMBER-BASED CONSTRUCTION

FINAL REPORT

HYNE TIMBER

SUMITOMO FORESTRY AUSTRALIA PTY LTD.

THE UNIVERSITY OF MELBOURNE

Australian Government
Department of Industry, Science and Resources

Cooperative Research Centres Program

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CONFIDENTIAL:	☐ Yes X No
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Disclaimer

ABBREVIATIONS

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
CLST	cross-laminated secondary timber
CLT	cross-laminated timber
CFRP	carbon-fibre reinforced polymer
DfMA	design for manufacture and assembly
EWP	engineered wood product
EWPAA	Engineered Wood Products Association of Australasia
FE analysis	finite element analysis
FRP	fibre reinforced polymer
GFRP	glass-fibre reinforced polymer
GLTAA	Glued Laminated Timber Association of Australia
GLT	Glued Laminated Timber
glulam	glued laminated timber
GPa	gigapascal
IRR	internal rate of return
JAS-ANZ	Joint Accreditation System of Australia and New Zealand
kN	kilonewton
kPa	kilopascal
LCA	lifecycle assessment
LCC	lifecycle cost
LVL	laminated veneer lumber
MC	moisture content
MDF	medium-density fibreboard
MGP	machine graded pine
MOE	modulus of elasticity
MOR	modulus of rupture
MPa	megapascal
MTC	mass timber construction
MW	microwave
NCC	National Construction Code
NDS	US National Design Specification
NLT	nail-laminated timber
NLTC	NLT-concrete
ROIC	return on investment and capital
SANS	South African National Standards

1. EXECUTIVE SUMMARY

The sawn timber industry must adapt to changes in market demand, climate change impacts and changes in harvested wood characteristics. The building industry should consider the supply capacity of the sawn timber industry, including engineered wood products. To scale timber construction faster and more efficiently, future research should focus on the development of cost-effective and marketable structural solutions that use more of the tree.

This project was a scoping study where the aim was to find promising avenues of research that will optimise our use of the Australian timber resource. Specific objectives were to: review the sawn timber product supply chain and identify points where technology, processes, products and building systems can be developed, improved, or transformed; review and evaluate previous research efforts into optimising the use of the timber resource; examine the current and likely future place of timber products in the marketplace; and develop research projects for consideration of the project participants.

The research allowed identifying opportunities for utilising low-grade timber in the construction of residential buildings and for using more of the tree more effectively while adding value to the built environment in ways that align with the global effort to reduce greenhouse gas emissions and grow profitability across the supply chain from growers and millers to builders and end-users. Future steps would involve: 1) leveraging off previous work, extending it into the built environment and feeding knowledge back to the growers; 2) overcoming material mechanical properties shortcomings using innovative technologies; and/or 3) advanced modelling.

2. INTRODUCTION

2.1 Background and problem statement

The Australian timber processing sector is being squeezed by increasing demand on the one hand and irreversible changes to the raw material characteristics on the other. Global consumption of logs is accelerating as efforts to decarbonise the economy gain traction [1] Demand for low carbon building materials, such as timber, is expected to increase with specialists anticipating an accelerated growth in demand for timber of 3.1% per year over the coming decades, driven by urbanisation, decarbonisation and increased housebuilding [2]. The bushfire season of 2019/2020 had a devastating impact on the timber industry. Victoria and NSW have lost 19% and 25% of their plantation timber, respectively, which effects will be fell for many years [3].

The stark reality is that the required growth in the production of high stiffness sawn timber products sufficient to meet increasing market demand cannot be met if current practices continue. Volume of harvested logs has risen from 20 to 30 million m^3 over the last 2 decades in Australia and forecasts of log availability remains flat over the next 5 decades [4]. In addition, properties of wood produced from intensively managed plantations are different from wood produced in natural stands [5,6]. By the time of harvest around 30 years old, the proportion of juvenile wood in fast growing pine plantations is often more than 70% of the log volume [5–8].

When a log is sawn into boards, a key characteristic of interest is bending stiffness. After being seasoned, boards are mechanically and/or acoustically tested to determine their modulus of elasticity (MOE). As highlighted in numerous studies, the percentage of high stiffness wood available is reducing, notably because of a higher proportion of juvenile wood (more variability, lower mech. properties). As a natural product, there is substantial variation in the structural performance characteristics, and hence the economic value, of sawn timber within a given tree. Large portions of this lower stiffness timber does not meet the requirements of the commonly used and in high demand machine graded pine (MGP) grades. Ultimately, the construction industry, pivotal in the shift towards sustainable building practices, faces a critical challenge in aligning new building designs and methodologies with the qualitative and quantitative capacities of the forest industry chain. As demand for timber, a key renewable resource grows, there is an increasing risk of misalignment, which could hinder the effective use of forest resources. Therefore, optimising resource use and exploring methods to utilise more parts of the tree are essential strategies to manage supply growth and enhance the sustainability of construction practices.

2.2 Aim of the study and project objectives

This project was a 12-month scoping study where the aim was to find promising avenues of research that will optimise the use of the Australian timber resource.

The sawn timber industry must adapt to changes in market demand, climate change impacts and changes in material characteristics. The building industry must consider the supply capacity of the sawn timber industry, including engineered wood products (e.g. glulam, LVL, MDF, truss). An opportunity exists to find ways of using more of the tree more effectively while adding value to the built environment in ways that align with the global effort to reduce greenhouse gas emissions and grow profitability across the supply chain from growers and millers to builders and end-users. To scale up timber construction more rapidly and efficiently, future research should focus on the development of cost-effective and marketable structural solutions for timber, including the lower performing portion that is grown and produced alongside the high-grade products.

Therefore, the main aim of this study was to find promising avenues of research that will optimise the use of the Australian softwood timber resource. This aim will be served by meeting the following 4 objectives:

- Review the sawn timber product supply chain and identify points in the supply chain where technology, processes, products and building systems can be developed, improved, or transformed.

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- Review and evaluate previous research efforts into optimising the use of the timber resource.
- Examine the current and likely future place of timber products in the marketplace.
- Develop research projects for consideration by the project participants. The study will also provide opportunities for industry partners to identify collaborative projects that they may wish to pursue within the Building 4.0 CRC.

Figure 1. Project objectives.

2.3 Scoping study methodology

The study reviewed the sawn timber product supply chain from a technical/structural perspective, starting with resources characterisation techniques, through processing, structural design and installation. For this review, the research team considered manufacturing process of engineered wood products (EWPs), 'stick' and framed type of construction, and mid-rise applications. Current international uses of timber products were reviewed from the literature to identify promising avenues of research and equip industry partners with new knowledge about products and systems that use more of a harvested tree. Non-structural factors (such as economic and supply issues) and competition from substitute systems were used to supply context for the technical considerations. The study also evaluated risks and opportunities arising from the market and examined the influence of codes and other factors such as embodied carbon, grading of structural timber and construction method. Finally, the study explored the use of efficient advanced manufacturing techniques to formulate concepts/proposals and avenues to address the development of cost-effective and marketable structural solutions for low grade timber.

The methodology and activities included:

- an academic and industry literature review
- an observation tour (e.g. sawmills)
- structured interviews and workshops with stakeholders and experts in the field
- research and development proposals on basic principles observed, technology concepts formulated and findings from the scoping study

2.4 Overview of the sawn timber supply chain

2.4.1 ABARES data

In 2019, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) published a National Wood Processing Survey for the 2016-2017 financial year. This report and the subsequent Australian forest and wood product statistics report contained findings that answer some key questions around the timber supply chain in Australia [4,9].

What is the timber used for?

Of the 3,908,000 m^3 of total sawn wood produced in Australian softwood mills in 2016-17, the majority (2,019,000 m^3 or 51.7%) was utilised in *dry structural* applications. *Dry structural* includes all the most common structural timber products, i.e. joists, studs and bearers, as well as component boards in glulam and cross-laminated timber (CLT). A further 25.3% (989,000 m^3) was not seasoned and sold as green timber for pallets, fencing, landscaping, etc. The remaining 23% (869,000 m^3) was seasoned and further processed into flooring, furniture, pallets and other appearance products. Alongside this sawn wood production, 1,634,000 m^3 of wood-based panels such as MDF, particle board and plywood, and 196,000 m^3 of posts and poles were produced. So, although significant non-structural applications are identified for timber, most of the softwood milled in Australia is prepared for structural purposes.

How much low-grade timber is imported?

The ABARES reports do not identify any low-grade timber[1] imports. However, $689 million of wood-based panels (MDF, particleboard and plywood) were imported in 2020-21. The total timber import value in 2020-21 was $5.4 billion (down 3% from the previous year). The majority of this was made up of paper and paperboard imports ($1.9 billion). The rest was made up of miscellaneous forest products, paper manufacture and pulp.

How much low-grade timber is exported?

The total value of exported low- and high-grade wood products in 2020-21 was $2.7 billion. This was an 18% decrease in total export value from the previous year. Most of this decrease in export value was due to a fall in the value of woodchip and paper products internationally, which make up most of the export volume.

How do these values vary over time?

The softwood logged volume has remained relatively steady over the past 5 years at around 16,000,000 m^3. Almost 65% of that is sawlogs, with the remaining 35% being pulp log. Hardwood log harvest volume had increased in the years from 2015-19, but has since dropped due to falling export prices for woodchips (+95% of Australian hardwood logs are pulpwood). The gross value of softwood logs decreased in 2020-21 to $1.2 billion due to trade restrictions on softwood logs. This lowered the export prices received and so the volume harvested for export.

[1] For the present report, low-grade timber refers to a mechanically and/or acoustically tested softwood board that does not meet MGP10 grade bending stiffness requirements.

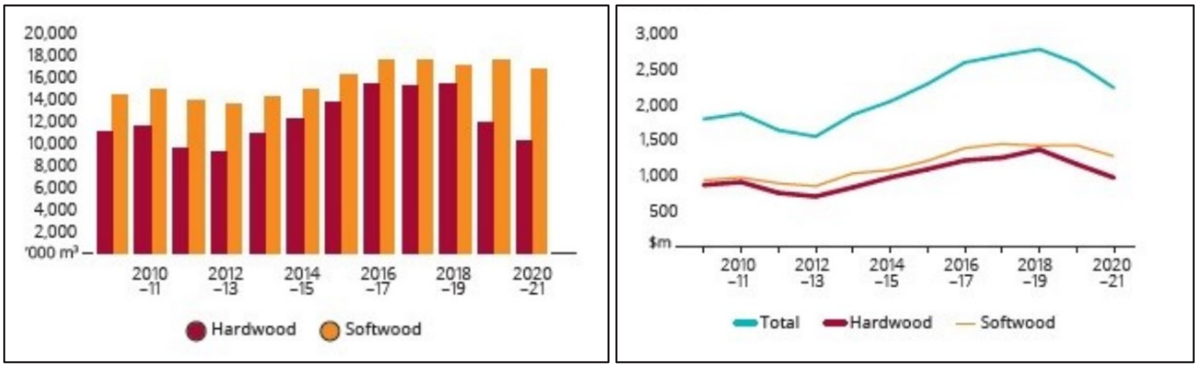

Figure 2. Volume and gross value of softwood and hardwood logs harvested in Australia between 2010-2021 [4].

The 2016-17 ABARES National Wood Processing Survey also reported the responses of softwood mills to a questionnaire asking what they saw as the main issues facing their industry. Of the 6 issues nominated by respondents, log quality was the least common (5%), with log costs, product demand, mill costs, skilled labour and log supply all featuring higher.

2.5 Academic and industry literature review methodology

2.5.1 Identification of relevant studies, study selection and charting the data

A scoping study has been performed to identify, review and evaluate previous research efforts into optimising the use of the timber resource (Figure 3). The scoping study considered a list of keywords of interest by project partners that allowed effort to focus on research areas deemed relevant. The identification and selection of relevant actors and studies started with a broad search strategy. The process was not linear but rather iterative to allow for flexibility and comprehensive searches. Through a reporting and consultation process, iterative selection allowed for refining the search strategy, research priorities and decisions surrounding study inclusion and exclusion.

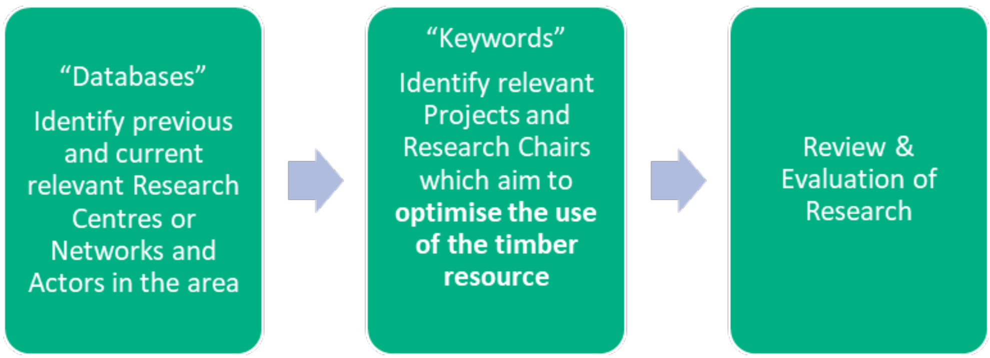

Figure 3. Approach adopted for the academic and industry literature review.

2.5.2 Low-grade timber and optimisation – timber production strategies around the world

Strategies around the world to increase the quantity and quality of timber produced have been adopted essentially to address climate change and wealth creation. As a result, most timber production strategies are aimed essentially at producing more volume or fibre directed to non-structural markets and applications. However, a decline in material characteristics i.e. stiffness, is not appearing at the forefront of industry discussions and research efforts [10–12].

Canuel et al. [12] identified 4 main possibilities that can be considered to increase wood supply value:

1. increase the quality of products extracted from forests and plantations.
2. increase the quantity of products and by-products.
3. increase the productive area, or
4. increase the amount of wood produced per unit area.

Other possibilities not listed by the authors include increasing demand, value adding through processing, reducing waste, optimising processing, optimising growth duration and silviculture practices e.g. planting, pruning, controlled burning, and pest/disease management.

From a grower's perspective, it is possible to increase the value of a plantation by increasing the volume of wood produced per unit area. Such a solution usually requires the adoption of intensive silvicultural practices whose impacts do not necessarily align with an increase in the quality and unit value. Rather, it aims to produce a greater volume of wood (i.e. m^3/ha*year), focusing mainly on characteristics that ensure efficient operations with less regard for the quality produced. This approach based on monoculture has been adopted by several countries, including New Zealand [11] and Scandinavian countries [10].

In North America, Canada advocates for a diversified approach by favouring development based on sustainable development principles [12–14]. These are usually inspired by natural disturbances. Currently, only certain stems or parts of stems are harvested according to their species, their dimensions or the quality of their fibre. Where the strategy in place prioritises the production of timber with desired characteristics, the focus is on: (1) a short-term optimisation of operational conditions to increase the harvest of available timber; (2) a medium- and long-term increase of timber harvested volume with actions designed around increasing the robustness of management strategies to be able to withstand risks and uncertainties in the context of climate change; and (3) improving forest productivity by intensifying silviculture and increasing the size of areas to be used for forest production. Strategies to improve the quality and quantity of timber available for harvest include selecting species based on phenotypic traits such as height, yield, colour, wood properties, and stress resistance. Additionally, efforts are made to improve fibre recovery by reducing waste, modernising timber processing equipment, and focusing on underutilised species. This approach is partly driven by the fact that only 50% of softwood production is used for solid wood products, with the remainder processed into pulp and paper. Another driving factor is the growing interest in diversification, notably in packaging due to the surge in online shopping post-pandemic, as well as in bioenergy and lignocellulose production.

A few challenges have been identified around the world when it comes to timber production and value creation. However, no emerging evidence has been found related specifically to the quality of produced wood fibre nor tangible efforts to understand or optimise the use of the timber resource in a context of changing material characteristics and getting them across the line meeting required stress grade. Increasing value based on quality, and quality based on quantity, are not mutually exclusive.

2.5.3 Low-grade timber, juvenile wood and rotation age

The review revealed that there is very little literature that draws on the use of low-grade timber. A review of the publications available via Web of Science since 2018 returned one result published by Cherry et al. [15]. The authors provided a critical review of the out-of-grade characteristics of pine timber to gain an understanding of the strengths and weaknesses of this resource as a structural building material. Methods to incorporate out-of-grade timber into current building systems were also presented and building technologies that can facilitate this use identified, such as CLT. An assessment of the literature citing Cherry et al. [15] returned a few results, although most were not deemed to fit the scope and limits of the present study and excluded as part of the scoping study search strategy (Figure 4).

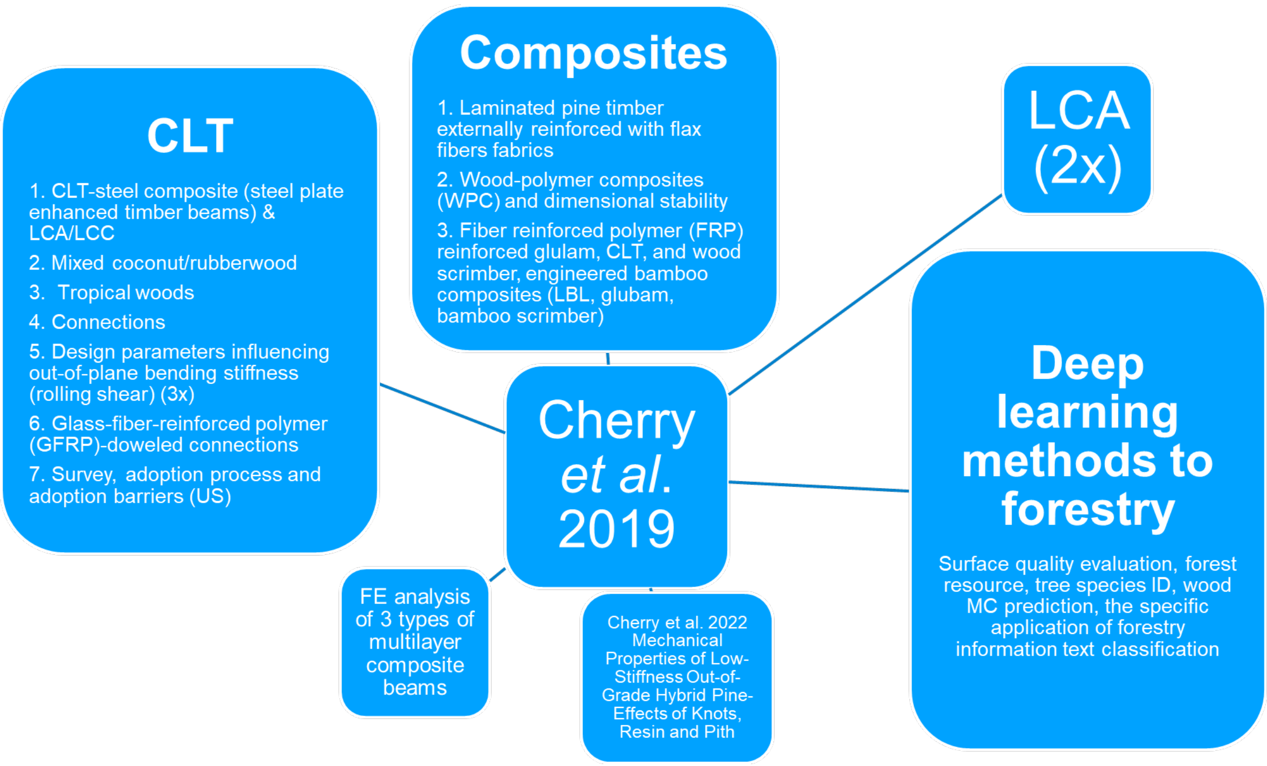

Figure 4. Literature review using low-grade timber as key words (since 2018)

Similarly, a review of the publications available via Web of Science since 2018 on juvenile wood returned only a few relevant results, with most covering tree breeding and selection. Burden and Moore [16] from Scion NZ (Forest Research Institute) discussed the need for structural wood products (including conventional timber) with a focus on Radiata pine and the adverse genetic correlations and impacts of silviculture involving wood properties. The review paper identifies key trade-offs and effects on the wood quality of silvicultural interventions that raise site productivity and/or reduce harvest age. The authors note that wood quality and juvenile wood are of major interest. However, almost all published results relate to the relationships among individual trees early in the rotation, whereas the practical interest lies in how the trade-off plays out for the whole crop at harvest age. Burden and Moore highlight an intriguing aspect: "a higher proportion of juvenile wood could lead to further loss of stiffness, and possibly poorer dimensional stability, though it may also result in a lower spiral grain angle and reduced fibre coarseness." The authors identified three primary determinants of profitability: productivity, measured by the amount of wood grown per unit of time; the price per unit volume of that wood; and harvest age, noting that earlier harvests can reduce effective growing costs. They concluded that addressing profitability requires the breeder's work to be supplemented by the careful deployment of improved breeds or clones to appropriate sites and silvicultural regimes.

The literature demonstrates that juvenile core wood does exhibit different properties to outer wood and improving the properties of juvenile wood would be financially beneficial. Detecting the extent of juvenile wood in a standing tree would be valuable to processors, but research is required to quantify the extent of juvenile core wood and wood properties, including spiral grain in combination with density, stiffness and strength.

2.5.4 EWPs, design and future trends

Modern EWPs like CLT are experiencing rapid market growth and becoming increasingly popular with designers. In addition to the building sector, the demand for natural textile fibres, sustainable packaging and biochemicals, as well as thermal and electric energy, is also poised to rise in the coming decades [17]. Adding to this, the ongoing adaptation of natural forests caused by climate change is expected to lead to a shift from a few dominant conifers (softwoods) towards a wider range of potentially more resilient deciduous (hardwood) tree species [18]. As suggested by Pramreiter et. al [17]., the situation is further complicated by the fact that the timber industry is predominantly optimised for homogeneous softwood assortments. Against this background, 3 solutions are proposed: (1) incorporate the resource efficiency of products into the decision-making processes of industry stakeholders; (2) promote a mix of available processing technologies e.g. combining sawmilling and stranding in a single process, and (3) optimise the efficiency of existing material concepts (Figure 5).

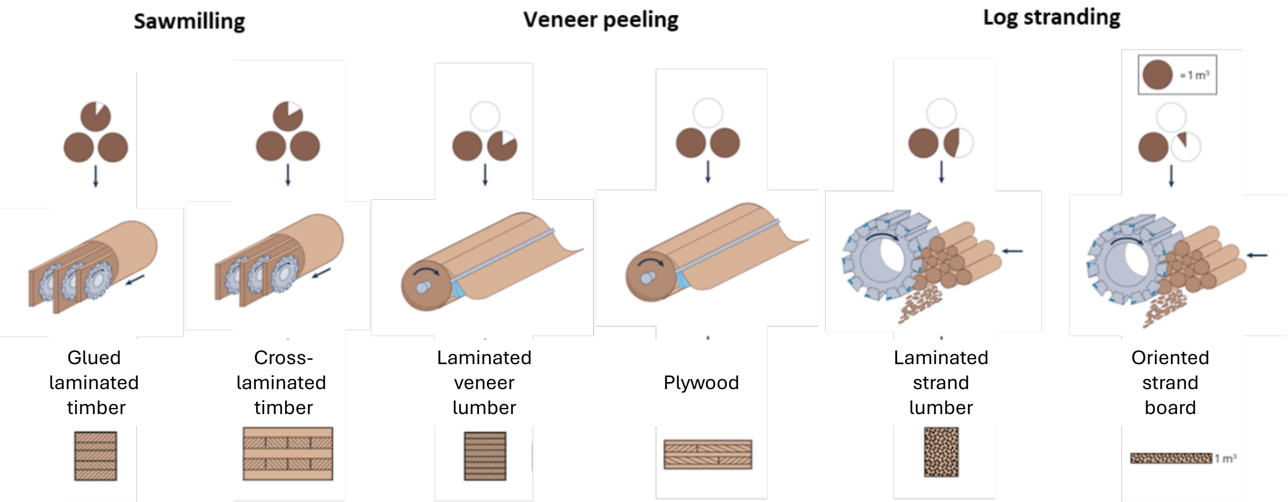

Figure 5. Resource demand of established engineered wood products. Estimated amount of round wood (without bark) required to produce 1 m³ of glued laminated timber, cross-laminated timber, laminated veneer lumber, plywood, laminated strand lumber or oriented strand board [17].

Limited opinion and scientific papers are pointing towards new material concepts that can add value to low-quality forest resources and the development of co-products from existing process streams. Using an old idea of analytically shaping individual components based on stress distributions unique to a given design situation [19]. As an example, a timber beam with a variable width could provide material savings up to 20% [19]. This example presented as a feasible example in terms of design and fabrication because it does not require adaptation of partition walls or floor-to-ceiling heights. The material savings presented in this report are the result of optimisation that aims to minimise the volume of structural material and demonstrate the possibilities of optimal design.

3. CASE OF AUSTRALIAN SAWN TIMBER PRODUCTION

3.1 Introduction

A descriptive industry case was explored to provide a specific example of Australian sawn timber production to compliment the broader and more general findings from the ABARES data. The site chosen was the Tuan softwood mill in Maryborough (Queensland), operated by Hyne, and the Tuan Forest plantation, managed by HQ Plantations. The case was informed by a site visit to the both the Tuan Forest plantations and the Tuan mill, as well as discussions with HQ Plantations and Hyne Timber representatives.

A visual summary of the sawn timber production process is shown in Figure 6. The process is split into the 3 broad stages of 'Plantation', 'Sawmill' and 'Construction'. At Tuan mill, the arrangement between Hyne and HQ Plantations is a volume supply agreement. This involves an agreed upon volume of logs being harvested that have met the required age and geometry parameters. No pre-harvest assessment of density or elastic modulus is used to inform value of the logs or prices charged to the Tuan mill. Within the plantation stage of the sawn timber production process there was also a projected decrease in fibre quality (predominantly stiffness). This has been identified by the Tuan mill, with smaller proportions of the processed logs achieving the minimum requirements for MGP10. The construction stage of the sawn timber production process includes all the post-production customers, (e.g. truss manufacturers, builders and homeowners).

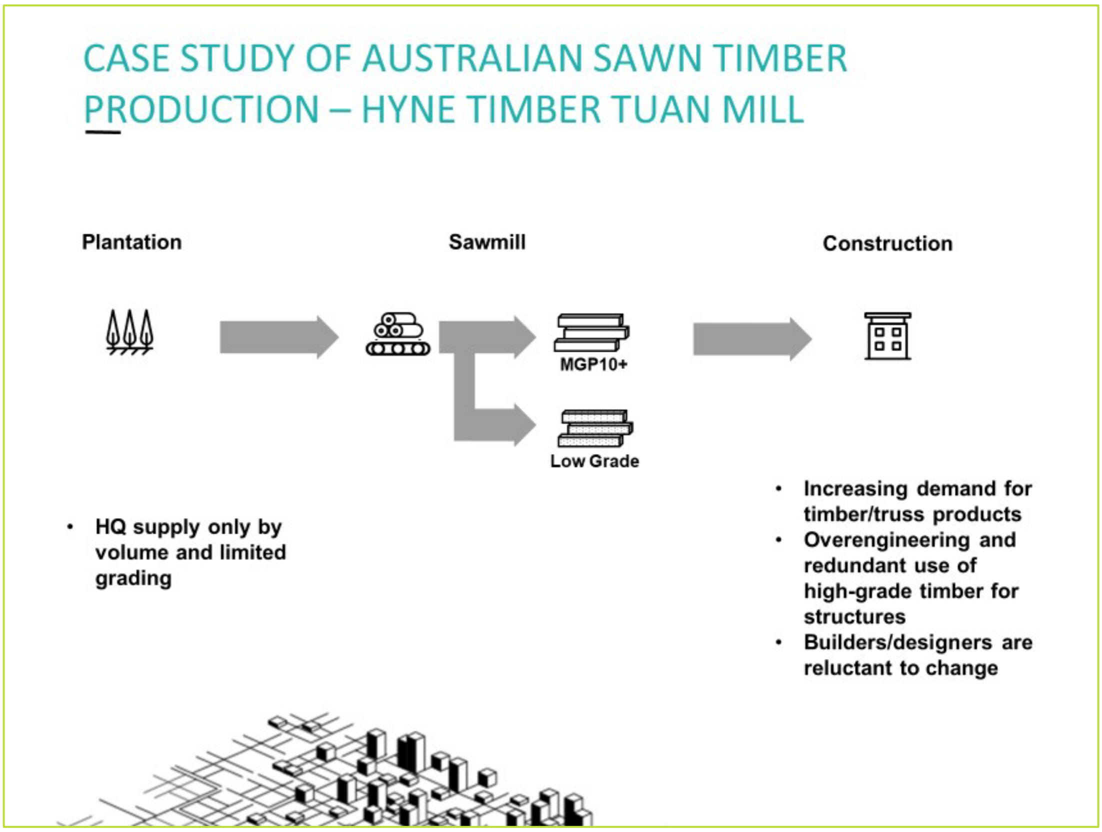

Figure 6. Case study of Australian sawn timber production – Hyne Timber Tuan mill.

The next stage was to identify opportunities for improvement within the process. These opportunities were broken into 3 categories by their relative time and cost investment: 'Low-hanging fruit', 'Mid-term with medium setup time or cost' and 'Long-term with large setup time or cost'. They are visually represented in Figure 7 with the colours red, yellow and blue respectively.

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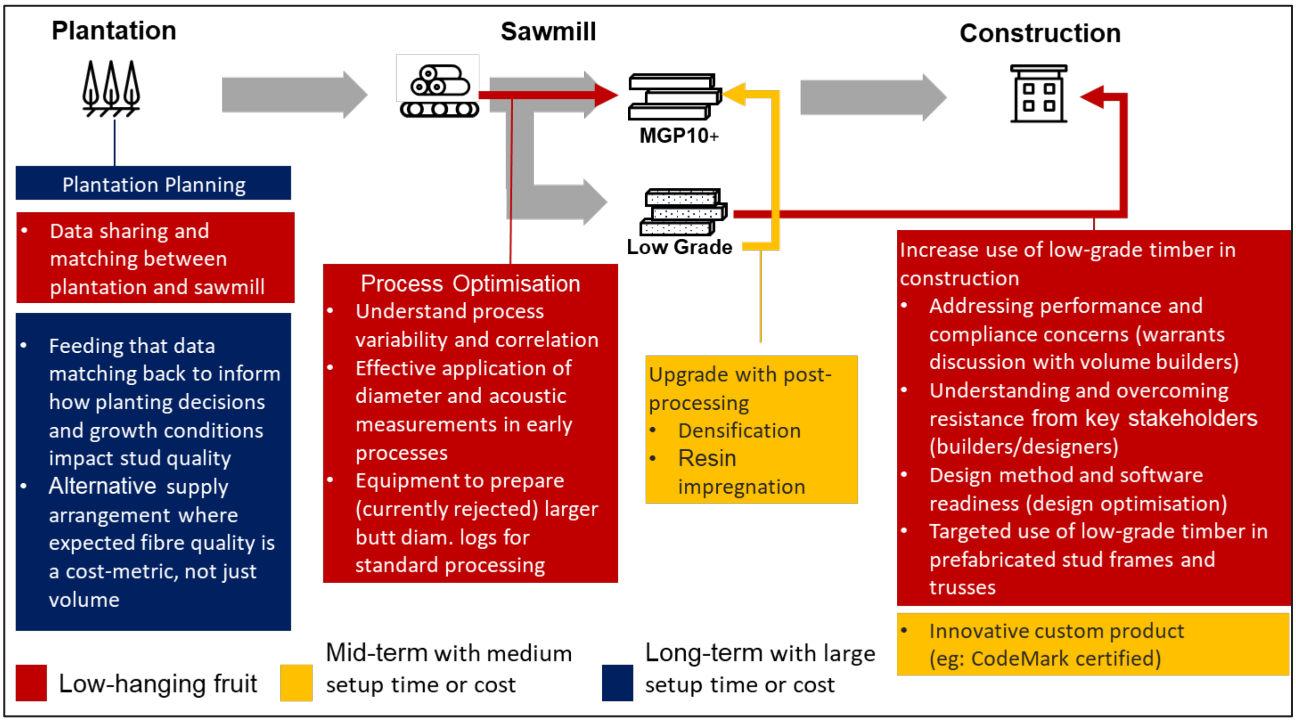

Figure 7. Opportunities of Australian sawn timber production – Hyne Timber Tuan mill.

3.1.1 Low-hanging fruit

There were opportunities with relatively low upfront time or cost investments identified across all 3 stages of the sawn timber production process. Within the plantation stage, data sharing and matching between Hyne and HQ Plantations could allow for a clearer understanding of the change in fibre quality over time and across the Tuan Forest plantation. This could benefit both parties as harvesting could be informed with more details by the exact products being demanded by the market to implement appropriate improvement strategies. The opportunities identified within the sawmill stage were centred around process optimisation. Understanding the variability and correlation between early material property measurements already in use (e.g. diameter, density, acoustic etc.) and the final product quality, along with an effective application of those measurements could allow for a lower proportion of lower-value boards being produced (at great expense considering the energy requirements of the drying kilns and operational costs of the planer and grading processes). Additionally, equipment that can handle the currently rejected larger butt diameter logs and prepare them for standard processing would provide more higher-value fibres for the mill. The opportunities identified in the third stage are focused on increasing the use of low-grade timber in construction. These opportunities include addressing performance and compliance concerns, overcoming resistance from builders and designers, and design software readiness. Targeted use of low-grade timber in prefabricated stud frames and trusses was also identified as an opportunity to increase the use of low-grade timber in construction.

3.1.2 Mid-term with medium setup time or cost

The opportunities identified by the Tuan Forest and mill case study that are achievable in the mid-term with medium setup time or cost address the sawmill and construction stages of the production process. Upgrading the low-grade timber with post-processing technologies such as resin impregnation and densification could allow for previously low-grade fibre to meet and exceed the minimum MGP10 grade standards. Innovative custom products (utilising the CodeMark certification process) were also identified as offering an opportunity to value-add to low-grade timber products.

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3.1.3 Long-term with large setup time or cost

The long-term opportunities identified were focused on the plantation stage of the production process. These included data matching between Hyne and HQ Plantations to inform how planting decisions and growth conditions impact stud quality. Alternative supply arrangements could be negotiated whereby expected fibre quality is a cost-metric with a high value weighting rather than the current agreement where volume is by far the most significant. These long-term measures could benefit all parties by allowing for preferred timber varieties (e.g. species or taxa) that yield superior fibre quality to be prioritised for planting, with high-quality fibre attracting a premium reflecting the market value of the final sawn product and meeting the needs of designers, builders and end users.

3.2 Observation tours

The research team undertook a site visit to HP Plantations to better understand the logistics and operations associated with plantation management (Figure 8). From plantation sites to harvesting site, HQ Plantations grow their estates 25–30 years depending on growth rate, volume achieved and client specifications. The second part of the tour was at the Hyne Tuan mill (Tuan Forest, Maryborough, Figure 9) which included group discussion between the research team and Hyne mill staff. The tour started at the log merchandiser and covered other manufacturing steps such as kiln-drying and the dry mill. The tour concluded with a visit of Hyne glulam mill.

Figure 8. Site tour observations – HQ Plantations.

Figure 9. Site tour observations – Hyne timber Green and glulam mills.

3.3 Structured interviews

As part of our project, we conducted a comprehensive investigation into the use of low-grade timber within the industry. To gather detailed insights into the barriers associated with this practice, we developed a questionnaire in consultation with all team members and industry partners. The questionnaire was meticulously crafted to ensure it addressed the pertinent issues, reflecting the collective expertise and concerns of both our academic team and industry stakeholders. The interview candidates were nominated by our industry partners, ensuring a relevant and informed pool of participants. The candidates primarily consisted of senior structural engineers, sales managers from large construction material suppliers, truss manufacturers, and builders. This diverse group brought a wealth of experience and perspectives to the study. We conducted interviews with six industry professionals using the questionnaire as a structured guide. These interviews were carried out by a senior researcher who is also a structural engineer, ensuring that the discussions were both technically informed and relevant to industry practices. The process allowed for an in-depth exploration of the topics covered in the questionnaire, facilitating a rich exchange of knowledge and perspectives. The detailed questionnaire is available in Appendix A of our report, and the key findings from the interviews are summarised in Table 1. In summary, an increasing demand for timber and timber-truss products was identified, along with a reluctance from builders and designers to deviate from the long established and familiar processes and products.

Table 1. Key findings from structured interviews.

Aspect	Key findings
Structural grade	All participants agreed that the minimum structural grade suitable for construction is F4 according to Australian Standards 1720 (no other performance or code mark solutions were highlighted).
Timber availability and grades	Availability of timber grades varies; consistent supply advantageous. Different grades used in wall, floor and truss components.
Timber grades used	Roof trusses, floor trusses and wall frames employ F5, MGP10, MGP12, MGP15 and F27 grades.
Lower-Grade Consideration	Lower-grade timber considered for non-load bearing walls and web material in trusses, depending on design requirements and software.
Optimisation opportunities	Potential for optimising truss and frame designs for cost reduction without compromising integrity.
Software tools	Commonly used programs for truss analysis and design: Mitek 20/20, Pryda. Adjustments made to meet structural and cost requirements.
Use of larger lower-grade sections	Consideration of using larger sections of lower-grade timber for comparable outcomes, assessing cost-performance trade-offs.
Engineered wood products (EWPs)	Consideration of laminated veneer lumber (LVL) or glued laminated timber (glulam) for improved properties and strength at higher cost.
Incorporating lower-grade timber	Lower-grade timber (lower than F4) use in specific truss or wall frame sections without compromising overall performance.
Stud suitability	Stiffness primary criterion for stud suitability in truss manufacturing, other factors like straightness and stability also significant.
Timber characteristics importance	Straightness crucial for wall frames, aids in reducing bending effects in trusses. Shrinkage and swelling considerations in trusses.
Utilisation of lower-stiffness timber	Complexity in design and operation, willingness to replace some truss components with lower-grade timber depends on performance and cost.
Troublesome defects	Irregular-sized timber, stock management and availability issues identified as troublesome. Various defects in final product noted.
Acceptance of repaired timber with defects	Acceptance of repaired timber (by filling Knots and Cracks with epoxy Resins, reinforcing with steel and FRP, heat and Moisture Treatment, sanding minor warping; and cutting and Patching) depends on structural performance, cost and feasibility of repair process..
Need for further exploration and solutions	Findings highlight the need for further exploration and solutions to overcome barriers in using low-grade timber in the industry.

3.4 SWOT analysis

The review of the sawn timber supply chain included examining the current and likely future place of timber products and conducting a SWOT analysis to highlight where opportunities might exist and recommendations for more in-depth study by the Building 4.0 CRC. This exercise identified 3 main themes: 1. Maximise yield of high-grade timber; 2. Convert low-grade timber to high-grade or equivalent; and 3. Find value-added uses for low-grade timber. Other themes discussed in the beginning of the project (e.g. reinforcing low-grade timber with other material) were not taken forward as a potential direction by the industry partners. It was agreed that the focus would be on sawn timber (studs, truss-frames etc.), grade recovery and alternative grades.

3.4.1 Theme 1 – Maximise yield of high-grade timber

Figure 10 summarises the analysis results for theme 1.

Strengths	• Ease of collecting data • Efficient and optimised existing process
Weaknesses	• Limited ability to efficiently separate fibre through the whole process (limited separation)
Opportunities	• Product (log at start of milling through to post-drying) identification and tracking method • Better log fibre understanding and grading to optimise the whole log, minimising waste, and creating the best products from a known resource
Threats	• Financial feasibility (can it bring any benefit financially, charge a premium?) • Interruption to existing operations (Hyne altering their 'mix-bin' approach) • Concerns regarding data sharing (IP)

Figure 10. SWOT analysis for theme 1 – Maximise yield of high-grade timber.

3.4.2 Theme 2 – Convert low-grade timber to high-grade or equivalent

Figure 11 summarises the analysis results for theme 2.

Strengths	• Timber can be rather easily modified/densified • Sustainable and renewable (compared to steel and concrete)
Weaknesses	• Product price, capital investment • Significant R&D effort
Opportunities	• Microwave treatment - Flexible outcomes • Densified timber column for high rise buildings • Shorter drying schedules
Threats	• Increasing energy price may limit feasability • Steel beams are more ductile

Figure 11. SWOT analysis for theme 2 – Convert low-grade timber to high-grade or equivalent.

3.4.2 Theme 3 – Find value-added uses for low-grade timber

Figure 12 summarises the analysis results for theme 3.

Strengths	• High supply (lots of low-grade timber to apply this to) • Existing use/processing for low-grade timber, through green mill • Low-hanging fruit, minimum cost, no physical change to product (i.e., just a codemark certification process)
Weaknesses	• Already not enough cost incentive for a builder to push F5 over MGP10 in nonvolume builder scenarios • Capital expense to capture additional grade sorts
Opportunities	• More efficient use of timber for <u>structural efficiency</u> and <u>sawing yield</u> • New codemark product will allow <F5 • Prefabricated timber wall (including insulation), more efficient profile (130x30?)
Threats	• Market currently over engineering timber framing and engineer's safety margin • Low industry uptake of codemark products • Possible dimensional stability issues (distortion)

Figure 12. SWOT analysis for theme 3 – Find value-added uses.

3.5 Findings and opportunities

3.5.1 Microwave treatment and densification

Recent research in Maryland University, USA [20] has shown that wood can be transformed into a material (*Superwood*) with significantly higher strength properties after removing a portion of its lignin and hemicellulose contents followed by densification [20]. The technology developed has the potential to use plantation grown timber and convert it into a material with properties comparable to steel.

Although it could offer a material of choice for buildings and other applications, there are manufacturing shortcomings which would need to be addressed to provide a solution that works not only in the laboratory but also at scale: (1) usage of high dosage of expensive and environmentally unfriendly pulping chemicals for delignification; (2) high energy and water requirements; (3) size and species limitations → Time of partly delignification process too long for commercialisation if timber pieces are thick or wood is impermeable; and (4) high operating and capital costs.

The proposed idea would overcome the above-mentioned shortcomings using a 3-step manufacturing approach: (1) Microwave (MW) wood modification of timber; (2) Partial delignification of MW treated timber; and (3) a thermomechanical treatment to densify the resulting delignified timber component.

Microwave-treated timber has high porosity and very high permeability for liquids and gasses, as the treatment process ruptures the wood cell wall structures breaking the linkages of the various wood components. This will, therefore, make it easier to use reduced amounts of and less harsh pulping chemicals for partial wood delignification.

Benefits for users are: a material with superior strength to weight ratio; improved fire resistance properties; improve sustainability of the forest and wood products sector; reduced reliance on steel in the construction and transportation industries; reduced CO_2 emission from the manufacture of steel and alloys; and reduced water and energy usage (e.g. reduced kiln-drying schedules, Song et al. [20], Hertwich et al. [21]).

Research and further development are essential for acquiring the necessary knowledge and expertise to design and manufacture a pilot plant for new material production. The goals of this phase include:

- Manufacturing prototype of new materials to cover a range of MW intensity and determining their mechanical and physical properties in comparison to marketable product specifications.
- Determining process parameters for Superwood manufacturing, including MW, partial delignification, and thermomechanical treatments.
- Establishing baseline data and parameters for designing a semi-commercial plant for material manufacturing.
- Conducting an economic assessment of the technology and outlining the steps to commercialisation.
- Filing a patent application for Superwood technology.

2.5.2 Data sharing and timber supply issues

There is significant potential to share data between HQ Plantations and Hyne Timber to anticipate and improve log quality. HQ Plantations has collected data for over 40 years, including management information, diameter at breast height, height, and plantation resource assessment. More recently, resistograph density measurements have been conducted for the past 2–3 years. On the other hand, Hyne has been collecting a significant amount of data starting from the log merchandiser (where harvested logs are delivered for measuring volume and sorting based on diameter and quality of log to 46 bins) at the green mills (e.g. acoustic grade). Additionally, data is collected as the log is deconstructed, including recovery, Ecoustic grading (grade, MOE, density, volume).Merging the databases from both Hyne and HQ Plantations could have significant long-term value. Some of the benefits include:

- Identifying elements/patterns impacting log quality (from Hyne’s quality perspective, not just volume).
- Proposing cost-metric benchmarks/methods to assess standing tree quality (not just volume).
- Providing feedback to HQ Plantations to inform how planting decisions and growth conditions impact stud quality, allowing them to grow trees that match Hyne's product portfolio requirements while reducing the amount of low-grade timber produced from logs of unknown quality (representing up to 25% of current production).

4. CURRENT AND FUTURE PLACE OF TIMBER PRODUCTS

4.1 Traditional stick-build vs panelised prefabricated timber construction.

Structural timber has traditionally been employed in a conventional stick-build approach of 1-dimensional elements i.e. post, beam and joists. Floor and roof trusses are an extension of this stick-build approach. In more recent years, 2-dimensional timber systems have been pioneered, including panelised/framed floors and walls, CLT floor/wall panels, laminated veneer lumber floor cassettes, etc.). These off-site approaches typically utilise larger prefabricated EWPs than a typical stick-build approach and accommodates shorter construction cycles, since a large portion of the traditional on-site fixing and carpentry has been completed off-site. Although traditional stick-build is still the common option for building low-rise timber housing (one or 2 stories), there is a shift toward prefabricated 2-D frames and volumetric modular construction for taller timber buildings, according to a recent international study by Orozco et al. [22]. Of 350 timber buildings 3 or more stories high constructed between 2000 and 2021 in Europe, North America, East Asia, Australia and New Zealand, 157 were conventionally1-D framed (i.e., stick-build from post and beam), 111 used two-dimensional prefabricated panels and 27 used 3-dimensional modules [22]. Most of the taller buildings employing a 1-D frame approach are using mass timber (typically glulam) for the post and beams. However, the actual structural elements are not conventional sawn timber posts and joists and more EWPs are employed.

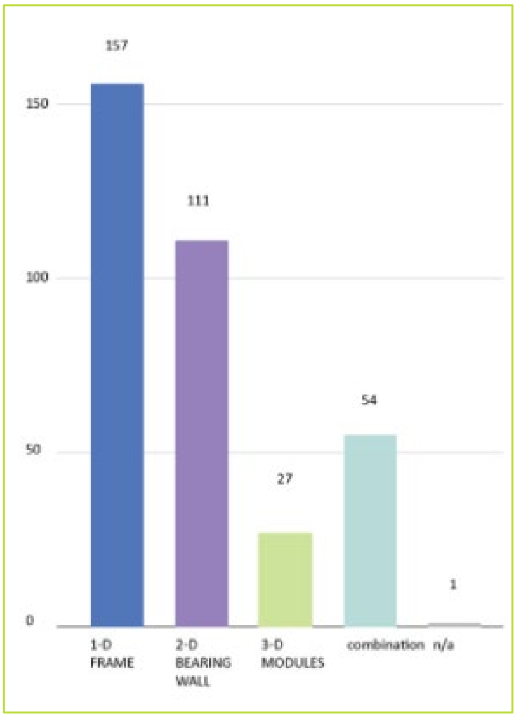


Figure 13. Number of timber mid- to high-rise building projects by structural category [22]

Mirvac presented findings from their prefabricated housing at the 2022 Prefab Aus conference [23], focusing on the residential sector in VIC and NSW, Australia, particularly single- and double-storey detached houses and townhouses. They undertook 5 trials of increasing size from 2013 to 2021 across Victoria and NSW (Table 2). The first was a 2-home trial with the timber frame floors and walls prefabricated off-site in NSW in 2013. They realised a 10-week reduction in program, amounting to a 42% time saving on a traditional construction approach. A large part of this success was attributed to the very simple rectilinear floor layouts. This was followed by a larger 110-home trial, again utilising prefabricated timber frame floor and walls. However, only a 27% program reduction was achieved in this second trial due to the increased complexity of the floor layouts bought about by customer requirements for personalised amendments to standard designs.

#15: Using the whole tree for future timber-based construction

Two further trials employing prefabricated walls and floors were carried out in Victoria consisting of 36 and 11 homes. These achieved a 25% and 23% saving in program, respectively. The fifth and final trial was carried out in 2021 across 26 homes where the 52-bathroom pods (produced by SYNC) were prefabricated offsite delivered and installed in less than 20 minutes each. This targeted application of prefabrication to traditionally complex bathrooms resulted in an 88% reduction in on-site labour hours for bathroom work. There were additional flow-on benefits from the prefabrication around the coordination of work, with a 75% reduction in call hours, a 94% reduction in emails, a 40% reduction in meeting hours, and a 71% reduction in inspection hours, presented as the combined learnings of these 5 trial builds for the builder, customer, and developer.

Table 2. Flow-on benefits of prefabrication for builder, customer and developer from a 5-site trial by Mirvac [23].

Benefits for the builder	Benefits for the customer	Benefits for the developer
Shorter construction program (20-40% reduction)	Certainty of delivery	Improved project metrics internal rate of return (IRR) and return on invested capital (ROIC) through shorter program times.
Less cost for site prelims (20–40% reduction)	Reduction in post-completion issues	Reduced project delivery risk
Less construction waste (40–50% reduction)	A higher-quality finished product	
Reduced period for scaffolding hire (30–50% reduction)		
On-site labour requirement reduced		
Construction admin tasks reduced		
Manual handing reduced		
Incidents and injuries reduced		

The challenges of prefabricated construction were also identified (Table 3). These were predominantly found to be linked to increased upfront costs for planning, materials and manufacture without being able to realise the continued progression of the build in the same was as conventional on-site building approaches. Client and contractor expectations and preferences also featured highly as hurdles that required particular attention to ensure a successful prefabrication project.

Table 3. Challenges and solutions of prefabrication projects [23].

Challenges of prefabricated construction	Solutions
Prefab costs more[2]	Demonstrate total project savings upfront for mass production
Customers expect infinitely personalised/bespoke designs	Educate customers on how to balance design excellence and design for manufacture and assembly (DfMA) to save on final product cost
Change management (tendency to resist doing things differently)	Educate stakeholders on change management principles and demonstrate values/benefits
Manufacturing supply chain	Developing industry partnerships to overcome offsite manufacturing requirements
Intense planning requirements	Utilise technology (BIM, digital engineering) in comparison to current 2D documentation
Adopting digital engineering	Invest in software and training to unlock benefits

[2] Note: Based on a case study by Mirvac which included townhouses on either side of a road. One side adopted traditional stick build method and the other prefab timber walls and roof. The study demonstrated more costs for prefab.

Smith et al. [24] compared mass timber construction (MTC) with traditional stick-build construction in an international study spanning 8[3] countries over 17 projects (Figure 14). The study identified examples of mass timber building projects and collected data on project costs and program from architects, builders and mass timber manufacturers. Data from the MTC projects were compared to benchmark project data supplied by a cost consultancy firm. For each MTC case, a corresponding conventionally built project of similar size and scope was identified for comparisons of cost and program. Where possible, estimates for the comparisons were based on actual items of work. Where data was not available for actual items of work, values from other projects of similar size and scope were interpolated for these comparative projects. They found that panelised prefabricated timber buildings took on average 3 months to fabricate and 2 months to construct on site. They also noted that the on-site phase of construction required fewer contractors. These are similar findings to those noted by Mirvac.

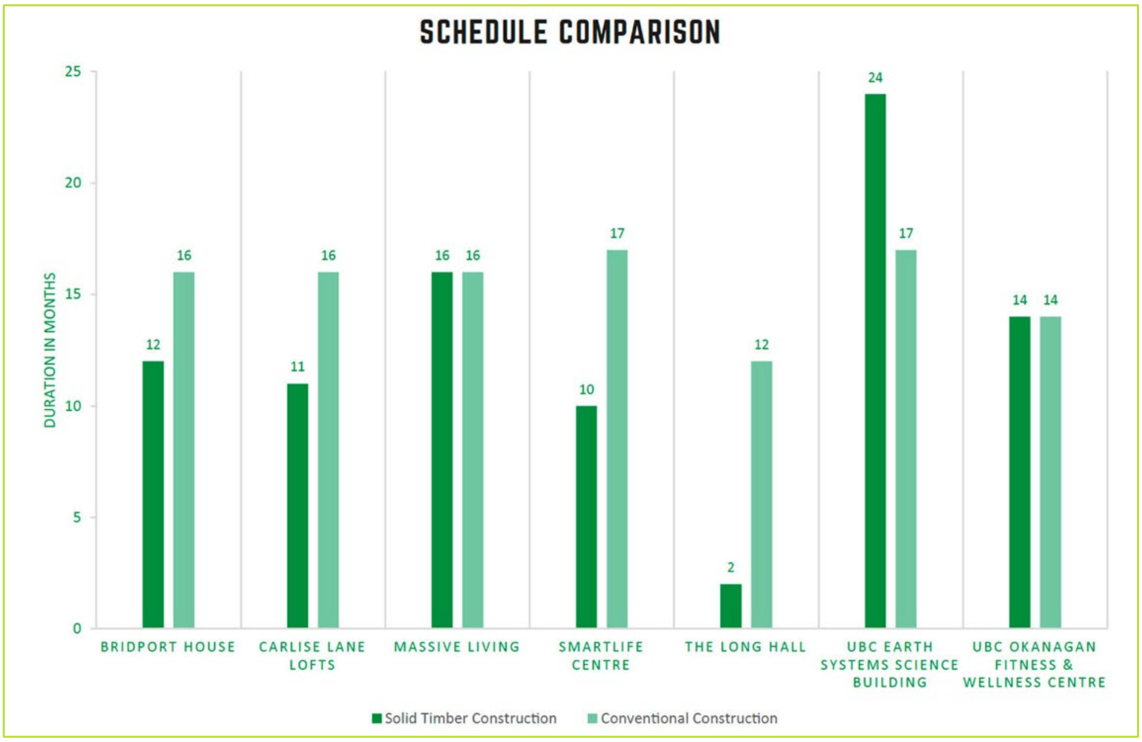


Figure 14. Comparison between panelised and conventional timber construction from 7 cases [24].

Figure 14 shows panelised timber construction reduced the overall build time compared to conventional stick-build construction in most cases. A greater versatility to changes in weather conditions from achieving an enclosed building envelope sooner than stick-build construction was also identified as an advantage of the panelised prefabricated approach.

4.2 Stress groups and stress grades

The process of structural grading in Australia involves categorising timber into stress grades based on their structural properties, with the aim of achieving consistency within each group. However, due to the natural variation in timber properties, there is still a significant range of properties within each group and some overlap in properties between different groups [25]. The following sections detail various methods used to perform structural grading.

4.2.1 Visual stress-grading

Visual grading is a method that involves a trained grader examining each piece of timber to determine its characteristics and size, and then assigning it to a structural grade. The highest

[3] Australia, Austria, Canada, Germany, Italy, Switzerland, UK, USA.

grades allow fewer and smaller characteristics in each piece of timber. The process is complex, relying on the skill of the graders, who must check more than 20 different characteristics. There are different limits on knots – estimated by the knot area ratio – and different limits on resin or bark pockets, sloping grain, wane, and spring and bow. Each species of timber listed in the visual grading standard has been tested to find the strength of the wood fibre, which is used to assign a strength group to each species. The sawn timber is sorted into various structural grades by the grader based on the presence of strength-limiting growth characteristics such as knots. Each of these structural grades is assigned a stress grade, commonly referred to as its F-grade. The visual grading standards provide tables that link the structural grades for each species to a stress grade.

4.2.2 Machine stress-grading

Machine stress-grading uses a machine to measure the stiffness of each piece of timber and assigns a stress grade based on a loose correlation between stiffness and strength. This method is perceived as more objective and efficient than visual grading methods. It produces better separation of grades but still has a significant overlap between the strength properties of different grades. The reliability of structural design properties used by a structural designer is linked to the type and effectiveness of the grading operation, and quality control is necessary to ensure continued reliability in the sorted product. A grade stamp is applied at the tail end of a machine stress-grading process, which allows subsequent people in the marketing, distribution and delivery chain to recognise the marked grade.

4.2.3 Machine proof-grading

Proof-grading involves testing every piece of timber with a high load applied to it; pieces that survive the proof load without failure, excessive deformation or other signs of damage are deemed to qualify for the stress grade. The proof load is usually estimated to break 1–5% of pieces passing through the grading machine. This process differs from machine stress-grading in the way timber is loaded, the amount of load applied, the intention and the speed of operation. Although not as widely used, it is used to grade some Australian hardwoods, and cypress pine and radiata pine underpurlins, and may find application in grading treated timber. Proof-loading can also be applied to structural assemblages or complete structures for a high level of reliability. Its primary application is grading utility poles.

4.2.4 Mechanical properties of minimum structural grade timber around the world

Table 4 summarises the review of minimum structural grade timber for different countries. The EU's C14 grade generally has the highest strength properties’ requirement among the timber grades listed, including the highest bending strength and compressive strength parallel to grain. Australia's F4 grade follows closely behind in bending strength, while China's TB11 grade ranks well in tensile strength parallel to grain. The USA's Northern White Cedar Stud consistently allows for the implementation of structural timber with lower strength properties compared to the other grades.

Table 4. Review of minimum structural grade timber for different countries.

Country / Region	Standard	Minimum grade	Strength properties (MPa)						Stiffness properties (MPa)	
			f_b	$f_{t,\parallel}$	$f_{t,\perp}$	$f_{c,\parallel}$	$f_{c,\perp}$	f_s	$E_{Avg,\parallel}$	G_{Avg}
Australia	AS 1720.1	F4 (Visual grade)	12	HW 7 SW 5.8	NA	8.6	NA	1.3	6,100	410
		MGP 10 (mechanical grade)	14-17	6.1-7.7	0.5	16-18	NA	2.3-2.6	10,000	670
China	GB 55005	TB11	11	8	NA	10	2.1	1.3	7,000	NA
EU	EN 338	C14 (Softwood from bending test)	14	8	0.4	16	2	3	7,000	440
		T8 (Softwood from tension test)	13.5	8	0.4	16	2	2.8	7,000	440
		D18(hardwood from bending test)	18	11	0.6	18	4.8	3.5	9,500	590
USA	NDS	Northern White Cedar Stud (Visual grade)	2.9	1.7	NA	2.1	2.6	0.8	4,100	NA
Canada	CSA O86-19	No.3 Stud (Visual grade)	4.5	2	NA	5.2	3.5	1.3	6,500	NA

f_b Bending strength, $f_{t,\parallel}$ Tension parallel to grain, $f_{t,\perp}$ Tension perpendicular to grain, $f_{c,\parallel}$ Compression parallel to grain, $f_{c,\perp}$ Compression perpendicular to grain, f_s Shear in beam, $E_{Avg,\parallel}$ Average modulus of elasticity parallel to grain, G_{Avg} Mean shear modulus, HW hardwood, SW softwood (Note: Some standards refer to the 5th percentile mechanical properties, while others refer to the average values.)

Cherry et al. [26] conducted a comprehensive study to assess the mechanical properties of out-of-grade timber at the Hyne production line. Figure 15 demonstrates the comparative values measured for clear samples, alongside those containing resin and knots, in comparison to the minimum F4 grade requirements. The study revealed the primary limitation of out-of-grade studs pertains to their average MOE in the longitudinal direction. However, most of the strength criteria for F4 grade are still met (as per AS/NZS 1720.1). The observed average MOE values are relatively closer to the limits specified in the US National Design Specification (NDS) for Northern White Cedar Stud.

This result indicates the need for further analysis to evaluate the impact of this shortcoming on the structural performance of residential timber buildings. It becomes crucial to determine whether further comparisons and considerations can be made to introduce a new grading system to predictably and reliably utilise some of the out-of-grade timbers in construction projects. By conducting additional investigations, researchers can better understand how the structural performance of low-stiffness out-of-grade timber can or cannot meet the requirements of various timber members in timber buildings. This knowledge will help the development of grading rules to capture timber that meets the requirements of the application and determine whether alternative approaches, such as reinforced design or additional measures, can be employed to compensate for any shortcomings associated with the out-of-grade timber.

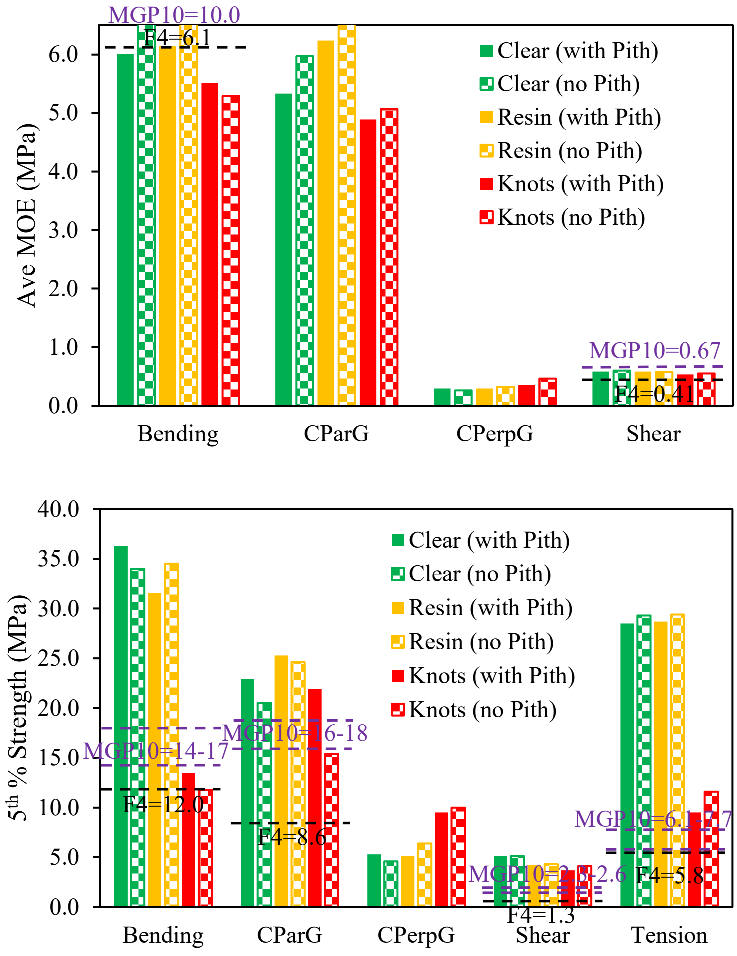


Figure 15. Mechanical properties of out-of-grade timber at the Hyne [26]. *CParG: compression parallel to grain; CPerpG: compression perpendicular to grain.*

4.3 Timber-product specification requirements by end-users

Johansson et al. [27] conducted interviews with end-users of timber products to evaluate their knowledge and satisfaction levels. The results highlighted a significant lack of timber expertise among end-users, while building contractors expressed dissatisfaction with timber quality due to excessive warping problems. These concerns were not effectively communicated to producers in the forest and sawmill industry. To tackle this issue, it is important to establish clear specifications for each timber product, outlining the desired quality standards.

To illustrate this approach, a systematic analysis of end-user expectations was conducted, with a specific focus on wall studs [27]. By interviewing contractors and aligning their requirements with wall specifications, proposed acceptance levels were determined. These proposed levels were more stringent compared with current grading rules, but field tests conducted by carpenters indicated their reasonability. Moreover, a study examining commercially available studs suggested that it is technically and economically viable to produce studs that meet these requirements [28]. Although achieving this is not always possible, because processes like sawing strategy and drying are employed to minimise distortion, timber stud can still be excluded from the high-grade category due to distortion, resulting in the stud’s presence within the low-grade timber populations. To maintain timber's competitiveness as a building material, the forest and sawmill industry should prioritise the production of products that meet the preferences and specifications of end-users [28]. Additionally, plasterboard manufacturers allow tolerances of 4, 5 and 6 mm on an underlying timber framing, depending on the desired finish quality. The grading and supply of consistent timber framing products is critical to achieving optimal results during the plasterboard installation and finishing process.

5. APPLICATION OF LOW-GRADE TIMBER AS CONSTRUCTION MATERIAL

5.1 Panelling and flooring

5.1.1 CLT production

Cherry et al. [15] reviewed the opportunities for out-of-grade timber in CLT. The authors stated that CLT could offer a solution to utilise the out-of-grade timber, but thorough research is needed to investigate all the mechanical properties, gluability and fire performance. Based on the stiffness and strength criteria for MGP grades specified in AS1720.1 (Standards Australia 2010), it is expected that a certain portion of timber that falls outside the grade limits in terms of strength and stiffness will still meet the requirements for layers within CLT panels. Additionally, if smaller span/depth ratios are deemed acceptable, timber with very low stiffness can be utilised, particularly for central layers. However, it should be noted that the importance of rolling shear stiffness will become more pronounced in such cases. According to Gagnon and Popovski (2011), the allowable span is only reduced by 1.3% in a typical European CLT panel with outer E0 = 11 GPa and inner and central E0 = 8 GPa, when compared with a CLT panel with E0 = 11 GPa for all layers. Importantly, it was argued that the potential layers within CLT for out-of-grade timber can be associated with their out-of-grade characteristics [15], as shown in Table 5. Furthermore, Rose and Stegemann [29] examined the innovative idea of repurposing secondary timber as a source material for 'cross-laminated secondary timber' (CLST) to substitute conventional CLT. They highlighted several research areas that need to be addressed to promote its commercial adoption.

Sigrist and Lehmann [30] investigated the feasibility of manufacturing CLT with non-structural radiata pine as the central layer and MGP12 or wing boards as the surface layer, which showed similar performance to the ones on the European market. To ensure a smooth production process and meet the minimum quality standards for the final CLT product, a rough grading is necessary for the non-structural boards. Additionally, roughly graded non-structural boards can also be used as a surface layer to provide non-critical bending strength. Ma [31] evaluated the mechanical properties of CLT made with low-value sugar maple and/or salvaged spruce with 3 layups. Compared with the reference value, low-value sugar maple CLT showed 50–80% increase in MOE and 5 times higher MOR, while salvaged spruce CLT showed 15.6% decrease in MOE and 52% increase in MOR. For mixed-species CLT, similar enhancement was reported in MOE and modulus of rupture (MOR) when applied with the hardwood transverse layer.

Table 5. Out-of-grade characteristics potential for layers within CLT [15].

Out-of-grade characteristic	Potential for CLT layers
Low longitudinal stiffness	Transvers layers Central layer
Sloping grain	Transverse layers Central layer
Knots	Top layer under compression Transverse layers Central layer
Shakes, splits, checks, resin and back pockets	Depending on extent and orientation of separation – transverse or central layers Bottom layer
Distortion	All layers – where distortion can be reduced to within acceptable limits through preparation for gluing

5.1.2 Hardwood panels

Using small and low-grade hardwood logs, the US Forest Products Laboratory developed an experimental solid wall panelling that is equally suitable for flooring while short cut-offs can be used as parquet block flooring [32]. Different from the traditional process of manufacturing panels, the logs are directly broken down at the head saw close to the thickness of the finished panels. For the drying process, both conventional kiln drying and press drying schedules were adopted for this product. Overall, press-dried boards were slightly thinner than kiln-dried boards. After reaching equilibrium moisture content, the boards were planed to a final thickness of 7/16 inch.

Figure 16 illustrates the ventilated cauls and screen detail used in press drying, which enabled a 25% reduction in width shrinkage compared to kiln-dried boards as well as augmented its unique appearance. Additionally, the installation of such panels is simple, which only required a few carpenter's tools; at the same time, a completely random pattern can be created by various combinations of pieces. The manufacturing process for the original wall or floor panelling involves selecting random slats of varying lengths and machining their edges and ends to include tongue and groove connections while bevelling the edges. Moisture content is controlled to be below 8%, and quality standards dictate that the face of the panels must be free from major defects but can have minor, tight defects, while open defects are allowed on the back. The face is sanded for a smooth surface and a natural finish can be optionally applied for enhanced aesthetics or protection. This process ensures the production of high-quality panelling with a consistent finish.

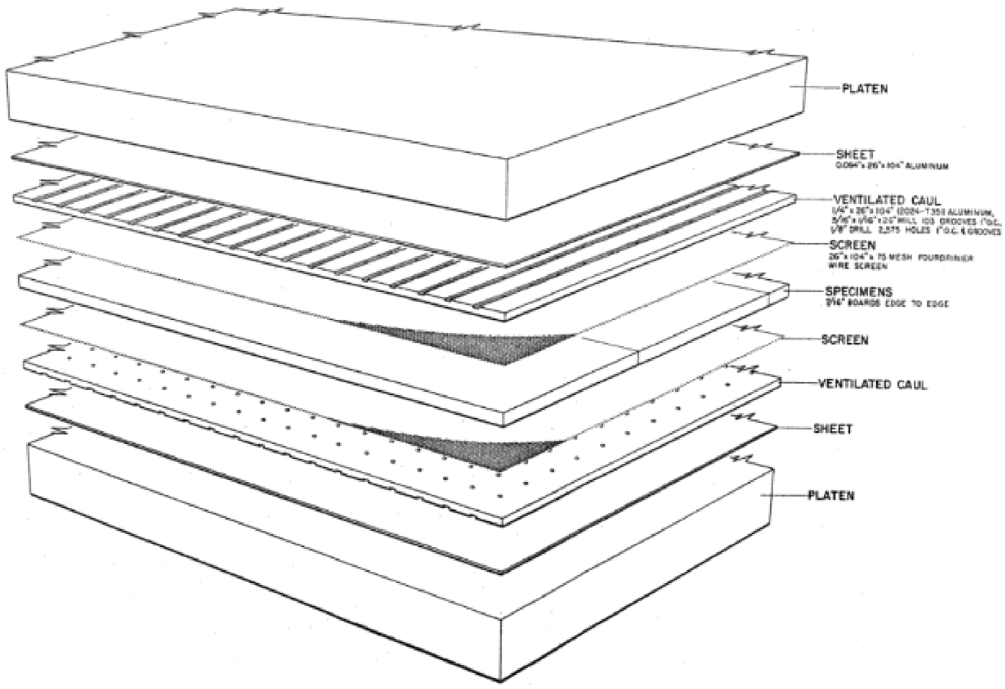


Figure 16. Detail of ventilated cauls and screens used in press drying.

5.2 CFRP and GFRP reinforced flexural members

The use of fibre-reinforced polymer (FRP) reinforcement in the renovation and repair of civil structures is widespread [33] and has now been introduced into the manufacture of laminated beams to incorporate low-grade wood species for structural applications [34] (Figure 17). Of the available reinforcing fabrics, glass-fibre reinforced plastics (GFRP) with E-glass (a type of glass that has high electrical resistivity and is designed for use in glass-reinforced composites due to its high strength and excellent resistance to chemical and environmental factors) provides a good solution with low cost to good mechanical properties, with its suitability in low-grade species confirmed by Moulin et al. [35].

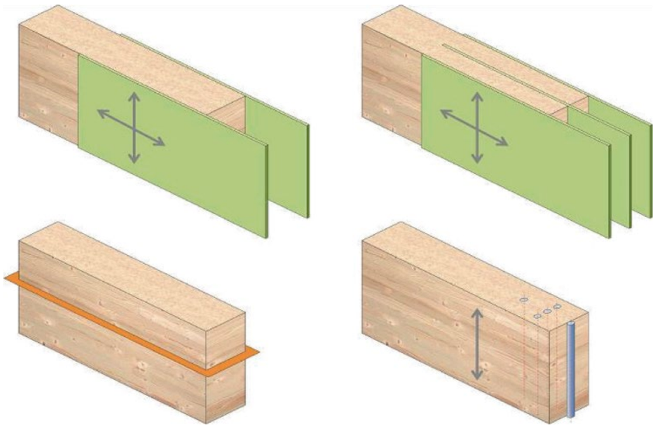


Figure 17. Schematic diagrams of the reinforcement of wood with FRP (Kasal and Yan 2021).

Raftery and Harte [36] studied the reinforcement of low-grade glued laminated timber using a pultruded GFRP composite plate. They reported that the addition of practical reinforcement percentages (1.12–1.26%) strategically located in the tension zone resulted in moderate enhancement in the stiffness (13%) and more significant improvement in the ultimate moment capacity (38%). A further enhancement in stiffness of up to 55%, was observed with a sacrificial lamination added below the FRP plate, however, the additional beam depth can be problematic in applications where space is limited. Further research was conducted to investigate various reinforcement configurations and arrangements of GFRP [37]. The stiffness was demonstrated to increase 11–14% with 1.4% reinforcement ratios when reinforcement was only in the tension zone and reached 22–29% when reinforced in both tension and compression. They also proved that the same adhesive can be used for all bond interfaces in the reinforced beam to avoid using more expensive epoxy adhesives at the FRP–wood bond interface [38]. Further, Raftery and Kelly [39] found that low-grade glued laminated timber reinforced by basalt FRP rods performed comparably to that reinforced by glass FRP rod, when using same reinforcement ratio.

The University of Valladolid in Spain has conducted a research program to determinate new structural applications for fast growing and low-grade wood species. At the beginning, Basterra et al. [40] proposed the vertical placement of reinforcements in the duo beam for a better aesthetics and lower fire risk, which even though this sacrifices some mechanical effectiveness. That study found using carbon-fibre reinforced polymers (CFRPs) results in significant improvement for MOE and MOR GFRPs. In particular, E-Glass fibre seems to be the most viable reinforcement due to its low cost and suitable mechanical properties. Later studies found a 1.07% GFRP reinforcement can increase the bending stiffness (MOE) of a beam by up to 12.1% and the ultimate moment (MOR) by up to 18.4%. Both results were higher than the theoretical value because GFRP reinforcement homogenises the features of wood and reduces the effects defects [41,42]. Further, Balmori et al. [43] confirmed a good bonding performance of GFRP strips to low-grade wood.

5.3 Truss production

Crafford and Wessels [44] evaluated the potential of using the young, green finger-jointed Eucalyptus grandis timber as a structural component in roof truss structures while the timber is still in the green, unseasoned state. Drying will occur naturally while the timber is fixed within the roof truss structure. Results indicated comparable flexural properties, tensile parallel to grain, compression parallel to grain and shear strength compared to current South African pine. Even though the 5th percentile values of tensile perpendicular to grain and compression perpendicular to grain strength did not conform to South African National Standards (SANS) requirements for the lowest structural grade, these 2 properties are of lesser importance in nail plated roof truss structures. However, further research is required to assess the effect of deformation, splitting and checking on nail-plate or mechanical joints within full scale trusses, the load capacity of nail plates on this timber and the effect of wood shrinkage within the truss system. According to Muhammad et al.[45], acceptable effects can be observed on the physical and mechanical properties and dimensional stability by converting lower grade timber into LVL where the strength could improve into 2 grades higher, which can then be safely used in roof truss system. The detailed review of utilising low-grade timber for manufacturing LVL will be discussed in section 5.6.

5.4 Timber framing

Wallace [46] investigated laminating and resawing low grade timber into a new product called LamStud to achieve a structural grade stud that meets the Canadian standard (CSA O86). White wood species were assessed including ponderosa pine, lodgepole pine, Engelmann spruce and Douglas fir. The manufacturing of LamStuds includes low-grade stud (economy stud) categorisation (Figure 18), assembling/gluing 5-board cants, and resawing and ripping (Figure 19). The study included establishing visual grading guidelines for the remanufactured studs, developing the gluing and laminating process, performing structural testing of prototypes (LamStuds) and establishing LamStud mechanical properties including MOE, compression strength parallel to the grain, tensile strength and bending strength. Results demonstrated the developed LamStuds can meet or exceed the design values for solid sawn timber. Improvement in tensile strength was reported for LamStuds reinforced by glass fibre while more research is required to eliminate the delimitation under extreme loads. In addition, the financial analysis demonstrated LamStuds has potential for commercialisation.

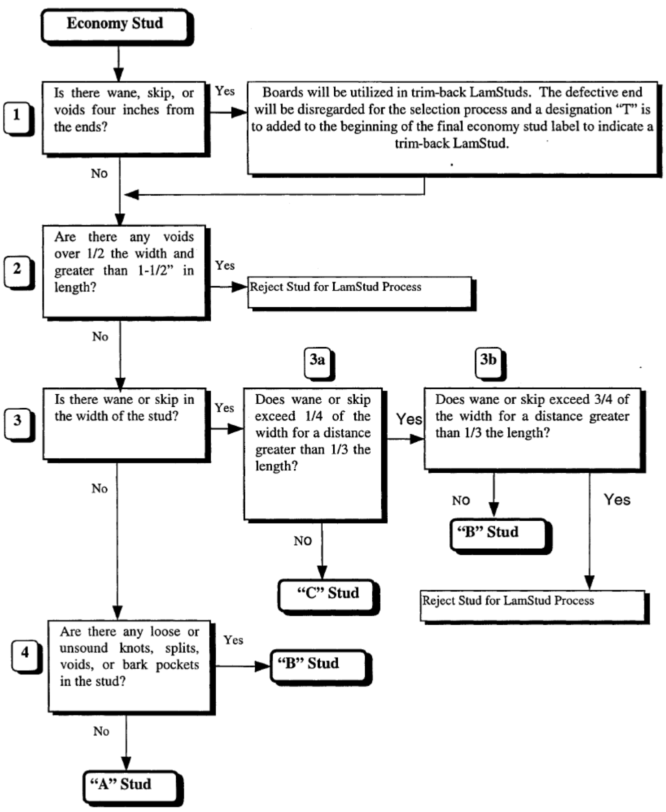


Figure 18. Flowchart of economy stud categorisation [46].

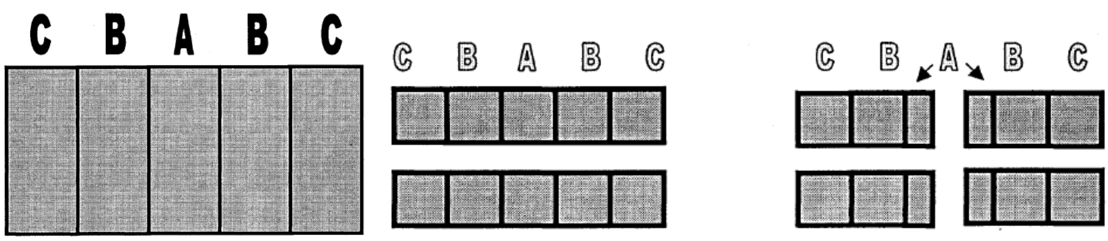


Figure 19. Layup, re-sawing, ripping of Cants (from left to right) [46].

5.5 Stress-laminated timber

Stress lamination is a straightforward and relatively simple construction technique that has been successfully deployed on timber bridge decks for over 4 decades [47,48]. In stress-laminated timber, timber laminates are drilled and prestressed together with outer bearing plates and basic steel bars, where the load is transferred through friction forces between two adjacent laminates (Figure 20).

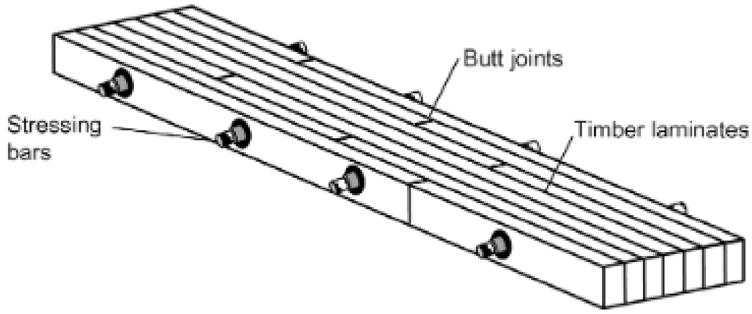


Figure 20. Stress-laminated timber plate/deck [48].

Freedman and Kermani [48] explored stress lamination as a construction method designed to utilise lower-quality, smaller softwoods from UK forests. Their preliminary study assessed the structural performance of stress-laminated timber decks in arched forms, which comfortably sustained loads of 50 kN at mid-span and withstood over 30 kN in a four-point bending test. These promising results led to further research involving the construction and testing of nine laboratory-scale arches and two field bridges with spans of 15 m and 20 m. This research [49,50] aimed to fully explore the capabilities of stress-laminated arched timber structures, ultimately facilitating the design and construction of 20 commercial bridges in rural areas that proved to be cost-effective.

The application of stress-laminated timber has since expanded to other structural uses, including roofing. Building on the successful application in timber bridges, the technique was further adapted for the construction of full-scale timber columns using low-grade spruce. Full-scale testing of a 2.4 m column under compression parallel to the grain revealed that stress-laminated columns performed comparably to solid timber and glued laminated timber (glulam) columns [51,52]. Freedman and Kermani [50] observed that prestress losses in stress-laminated columns were effectively controlled and mitigated in the long term by using over-dried hardwood bearing plates, achieving a lamination efficiency factor of 0.84, compared to 0.53 for timber columns connected by self-tapping screws. This factor indicates the effectiveness of maintaining intended friction forces and structural integrity within the structure, crucial for minimising and managing prestress losses for optimal performance and stability.

Moreover, developments in the Australian market have introduced a variety of large screws, which could further support the adoption of stress lamination techniques. According to Derikvand et al. [53], this broad range of available hardware may enable the expansion of stress-laminated timber applications across different structural contexts, potentially increasing both the efficiency and the scope of this innovative construction method within the industry.

5.6 Press-lam and veneer-based products

The manufacture of veneer-based engineered timber products (e.g. LVL and plywood) has been identified as a potential area of opportunity for poor-quality and small-diameter hardwood. Preliminary studies showed processing these logs into rotary veneers can yield a two to 6 times higher recovery rate when compared with the traditional sawn timber process [54]. Further, it can achieve 70% green recovery (the efficiency of obtaining usable material or rounded billets during the peeling process from a raw irregular truncated cone-shaped billet) by adopting the spindleless technology [55]. The resulting veneer was also reported to have suitable mechanical properties for manufacturing LVL or plywood for structural applications [56]. The Queensland Government tested plywood and LVL products manufactured from poor-quality hardwood veneers and found them to exceed the mechanical properties of similar products manufactured from mature plantation softwood [57,58].

Even though such juvenile hardwood has proven potential to be manufactured into high-grade veneer-based structural products, barriers still hinder their commercialisation. These barriers include a lack of a full investigation in the characteristics of their mechanical properties, such as density, MOE or knot locations due to the high proportion of natural defects [59]. Gilbert et al. [60] assessed the capacity and reliability of LVL beams manufactured from juvenile hardwood plantations logs through experimental testing and numerical modelling. That study found fabricated LVL beams are comparable and, in some cases, have up to 2.5 times higher design bending strength than the commercialised LVL products. In addition, the proposed design capacity factors (load duration, resistance, compression/tension shape, etc) were 5–12% lower than the ones currently adopted in Australia for beams manufactured from mature softwood logs [61].

Additionally, manufacturing high-quality veneer-based products from blending different wood species has proven to be feasible by utilising low-grade and low-density wood veneers as core layers [62–64]. A preliminary study conducted by Wang et al. [65] indicated veneer from low value red maple logs may be used to manufacture high-quality LVL products with veneers of high dynamic MOE values on the outer layers and veneers of low dynamic MOE values in the core. Similarly, H'ng et al. [66] found manufactured LVL with low-density hardwood veneer as the core and high-density hardwood veneer as the outer sheeting (11 and 15-plys) achieved the minimum requirement for stress, stiffness and delamination (<10%) of various grades according to the Japanese standard for structural LVL.

5.7 Glulam

An emerging opportunity for utilising low-grade timber is to manufacture glulam beams. Janowiak [67] found high-performance glulam can be effectively manufactured with lower-quality hardwood timber for highway-rated bridge structures. Wang et al. [68] assessed the mechanical properties of 5-ply and 7-ply glulam composed of low–grade laminae with face high–grade laminae outers and compared this with conventional E65–F225 grade glulam. Comparable performance was observed for both bending strength and stiffness, while fabricated glulam showed a 20% lower tension stiffness and 13% lower compression strength. Lannie [69] evaluated the bending strength and bonding properties of 5-ply glulam made from low-density timbers treated with chromated copper arsenate preservative. The results showed delamination, shear bond strength and timber failure percentage met the standard requirements, indicating satisfactory bonding properties. It should be note that Chromated arsenicals pose cancer and other health issues to workers in wood treatment facilities and currently banned in some countries around the world. Dziurka et al. [70] found manufactured glulam with wedge-jointed, small-sized timber pieces did not exhibit considerable deviation from conventional glulam manufactured with homogeneous (same mechanical properties) lamellas. The manufactured 3-layer glulam exceeded the European Standard EN 14080 requirement for MOE which can be classified as GL 32c grade, the highest grade specified within the standard. Apart from these examples, FRP can be used as reinforcement to improve the glulam products incorporating low-grade wood [35–43,71–73]. FRP was introduced in section 5.2.

5.8 Nail-laminated timber

Nail-laminated timber (NLT) is a mass laminated timber product manufactured by nailing timber boards together into desired dimensions (Figure 21). NLT has been adopted in various structural applications including floor systems, timber decks and bridges [74–76]. Due to the mechanical lamination, NLT can utilise low-grade timber without extensive pre-thicknessing, which is a necessary process for other mass laminated products such as GLT and CLT [77]. Further, it is possible to use medium to low-grade timber boards, either alone or in combination with higher-grade timber, to maximise the utilisation of low-grade timber. NLT exhibits a high load-sharing factor, which can be attributed to its inherent load-sharing capabilities.

Derikvand et al. [78] evaluated the bending performance of NLT and NLT-concrete (NLTC) floor panels with various span lengths and cross-sectional configurations. Nail-laminated timber (NLT) with concrete features screw connectors with concrete poured on top to enhance structural performance. This method combines the resilience of timber with the strength of concrete, improving durability and load-bearing capacity. These products were constructed from low-grade, fibre-managed (forest plantation specifically managed for production of wood fibre or pulp) Eucalyptus nitens and Eucalyptus globulus timbers and were subjected to vibration and 4-point bending tests. Results demonstrated the bending performance (MOE and MOR) of tested NLT panels was superior to some commercially available CLT and GLT products. The NLT panels also met short-term serviceability loading conditions in both office and residential building applications.

However, the Derikvand et al. study [78] also demonstrated the structural design of NLT from plantation eucalypt timber was more limited by serviceability than by strength requirements, and a high variability in stiffness was observed when the timber boards were randomly nail-laminated together. To reduce such variabilities, Derikvand et al. [79] developed a lamination pattern, joining 8 boards on their sides using 3.5 mm diameter and 75 mm length nails in a zigzag pattern with 2 rows. This pattern was designed to optimise the construction of NLT panels while maximising the utilisation of lower-grade timber boards. The performance of the modified NLT was evaluated through short-term and long-term bending tests that successfully passed the serviceability requirements and resulted in a less than 2.6% coefficient of variance for MOE.

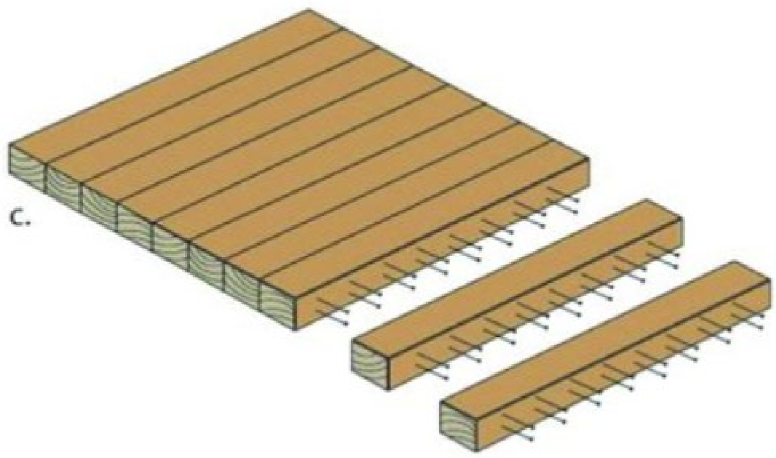


Figure 21. Nail-laminated timber [80].

5.9 Findings and opportunities

5.9.1 Australian Standards and the CodeMark Certification Scheme

Provision A5.2 of the National Construction Code (NCC) (Australian Building Codes Board, latest ed.) outlines the minimum level of acceptable evidence required to demonstrate that a building 'material, product, form of construction or design' meets the specific requirements of the NCC (Table 6). Builders and certifiers are obliged to reject products that do not provide this evidence of conformity.

Table 6. Overview of the acceptable forms of evidence required to demonstrate NCC building requirements.

NCC	EVIDENCE	DESCRIPTION	APPLICATION	EXAMPLE
A5.2 (1) (a)	CodeMark Certificate of Conformity	A certificate issued under the Australian Building Codes Board CodeMark scheme by a JAS-ANZ accredited third party body certifying compliance to the NCC	***New and innovative building products and systems***, that don't have a reference Standard	Timber preservation not meeting AS 1604
A5.2 (1) (b)	Certificate of Accreditation	Certificate issued by a State or Territory accreditation authority, e.g., Victoria's Building Regulations Advisory Committee	Products or systems ***applicable to a particular region***	NA
A5.2 (1) (c)	Certification	Certificates issued by a certification body experienced in the field of application and JAS-ANZ accredited	Confirming the product's performance or properties meet the specific product standard	Stress grades, compliance to product standards (i.e. EWPAA, GLTAA)
A5.2 (1) (d)	Testing Report	A report issued by an Accredited Testing Laboratory	New report or modifications to an existing test report	Acoustic or fire test report
A5.2 (1) (e)	Qualified Person	A certificate or report from a professional engineer or appropriately qualified person	Certifies compliance with Standards, specifications, or other publications	Span Tables Str. Design/Software Evaluation report WoodSolutions Guide [25]
A5.2 (1) (f)	Other forms of evidence	Other forms of evidence that is not covered above	First-party (company issued) document or prototype that demonstrates compliance	Product Technical Statement

Considering the varied methods for utilising lower-grade and customised grade timber, obtaining a CodeMark Certificate of Conformity is the most robust approach to gaining market acceptance. However, there are alternative possibilities outlined in A5.2 (1) (d–f) that may be considered for early adoption, such as in specific projects or applications. Typically this would involve prototype testing, followed by production series testing to determine statistically reliable characteristic values. Independent engineering assessment of the results would also be necessary. In the second part of the project, the focus shifts to deeper stud designs for 7- or 8-star rating configurations, user-specific grades, densified timber and non-standard cross sections. Questions regarding the gaps to achieve these goals and determine the value of conducting a full assessment for each opportunity will be addressed. This will involve preparing a SWOT analysis and developing a series of actions and recommendations for the selected opportunities.

5.9.2 Single storey and double storey structural design solutions

This section examines the potential utilisation of low-grade timber in the construction of one and 2-storey residential buildings. Two standard house designs from Henley Homes were used in the analysis: the Amalfi and Ashbury, shown in Figures 22 and 23. In the original design, 90 x 35 mm F5 studs were used for the single-storey building, while 90 x 45 mm studs were used for the double-storey structure. Studs were spaced at 600 mm centres for the single-storey and upper level of 2-storey buildings, and 450 mm centres for the ground floor of the double-storey building. All lintels and double/triple studs adhered to the original design. A dead load of 0.9 kPa was allowed for the tile roof and 0.4 kPa for the first floor. To comply with AS/NZS 1170.1, a live load of 0.25 kPa was allowed for the roof and 1.5 kPa for the first floor. Both buildings were designed to withstand N2 wind classifications, and standard load combinations as specified in AS/NZS 1170.0 were utilised. To obtain a comprehensive understanding of the structural performance of the buildings, 3D modelling using ETABS v20.3 was employed. The software allows to simulate various actions and maximum internal loads in all elements accurately. The investigation sought to shed light on the potential for incorporating low-grade timber into the construction of residential buildings. Understanding how such materials perform under real-life load conditions is crucial for promoting sustainable and cost-effective construction practices.

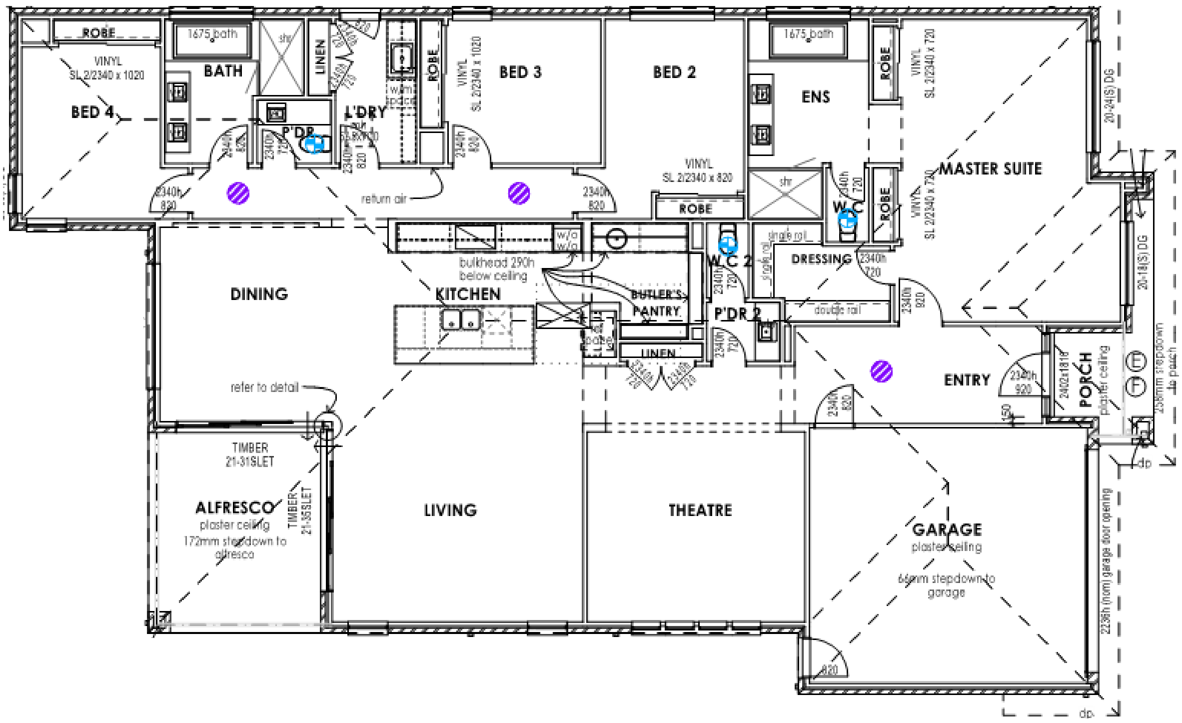
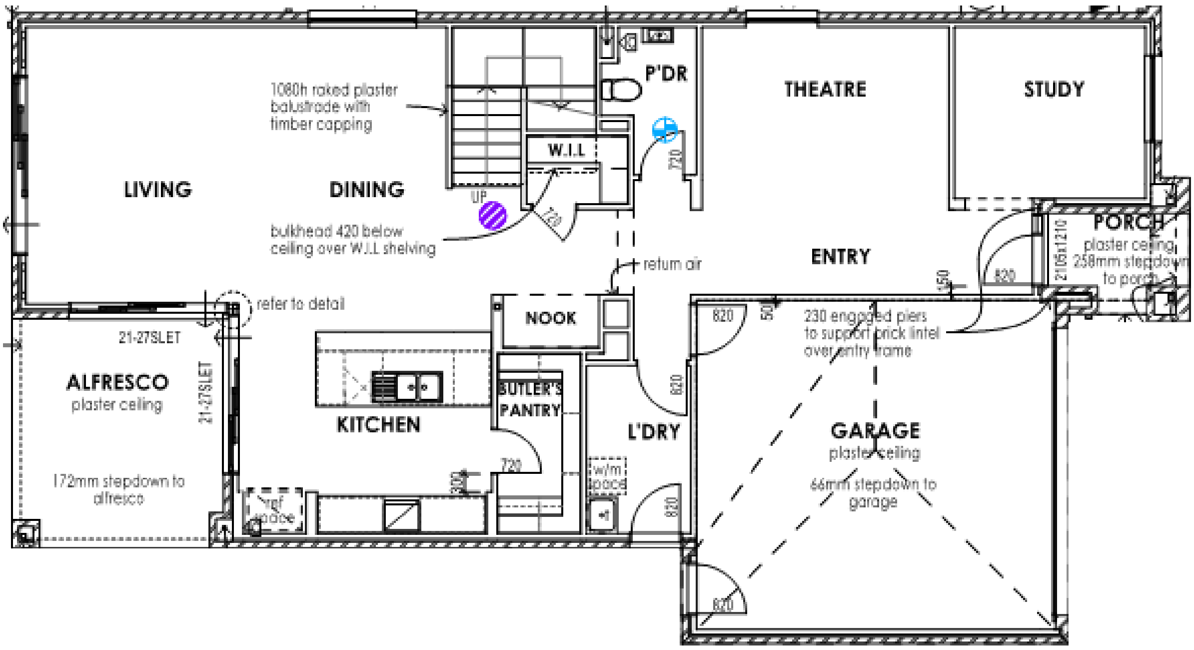
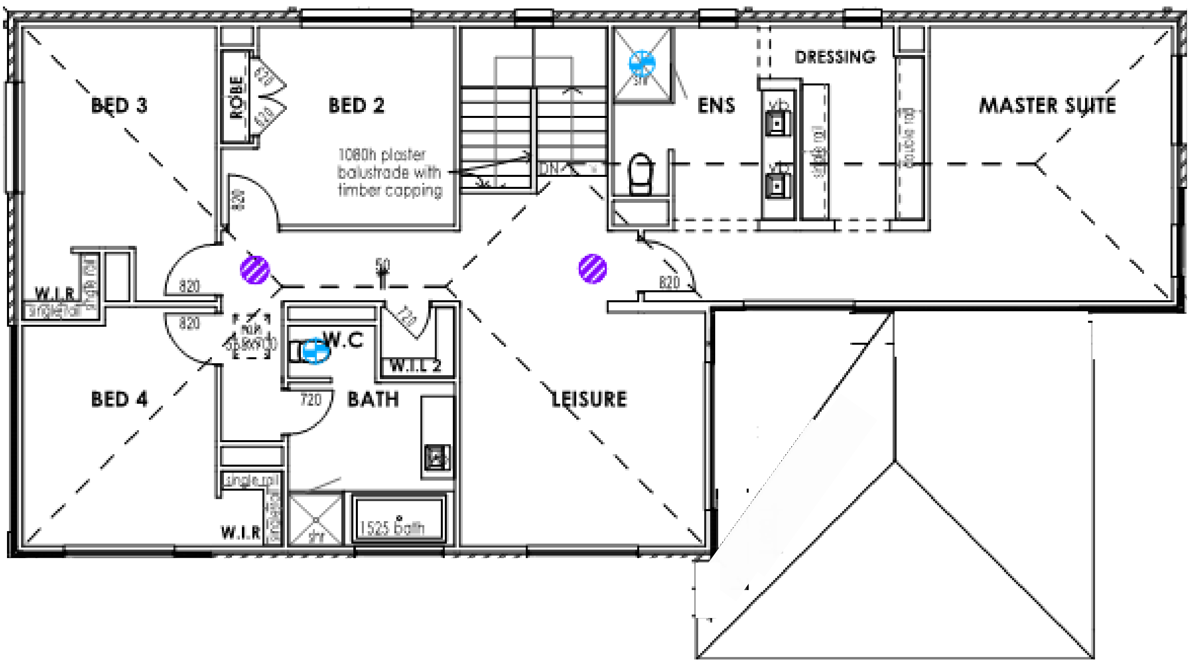


Figure 22. The single storey Amalfi architectural floor plan.



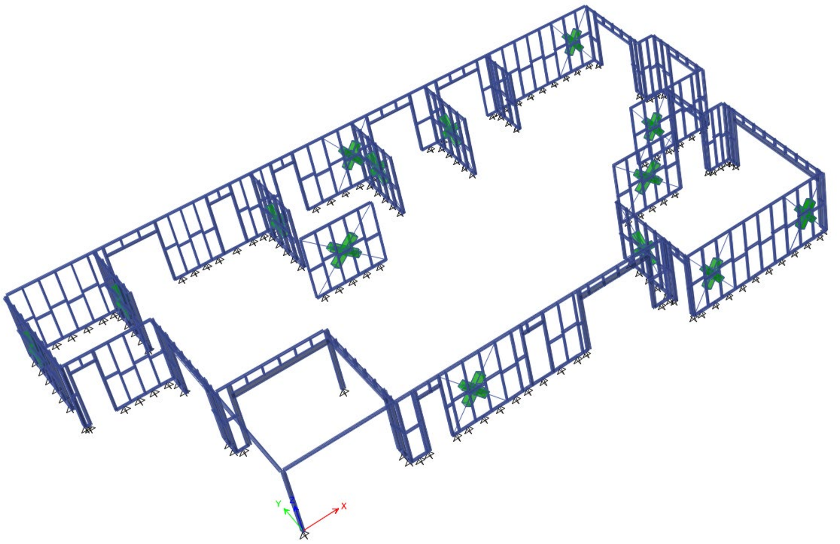
a) Ground floor plan



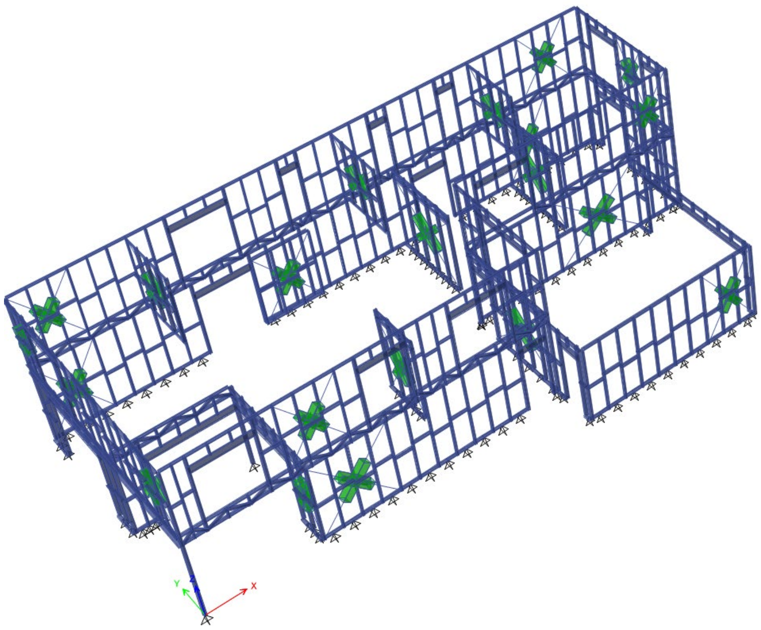
b) First floor plan

Figure 23. The 2-storey Ashbury architectural floor plans.

Figure 24 depicts the 3D analytical model of the consolidated buildings constructed in ETABS, capturing the structural component detail. To simulate strap bracing, link elements were combined with non-linear static analysis to ensure an accurate representation of behaviour under various loading conditions. Additionally, shell elements were used to model the impact of the roof truss and floor joists on the overall structure. However, it is important to note that the stiffness of the shell elements can significantly influence results. To achieve more precise outcomes, a 3D geometrical model must be established, considering the correct load transfer and distribution between the various structural elements. Proper load distribution is critical to accurately assess the performance and safety of the buildings when subjected to real-world forces and loads. By acknowledging these factors and refining the geometrical model accordingly, the reliability of analysis was enhanced and valuable insights into the structural behaviour of the buildings were gained. The use of link elements, non-linear static analysis and shell elements in the simulation was a step towards a comprehensive understanding of each building's response to different forces, but attention to detail in the model is crucial for obtaining more accurate and meaningful results.



a) One-storey building (Amalfi)



b) Two-storey building (Ashbury)

Figure 24. Three-dimensional analytical model of considered buildings.

The results were categorised and illustrated in Figure 25. This categorisation allows for a better understanding of the data. Specifically, the results for the one-storey building and the upper storey of the 2-storey buildings are represented by the label 'STUD1', indicating the maximum internal forces experienced by the studs in these sections. Conversely, the lower storey of the 2-storey building is represented by 'STUD2', encompassing the corresponding maximum internal forces in the studs for this particular area. Moreover, the analysis includes the assessment of maximum internal forces in other crucial elements. 'TOP' refers to the maximum internal forces in the top plate, 'BTM' represents those in the bottom plate and 'NAG' represents the maximum internal forces experienced by the noggings.

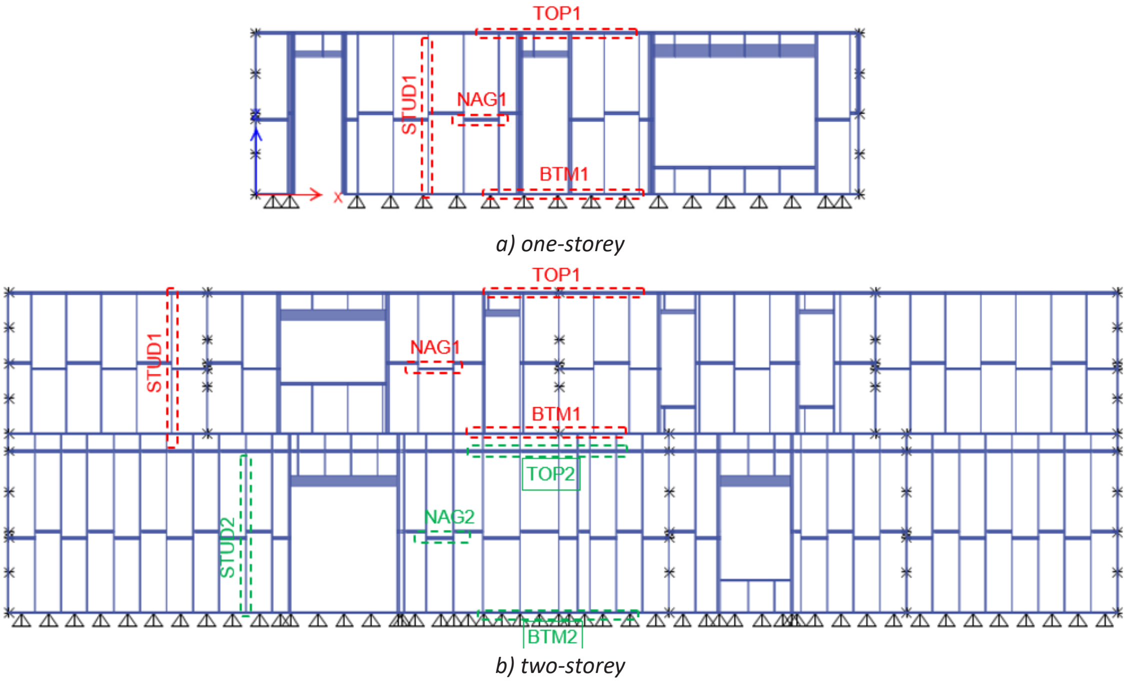


Figure 25. Framing elevations of 3D model. categorising convention for outcomes. STUD1: studs in the 1-storey building and the upper storey of the 2-storey buildings; STUD2: studs in the lower storey of the 2-storey building; TOP: maximum internal forces in the top plate; BTM: maximum internal forces in the bottom plate; NAG: maximum internal forces experienced by the noggings.

Figure 26 illustrates the characteristic stresses corresponding to different actions for the categorised elements shown in Figure 25. Characteristic strength values for F4 and MGP10 are also presented, allowing a comparison of the imposed actions against common strength grades in the Australian market. Characteristic stresses and strength were calculated based on 5% probability of failure according to ISO 2394. For instance, the characteristic tensile force (f_t) in the bottom plate of the 1-storey build and upper level of the 2-storey building is around 2 MPa, which is considerably lower than F4 grade characteristic strength of 5.8 MPa. As it can be seen, some of the internal forces exceeded the MGP10 strength. This can be attributed to the simplified model's limitations in capturing the true nature of structural behaviour and the distribution of internal forces. Specifically, the shell elements used in the model are unable to fully account for the effects of roof trusses, floor joists and concentrated loads applied to timber elements at nodal locations. Furthermore, to account for induced concentrated loads on the bottom plate due to wind uplift, supports were defined between the studs. This conservative assumption is based on the precise nailing of bottom plates at the centre of each stud spacing. However, for gravity loads, this assumption is not valid as bottom plates rest on an elastic linear spring (concrete slab). Due to computational complexities, this aspect was disregarded in the current case study.

The next phase of the project should incorporate a more accurate approach to model the support conditions for bottom plates. This will enhance the precision of the analysis and provide a more comprehensive understanding of the structural behaviour under various loading conditions. While the current model provides valuable insights, there is room for improvement to better represent the intricacies of the structural system and ensure more accurate results for future analyses.

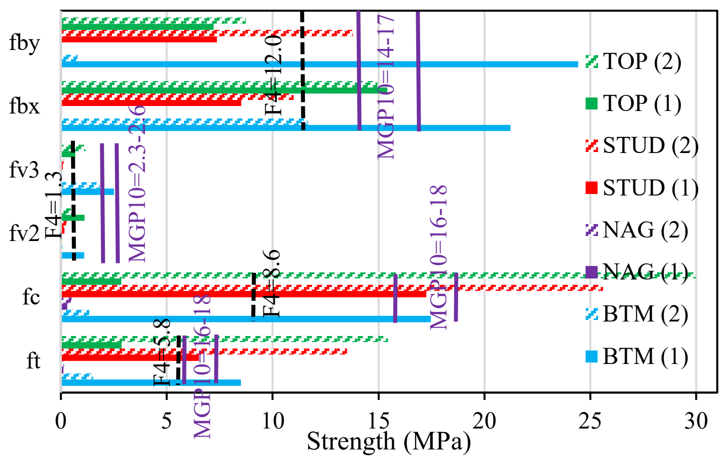


Figure 26. Characteristic stress vs F4 and MGP10 strength for different elements. STUD1: studs in 1-storey building and the upper storey of the 2-storey buildings; STUD2: studs in the lower storey of the 2-storey building; similarly, TOP: maximum internal forces in the top plate; BTM: maximum internal forces in the bottom plate; NAG: maximum internal forces experienced by the noggings. f_{by}: bending stress around strong axis, f_{bx}: bending stress around weak axis, f_{v3}: shear stress corresponding to f_{by}, f_{v2}: shear stress corresponding to f_{bx}, f_c: compressive stress, f_t: tensile stress.

Figures 27–30 demonstrate the probability density of imposed actions and mechanical properties of out-of-grade timber from the Hyne production line for various internal loads. The strength values are illustrated for 3 types of timber i.e., clear timber (red), timber with resin (green) and timber containing knots (purple). Each data point on the graph represents a test data, and a normal distribution is fitted to the entire population to determine characteristic values. The characteristic strength for each type of timber is indicated by vertical solid lines.

In these figures, the internal loads are shown separately for bottom/top plates, studs and noggings. Characteristic internal forces were also calculated for the entire elements in both studied buildings and displayed using dash lines. Characteristic stresses and strengths were calculated based on 5% probability of failure according to ISO 2394. This means that, in line with NCC standards, it is acceptable for 5% of elements subjected to the highest 5% of action loads to possess strength lower than 5% of the overall strength grade.

Upon examination, it can be observed that internal loads for noggings are negligible, indicating significant potential for replacing them with out-of-grade timber. Moreover, promising results are obtained for tensile, shear and bending forces, with characteristic strength (solid line) for timber with resin (green solid line), timber containing knots (purple solid line) and clear wood timber (red solid line) being greater than characteristic loads (dash line) for bottom plate (BTM: dash blue line), Nogging (NAG: dash grey line), top plate (TOP: dash orange line) and stud (dash black line) with a safe margin. However, the compressive forces shown in Figure 27 pose some concerns as they approach the limit, and in certain cases, with comparison to characteristic values, timber elements may fail. This issue is more prominent for studs and later for top plates.

In conclusion, the findings reveal that a considerable portion of structural elements experience internal forces lower than their characteristic strength, suggesting that out-of-grade timber may be utilised in these scenarios. For further accuracy, more advanced modelling of the structure and additional case study buildings should be considered to derive worst-case loading scenarios and true internal forces. Based on the results, appropriate geometries and structural elements can be recommended for the use of available out-of-grade timber in construction projects. This will help optimise the use of resources while ensuring the safety and reliability of the structures.

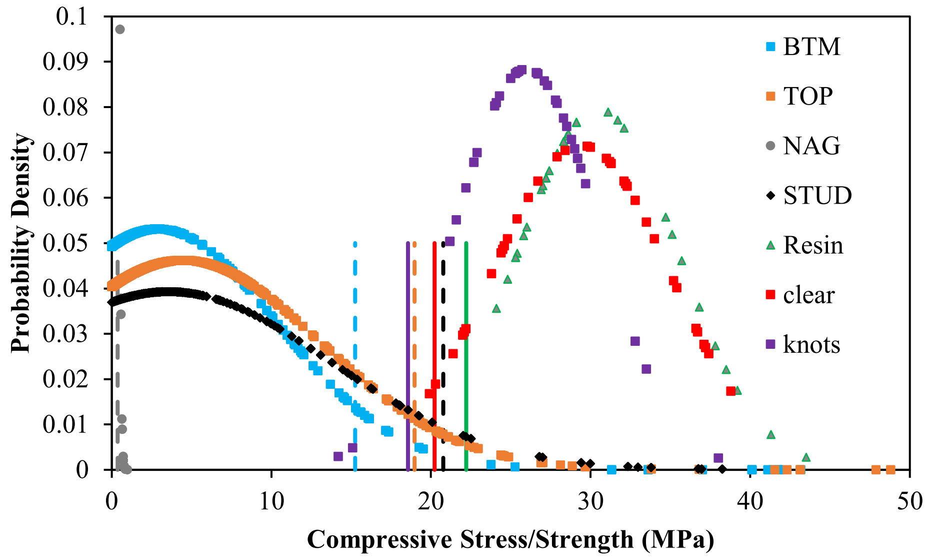


Figure 27. Probability density of compressive stress and Timber out-of-grade strength (vertical solid and dash lines represent characteristic strength and stress, respectively). Clear: clear timber (red); Resin: timber with resin (green); Knots: timber containing knots (purple); TOP: top plate; BTM: bottom plate; NAG: nogging.

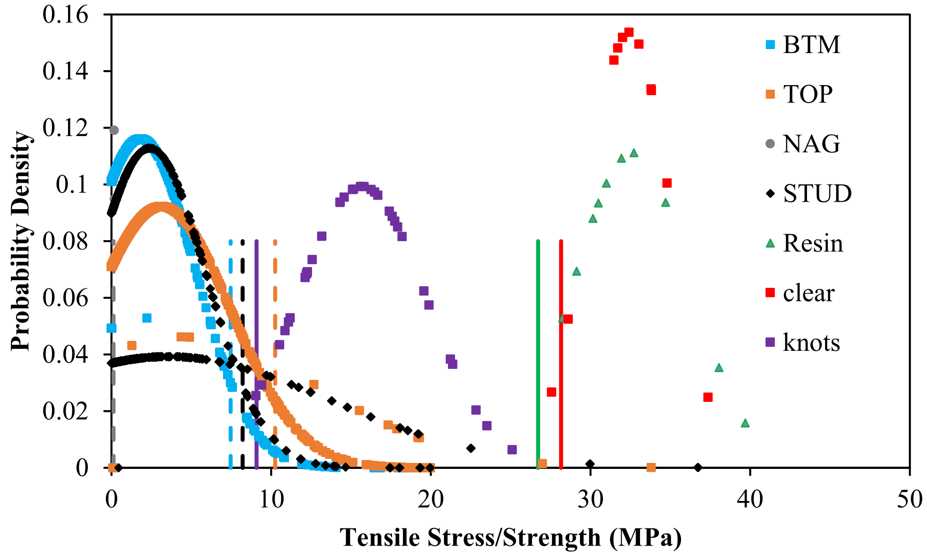


Figure 28. Probability density of tensile stress and Timber out-of-grade strength (vertical solid and dash lines represent characteristic strength and stress, respectively). Clear: clear timber (red); Resin: timber with resin (green); Knots: timber containing knots (purple); TOP: top plate; BTM: bottom plate; NAG: nogging.

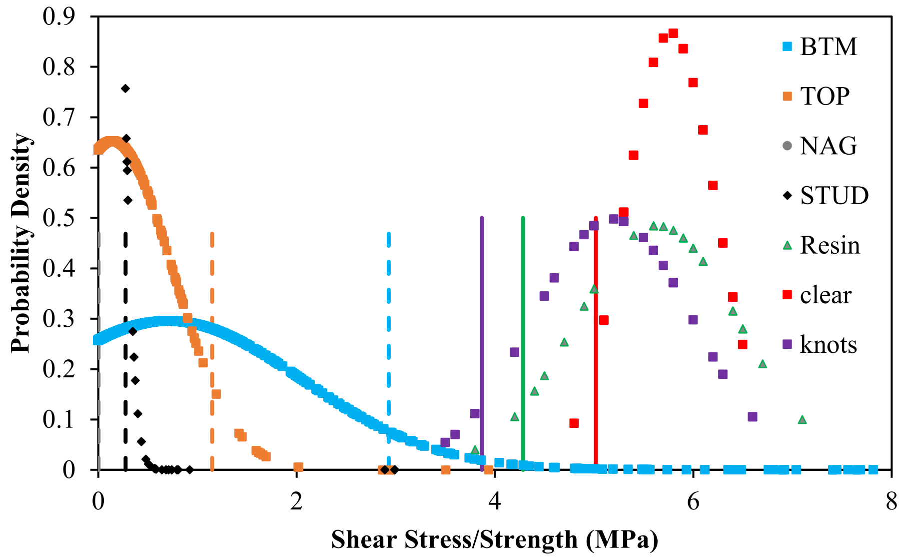


Figure 29. Probability density of shear stress and Timber out-of-grade strength (vertical solid and dash lines represent characteristic strength and stress, respectively). Clear: clear timber (red); Resin: timber with resin (green); Knots: timber containing knots (purple); TOP: top plate; BTM: bottom plate; NAG: nogging.

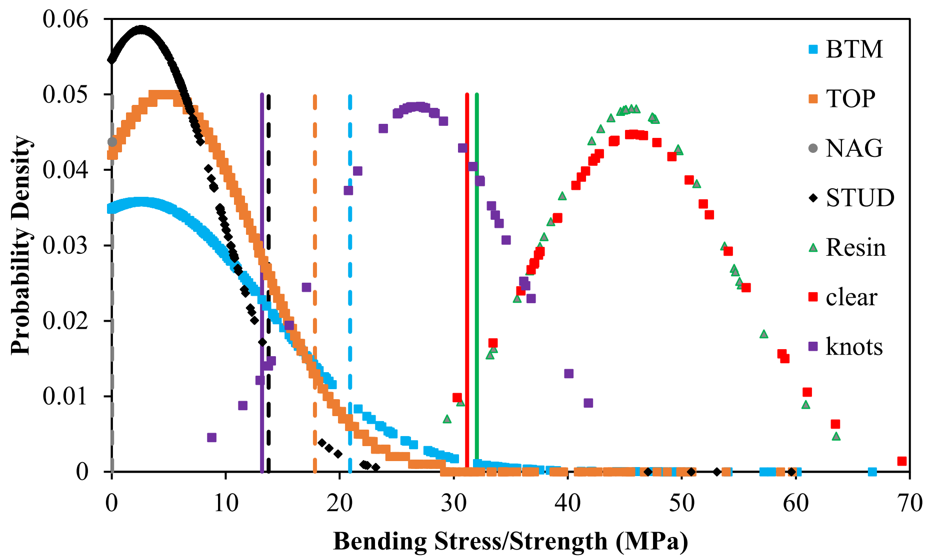


Figure 30. Probability density of bending stress and Timber out-of-grade strength (vertical solid and dash lines represent characteristic strength and stress, respectively). Clear: clear timber (red); Resin: timber with resin (green); Knots: timber containing knots (purple); TOP: top plate; BTM: bottom plate; NAG: nogging.

6. SYNTHESIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This scoping study aimed to explore existing research and define avenues of potential research for the optimisation of the Australian timber resource. Specific objectives were to:

- review the sawn timber product supply chain and identify points in the supply chain where technology, processes, products and building systems can be developed, improved, or transformed.
- review and evaluate previous research efforts into optimising the use of the timber resource.
- examine the current and likely future place of timber products in the marketplace.
- develop research projects for consideration by the project participants.

Strategies employed globally to enhance timber quantity and quality primarily target climate change mitigation and economic development. These strategies primarily aim to increase volume or fibre output for non-structural markets and applications. While challenges in timber production and value creation persist, there is a dearth of emerging evidence concerning the quality of produced wood fibre and efforts to optimise timber utilisation in building construction contexts where mechanical properties fall below minimum standard grades.

To complement findings from ABARES survey data, a descriptive case study was conducted on Australian sawn timber production, focusing on the Tuan sawmill in Queensland, operated by Hyne, and the Tuan Forest plantation, managed by HQ Plantations. The agreement between Hyne and HQ Plantations prioritises volume, with no utilisation of pre-harvest assessments of density or elastic modulus to inform log value or pricing at the Tuan mill. Despite an increasing demand for timber and timber-truss products, there is a noted reluctance among builders and designers to deviate from conventional processes and products.

The study then sought to identify opportunities for improvement in the sawn timber production process. Three categories were identified based on relative time and cost investment:

1. Low-hanging fruit
2. Mid-term with medium setup time or cost, and
3. Long-term with large setup time or cost.

There were opportunities with relatively low upfront time or cost investments identified across all 3 stages of the sawn timber production process. Within the plantation stage, data sharing and matching between Hyne and HQ Plantations could allow for a clearer understanding of the change in fibre quality over time and across the Tuan Forest plantation. This could benefit both parties as harvesting could be informed by market demand. Innovative custom products (utilising the CodeMark certification process) were also identified as an opportunity to value-add to low-grade timber products.

Long-term opportunities focused on the plantation stage of the production process. These included data matching between Hyne and HQ Plantations to inform how planting decisions and growth conditions impact stud quality. Alternative supply arrangements could be negotiated whereby expected fibre quality has more weighting as a cost-metric. These long-term measures could benefit both parties by allowing for preferred timber varieties that yield superior fibre quality to be prioritised for planting, with high-quality fibre attracting a premium to reflect the market value of the final sawn product. Upgrading low-grade timber with post-processing technologies, such as densification, could allow for previously low-grade fibre to meet and exceed the minimum requirements of MGP10 grade standards.

Interviews with industry professionals were conducted to gain insights into the barriers associated with the utilisation of low-grade timber. Overall, responses provided valuable insights into the utilization of lower-grade timber, optimisation possibilities in design, the importance of timber characteristics, cost factors, and the challenges associated with defects and waste. These findings underscore the need for further exploration and potential solutions to overcome barriers in utilising low-grade timber in the industry.

The potential for utilising low-grade timber in the construction of residential buildings with one and 2 storeys was also explored. Two typical floor plans were used to simulate various design actions and extract maximum internal loads in all elements present in each structural solutions. A considerable portion of the structural elements experienced internal forces lower than their characteristic strength, suggesting that out-of-grade timber may be utilised in these scenarios. For further accuracy, more advanced modelling of the structure and additional case study buildings should be considered to derive the worst loading scenarios and true internal forces.

LIST OF REFERENCES

[1] Deloitte Global. The 2030 decarbonization challenge: The path to the future of energy. 2020.

[2] Gresham House Asset Management Limited. Global Timber Outlook 2020. 2020.

[3] Whittle L. Analysis of effects of bushfires and COVID-19 on the forestry and wood processing sectors. 2020.

[4] Gavran M, Frakes I, Davey S, Mahendrarajah S. Australia’s plantation log supply 2010-2054. vol. 155. 2012.

[5] Bendtsen BA. Properties of wood from improved and intensively managed trees. 1978.

[6] Pearson RG, Gilmore RC. Effect of fast growth rate on the mechanical properties of loblolly pine. For Prod J 1980;30:47–57.

[7] Moore JR, Lyon AJ, Searles GJ, Lehneke SA, Ridley-Ellis DJ. Within-and between-stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery. Ann For Sci 2013;70:403–15.

[8] Zobel BJ, Sprague JR. Juvenile wood in forest trees. Springer Science & Business Media; 2012.

[9] Department of Agriculture Fisheries and Forestry (DAFF). Australian forest and wood products statistics. Canberra, Australia: 2020.

[10] Lindahl KB, Sténs A, Sandström C, Johansson J, Lidskog R, Ranius T, et al. The Swedish forestry model: More of everything? For Policy Econ 2017;77:44–55.

[11] Yao RT, Harrison DR, Harnnett M. The broader benefits provided by New Zealand’s planted forests. NZJ For 2017;61:7–15.

[12] Canuel C-M, Bernard A, Thiffault N, Gélinas N, Drapeau P, Thiffault E, et al. Analyse d’une stratégie de production de bois: perspectives d’experts. The Forestry Chronicle 2022;98:19–27.

[13] Bibliothèque et Archives nationales du Québec G of Q. Les produits forestiers, une richesse à cultiver. Stratégie de Développement de L’industrie Québécoise des Produits Forestiers 2018-2023. 2018.

[14] Beauregard R, Lavoie P, Thiffault É, Ménard I, Moreau L, Boucher JF, et al. Rapport du Groupe de Travail sur la Foret et les Changements Climatiques. Ministère Des Forêts, de La Faune et Des Parcs, Quebec 2019.

[15] Cherry R, Manalo A, Karunasena W, Stringer G. Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in cross laminated timber (CLT). Constr Build Mater 2019;211:858–68.

[16] D. Burdon R, R. Moore J. Adverse Genetic Correlations and Impacts of Silviculture Involving Wood Properties: Analysis of Issues for Radiata Pine. Forests 2018;9:308. https://doi.org/10.3390/f9060308.

[17] Pramreiter M, Nenning T, Malzl L, Konnerth J. A plea for the efficient use of wood in construction. Nat Rev Mater 2023;8:217–8.

[18] Keenan RJ. Climate change impacts and adaptation in forest management: a review. Ann For Sci 2015;72:145–67.

[19] Mayencourt P, Mueller C. Hybrid analytical and computational optimization methodology for structural shaping: Material-efficient mass timber beams. Eng Struct 2020;215:110532.

[20] Song J, Chen C, Zhu S, Zhu M, Dai J, Ray U, et al. Processing bulk natural wood into a high-performance structural material. Nature 2018;554:224–8.

[21] Hertwich EG, Ali S, Ciacci L, Fishman T, Heeren N, Masanet E, et al. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environmental Research Letters 2019;14:043004.

[22] Orozco L, Svatoš-Ražnjević H, Wagner HJ, Abdelaal M, Amtsberg F, Weiskopf D, et al. Advanced timber construction industry: a quantitative review of 646 global design and construction stakeholders. Buildings 2023;13:2287.

[23] Haller D. How Mirvac unlocked Prefab in the Residential Housing sector. PrefabAUS Conference, Brisbane, Australia: 2022.

[24] Smith RE, Griffin G, Rice T, Hagehofer-Daniell B. Mass timber: evaluating construction performance. Architectural Engineering and Design Management 2018;14:127–38.

[25] WoodSolutions. Structural grading 2024. https://www.woodsolutions.com.au/structural-grading (accessed April 21, 2024).

[26] Cherry R, Karunasena W, Manalo A. Mechanical Properties of Low-Stiffness Out-of-Grade Hybrid Pine—Effects of Knots, Resin and Pith. Forests 2022;13:927.

[27] Johansson G, Kliger R, Perstorper M. Quality of structural timber-product specification system required by end-users. Holz Als Roh- Und Werkstoff 1994;52:42–8. https://doi.org/10.1007/BF02615017.

[28] Woxblom L. Quality Variations in Wall Studs – A Study Conducted at Five Sawmills in Southern Sweden. Swedish University of Agricultural Sciences, 1993.

[29] Rose CM, Stegemann JA. Feasibility of cross-laminated secondary timber. Sustainable Construction Materials and Technologies, vol. 1, International Committee of the SCMT conferences; 2019, p. 495–507.

[30] Sigrist C, Lehmann M. Potential of CLT produced from non-structural grade Australian Pinus Radiata 2014.

[31] Ma Y. Properties of cross-laminated timber panel with low-value lumber and performance of cross-laminated timber wall system subjected to seismic and sequential seismic-wind loadings. Michigan Technological University, 2022.

[32] Heebink BG. Paneling and flooring from low-grade hardwood logs. vol. 122. US Department of Agriculture, Forest Service Forest Products Laboratory; 1966.

[33] Bakis CE, Bank LC, Brown VI, Cosenza E, Davalos JF, Lesko JJ, et al. Fiber-reinforced polymer composites for construction—State-of-the-art review. Journal of Composites for Construction 2002;6:73–87.

[34] Alam P. The reinforcement of timber for structural applications and repair. University of Bath (United Kingdom); 2004.

[35] Moulin JM, Pluvinage G, Jodin P. FGRG: Fibreglass reinforced gluelam—A new composite. Wood Sci Technol 1990;24:289–94.

[36] Raftery GM, Harte AM. Low-grade glued laminated timber reinforced with FRP plate. Compos B Eng 2011;42:724–35.

[37] Raftery GM, Whelan C. Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods. Constr Build Mater 2014;52:209–20.

[38] Raftery GM, Rodd PD. FRP reinforcement of low-grade glulam timber bonded with wood adhesive. Constr Build Mater 2015;91:116–25.

[39] Raftery GM, Kelly F. Basalt FRP rods for reinforcement and repair of timber. Compos B Eng 2015;70:9–19.

[40] Basterra LA, Acuna L, Casado M, Lopez G, Bueno A. Strength testing of Poplar duo beams, Populus x euramericana (Dode) Guinier cv. I-214, with fibre reinforcement. Constr Build Mater 2012;36:90–6.

[41] Basterra LA, Balmori JA, Morillas L, Acuña L, Casado M. Internal reinforcement of laminated duo beams of low-grade timber with GFRP sheets. Constr Build Mater 2017;154:914–20.

[42] Balmori J-A, Basterra L-A, Acuña L. Internal GFRP reinforcement of low-grade maritime pine duo timber beams. Materials 2020;13:571.

[43] Balmori JA, Branco JM, Basterra LA. Behaviour of the adhesive bond between low-grade wood and GFRP reinforcements using epoxy resin. Constr Build Mater 2021;271:121516.

[44] Crafford PL, Wessels CB. The potential of young, green finger-jointed Eucalyptus grandis lumber for roof truss manufacturing. Southern Forests: A Journal of Forest Science 2016;78:61–71.

[45] Muhammad NA, Ibrahim A, Ahmad Z. A Conceptual Review of Structural Performance of Mengkulang Laminated Veneer Lumber (LVL) Roof Trusses. InCIEC 2015, Singapore: Springer Singapore; 2016, p. 783–96. https://doi.org/10.1007/978-981-10-0155-0_66.

[46] Wallace CC. Structural laminated studs from low grade lumber. University of Wyoming; 1999.

[47] Taylor RJ. Prestressed wood bridges. Downsview, Ontario: 1983.

[48] Freedman GJH, Kermani A. Stress-Lamination: Utilising low-grade timber in construction. 2006.

[49] Kermani A, Freedman G. Performance of a stress-laminated-timber arch bridge. Proceedings of the Institution of Civil Engineers-Bridge Engineering, vol. 158, Thomas Telford Ltd; 2005, p. 155–64.

[50] Freedman G, Kermani A. Stress-laminated arches: a stronger case for timber bridges. Proceedings of the Institution of Civil Engineers-Civil Engineering, vol. 157, Thomas Telford Ltd; 2004, p. 172–8.

[51] Fleming PH, Ramage MH. Full-scale construction and testing of stress-laminated columns made with low-grade wood. Constr Build Mater 2020;230:116952.

[52] Fleming PH. Variations in low-grade wood modification and stress lamination. University of Cambridge, 2018.

[53] Derikvand M, Nolan G, Jiao H, Kotlarewski N. What to do with structurally low-grade wood from Australia's plantation eucalyptus; building application? Bioresources 2017;12:4–7.

[54] McGavin RL, Davies MP, Atyeo WJ, MacGregor Skinner J, Baillères H, Armstrong J, et al. Utilisation potential and market opportunities for plantation hardwood thinnings from Queensland and northern New South Wales 2006.

[55] McGavin RL, Bailleres H, Lane F, Blackburn DP, Vega M, Ozarka B. Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology 2014.

[56] Hopewell G, Atyeo WJ, McGavin RL. Evaluation of wood characteristics of tropical post-mid rotation plantation Eucalyptus cloeziana and E. pellita: Part (d) Veneer and plywood potential. 2008.

[57] McGavin RL, Bailleres H, Lane F, Fehrmann J. High value timber composite panels from hardwood plantation thinnings. 2013.

[58] McGavin RL. Analysis of small-log processing to achieve structural veneer from juvenile hardwood plantations 2016.

[59] Gilbert BP, Bailleres H, Zhang H, McGavin RL. Mechanical properties of rotary veneers recovered from early to mid-rotation plantation eucalyptus logs. Proc., 2016 World Conf. on Timber Engineering, Vienna Univ. of Technology, Vienna, 2016.

[60] Gilbert BP, Bailleres H, Zhang H, McGavin RL. Capacity and reliability of LVL beams manufactured from juvenile hardwood plantation logs. World Conference on Timber Engineering, 2018.

[61] Gilbert BP, Bailleres H, Zhang H, McGavin RL. Strength modelling of Laminated Veneer Lumber (LVL) beams. Constr Build Mater 2017;149:763–77. https://doi.org/10.1016/j.conbuildmat.2017.05.153.

[62] Kılıç M. Some important physical properties of laminated veneer lumber (LVL) made from oriental beech and Lombardy poplar. AIP Conf Proc, vol. 1479, American Institute of Physics; 2012, p. 397–401.

[63] Burdurlu E, Kilic M, Ilce AC, Uzunkavak O. The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech (Fagus orientalis L.) and lombardy poplar (Populus nigra L.). Constr Build Mater 2007;21:1720–5.

[64] McGavin RL, Nguyen HH, Gilbert BP, Dakin T, Faircloth A. A comparative study on the mechanical properties of laminated veneer lumber (LVL) produced from blending various wood veneers. Bioresources 2019;14:9064–81.

[65] Wang X, Ross RJ, Brashaw BK, Verhey SA, Forsman JW, Erickson JR. Flexural Properties of laminated veneer lumber manufactured from ultrasonically rated red maple veneer. Forest Products Laboratory 2003.

[66] H'ng PS, Paridah MT, Chin KL. Bending properties of laminated veneer lumber produced from Keruing (Dipterocarpus sp.) reinforced with low density wood species. Asian J Sci Res 2010;3:118–25.

[67] Janowiak JJ. Emerging opportunities for low-grade hardwood in glue-laminated timbers. Proceedings of the 1997 Conference on Eastern Hardwoods, Resources, Technologies, and Markets, 1997.

[68] Wang JB, Wei P, Gao Z, Dai C. The evaluation of panel bond quality and durability of hem-fir cross-laminated timber (CLT). European Journal of Wood and Wood Products 2018;76:833–41.

[69] Lannie F. Durability of treated glued laminated (glulam) timber manufactured from lower grade timber species. Universiti Teknologi MARA, 2013.

[70] Dziurka D, Kawalerczyk J, Walkiewicz J, Derkowski A, Mirski R. The Possibility to Use Pine Timber Pieces with Small Size in the Production of Glulam Beams. Materials 2022;15:3154.

[71] Kasal B, Yan L. Fiber-reinforced polymers as reinforcement for timber structural elements. Reinforcement of Timber Elements in Existing Structures: State-of-the-Art Report of the RILEM TC 245-RTE, Springer; 2021, p. 51–78.

[72] Dagher HJ, Kimball TE, Shaler SM, Abdel-Magid B. Effect of FRP reinforcement on low grade eastern hemlock glulams. Proceedings of the National Conference on Wood in Transportation Structures, 1996, p. 207–14.

[73] Nadir Y, Nagarajan P, Ameen M. Flexural stiffness and strength enhancement of horizontally glued laminated wood beams with GFRP and CFRP composite sheets. Constr Build Mater 2016;112:547–55.

[74] Hong KEM. Structural performance of nail-laminated timber-concrete composite floors. University of British Columbia, 2017.

[75] Weckendorf J, Toratti T, Smith I, Tannert T. Vibration serviceability performance of timber floors. European Journal of Wood and Wood Products 2016;74:353–67.

[76] Zhou J, Chui YH, Gong M, Hu L. Elastic properties of full-size mass timber panels: Characterization using modal testing and comparison with model predictions. Compos B Eng 2017;112:203–12.

[77] Lu Z, Zhou H, Liao Y, Hu C. Effects of surface treatment and adhesives on bond performance and mechanical properties of cross-laminated timber (CLT) made from small diameter Eucalyptus timber. Constr Build Mater 2018;161:9–15.

[78] Derikvand M, Jiao H, Kotlarewski N, Lee M, Chan A, Nolan G. Bending performance of nail-laminated timber constructed of fast-grown plantation eucalypt. European Journal of Wood and Wood Products 2019;77:421–37.

[79] Derikvand M, Kotlarewski N, Lee M, Jiao H, Chan A, Nolan G. Short-term and long-term bending properties of nail-laminated timber constructed of fast-grown plantation eucalypt. Constr Build Mater 2019;211:952–64.

[80] Abed J, Rayburg S, Rodwell J, Neave M. A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. Sustainability 2022;14:5570.

APPENDIX A

Questionnaire for Utilisation of Low-Grade Timber in Roof/Floor Truss or Wall Frame Construction

This Questionnaire is conducted in line with CRC project #15 'Using the Whole Tree for Future Timber-Based Construction'. The main aim is to find avenues for using low-grade timber in the production of roof/floor trusses or wall frames.

1. Have you considered using lower-grade or out-of-grade timber as roof/floor truss or wall frame components?
   a. If so, where do you think they would be best suited?
   b. If so, and decided not to use it, what are the reasons?

2. Have you identified obvious areas of over-engineering in truss and frame design that would provide an opportunity for optimisation around timber grade?

3. Do you think stiffness is the most appropriate way to determine the suitability of a stud for truss manufacturing? Would straightness, dimensional stability, and absence of specific defects be more appropriate in some cases? Please name any other criteria that you would consider.

4. Would you consider larger section sizes of lower-grade timber to achieve the same outcome?

5. Would you consider using EWPs such as LVL or glulam instead of stud if properties are equivalent? Would you choose this product for improved dimensional stability and strength for a higher price?

6. Are you required to use a certain minimum grade for the timber used in your product(s)?
   a. If so, what is the minimum useful grade?
   b. Is this a major obstacle for procurement?

7. Are all truss components the same timber grade? If yes, what barriers (e.g. equipment, warehousing, programming, education, risk reduction etc.) need to be addressed or overcome to use multiple grades within a truss and/or frame?

8. What are the timber grades currently used for:
   a. roof truss
   b. floor truss
   c. wall frames?

9. Is there an opportunity to utilise some lower-grade timber in specific parts of the roof/floor truss or wall frame without compromising or limiting the overall performance of the truss?
   a. If so, would a mix of different (lower) grade timber components complicate the manufacturing process and/or increase construction errors?

10. What are the lowest strength and stiffness properties that would be appropriate to apply to any component of the truss (if the standards allow)?

11. How important are the straightness, shrinkage and swelling characteristics of the timber components? Please quantify each of these characteristics, where possible.

12. How much would further complexity to design/manufacturing/operation be imposed if timber with the same quality to MGP10 with a lower stiffness is utilised in truss manufacturing? Is there any room in truss manufacturing to use such a product?

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13. What software do you use for truss analysis and design? Do you always follow the program recommendations, or do you opt for alternatives such as more economical solutions that still meet the structural performance requirements?

14. How much price reduction (percentage) will motivate you to consider replacing some of roof/floor truss components with lower-grade timber?

15. How much price reduction (percentage) will motivate you to consider replacing some of wall frame components with lower-grade timber?

16. What is the most troublesome defect of your process?

17. What is the most troublesome defect of your product?

18. What cost in waste does your company experience due to these troublesome defects (e.g. waste timber, extra labour, extra processing time, recalls/rework)?

19. Would you be willing to accept timber that had these defects reinforced or 'repaired' if the structural performance and/or processing ability was improved?

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Table 7. Participant responses to questionnaire on utilisation of non-standard or low-grade timber in construction industries

Question	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
1. Are you required to use a certain minimum grade for the timber used in the structures that you design/produce? a) If so, what is the minimum useful/required grade? b) Is this a major obstacle for ...	Builders can dictate a minimum grade they require such as MGP12 studs. F5 is the minimum currently. Availability varies throughout the cycle so constant supply would be an advantage.	All timber needs to be structurally graded	NA	F5	F4 grade, ensure straightness	F5 and MGP10
2. Are all wall/floor/truss components the same timber grade? If yes, what barriers (e.g. equipment, warehousing, programming, education, risk reduction etc.) need to be addressed or overcome to...	No there are multiple grades used in each truss	No	No, they are not. The industry manages a wide variety of grades through the use of software. Current issues exist with stocking both treated and untreated timber of the same size and grade. Increasing the number of grades available for use does pose logistical challenges but they are not insurmountable	Trusses use multiple grades, posing challenges in programming and storage. Different grades for wall, floor, and truss components demand efficient software, education and warehousing.	Negative, multiple grades in trusses. / No, they vary. / Variety of grades managed via software, stock complexities.	Education and programming for different grades
3. What are the timber grades currently used for a) roof truss b) floor truss c) wall frames	a) F5, MGP10, MGP12, MGP15 b) as above c) F5, MGP10, MGP12, F27	All structural grades of timber You'd be best talking to the software providers to better understand this as they provide the engineering solution.	MGP10, MGP12, MGP15, F5, F8, F17, F27 and a variety of LVLs	a) Roof truss: F5, MGP10, MGP12, MGP15 b) Floor truss: Same as above c) Wall frames: F5, MGP10, MGP12, F27	a) Roof truss F5, MGP15 b) Floor truss Similar grades as above c) Wall frames F5, MGP10	a) F5, MGP10, MGP12 b) Identical to roof truss grades c) F5, MGP10
4. Have you considered using lower-grade or out-of-grade timber as roof/floor truss or wall	Use of low-grade is possible F5, F4 in truss and frame design, out-of-grade can be used for frame	We wouldn't consider using lower-grade or out-of-grade unless the design software	Survey completed by Tim Rossiter - MiTek Australia Ltd. - identification requested by Ryo.	Non-load bearing walls	Limited to software-defined options	For specific truss elements, if needed

frame components? a) If so, where do you think they would be best suited? b) If so, and decided not to use ...	Noggings and some ceiling trimmers	allowed for this in its design	Yes in wall frames. In non-load bearing walls and in bottom plates on slab-on-ground i load-bearing walls. No, not out-of-grade in roof trusses - all elements contribute to structural performance. Lower-grade could be used in some trusses for web material			
5. Have you identified obvious areas of over-engineering in truss and frame design that would provide an opportunity for optimisation around timber grade?	Generally, no design is already optimised	It really comes back to the design. If this is not aligned, then it would be hard to consider different grades.	See above for wall frames. Trusses have been engineered very tightly; a lower-grade (with defined properties) has application for webs. Not all webs for all trusses.	Few instances of over-design	Design mostly optimised	Yes, some room for optimisation exists
6. What software do you use for truss analysis and design? Do you always follow the program recommendations, or do you opt for alternatives such as more economical solutions that still meet the struc...	Mitek 20/20 we review the designs and cambers etc., making changes as necessary but still redesign the job in the Mitek software	Pryda and yes, we follow the outputs	MiTek software. No substitution is permitted!!	Designed by others	Mitek 20/20, adjustments	Pryda
7. Would you consider larger sections of lower-grade timber to achieve the same outcome?	Yes	That would come down to the cost vs performance	Yes, they could fulfil structural requirements but may have impact on the use of the manufacturing equipment currently used in the market	Yes	Yes	Yes

8. Would you consider using EWPs such as LVL or glulam instead of solid timber if properties are equivalent? Would you choose this product for improved dimensional stability and strength for a higher...	Yes, but also price would need to be close, or the value proposition does not work	Maybe, but if the cost is more there would need to be advantages or the builder would need to pay more	Yes, cost governs	Yes, if cost aligns	Depends on cost-effectiveness	Consider if costs are reasonable
9. Is there an opportunity to utilise some lower-grade timber in specific parts of the roof/floor truss or wall frame without compromising or limiting the overall performance of the truss? a. If so, ...	Yes	Yes, if the design is aligned	Yes, there is opportunity without compromising as long as the new grades properties are defined. Yes, it will add complications and may lead to errors but much less likely in a factory controlled prefabrication environment. Expect more problem in on-site ‘stick’ or conventional framing builds where the carpenters are choosing the right stick to put where.	Possible, define usage areas	Yes, within defined scope	Opportunity if new grades meet performance needs
10. Do you think stiffness is the most appropriate way to determine the suitability of a stud for truss manufacturing? Would straightness, dimensional stability, and absence of specific defects be mor...	Yes stiffness Defects do limit opportunities as they have a negative perception from the end user Straightness and dimension will depend on the application	All criteria mentioned are essential but the team making trusses are looking at grade and overall quality	Mixed terms – studs are not used in trusses?? For trusses structural properties – stiffness/tension/ bending/compression etc. are needed for correct structural analysis. The industry uses stiffness purely as a method of grouping ‘bundles’ of properties.	Stiffness is significant, consider all	All attributes matter, grade focus	Stiffness primary, include straightness, stability

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			For wall frames straightness and stability would also be criteria but not instead of structural properties; could be used in addition.			
11. What are the lowest strength and stiffness properties that would be appropriate to apply to any component of the truss (if the standards allow)?	F4	NA	NZ standards would be fine, the old F4 properties were also useful. However, historically straightness, stability and appearance degrade in lower structural grades.	F4	F4 grade, ensure stability	NA
12. How important are the straightness, shrinkage and swelling characteristics of the timber components? Please quantify each of these characteristics, where possible.	Within code as a general comment	All important and should perform as per code requirements	Straightness needs to be tight – wall frames for appearance, trusses for structural performance to reduce secondary bending effects. Shrinkage and swelling is important in trusses for joint consistency.	Straightness crucial	Shrinkage impacts joints	Swelling affects stability
13. How much would further complexity to design/manufacturing /operation be imposed if timber with the same quality to MGP10 with a lower stiffness is utilised in truss manufacturing? Is there any room...	There was a study carried out 15 years ago using SP as a grade. The issue is introducing an additional stock line and the potential of the material being used in an incorrect application. That was why it never progressed. I did the testing.	No issue if the design accommodates Maybe issues around keeping more SKUs of timber	Webs easily. Chords less so, but quite possible; just more webbing required and/or larger sections used.	Significant complexity	Design and manufacturing impact	Limited by existing processes
14. How much price reduction (percentage) will motivate you to	Price is only one part of the equation; storage, stock management,	Cost vs performance is the measure we would use	NA	10–15% reduction	Cost-driven decisions	Depends on savings

consider replacing some of roof/floor truss components with lower-grade timber?	availability, all play a part in the decision making process.					
15. How much price reduction (percentage) will motivate you to consider replacing some of wall frame components with lower-grade timber?	As 14	Cost vs performance is the measure we would use	NA	15–20% reduction	Cost-effectiveness	Depends on savings
16. What is the most troublesome defect of your process?	Knots	Irregular sized timber	NA	Irregular sizing		Quality control
17. What is the most troublesome defect of your product?	Bow in studs	Timber no performing as expected	NA	Knots in timber	Bowing in studs	Inconsistent finish
18. What cost in waste does your company experience due to these troublesome defects (e.g. waste timber, extra labour, extra processing time, recalls/rework)?	Figures not kept	Not sure as we remove defects and utilise what remains	NA	Significant waste of timber	Extra labour and processing time	Occasional recalls impact
19. Would you be willing to accept timber that had these defects reinforced or 'repaired' if the structural performance and/or processing ability was improved?	Would need more detail.	Not sure – we'd have to see how the market would accept this	Yes	Conditional acceptance	Depends on improvements	Willing with enhancements

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