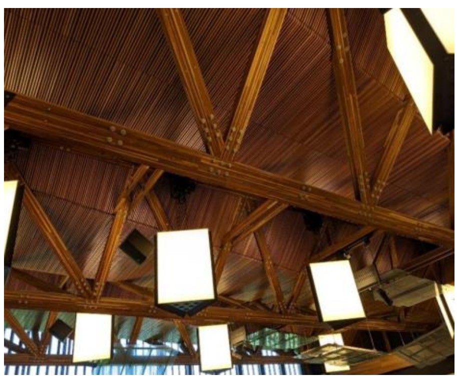
SOUTH + CENTRAL QUEENSLAND REGIONAL
FORESTRY HUB

REPORT: ADHESIVE RESEARCH FOR SOFTWOOD AND HARDWOOD ENGINEERED WOOD PRODUCTS



Queensland Government

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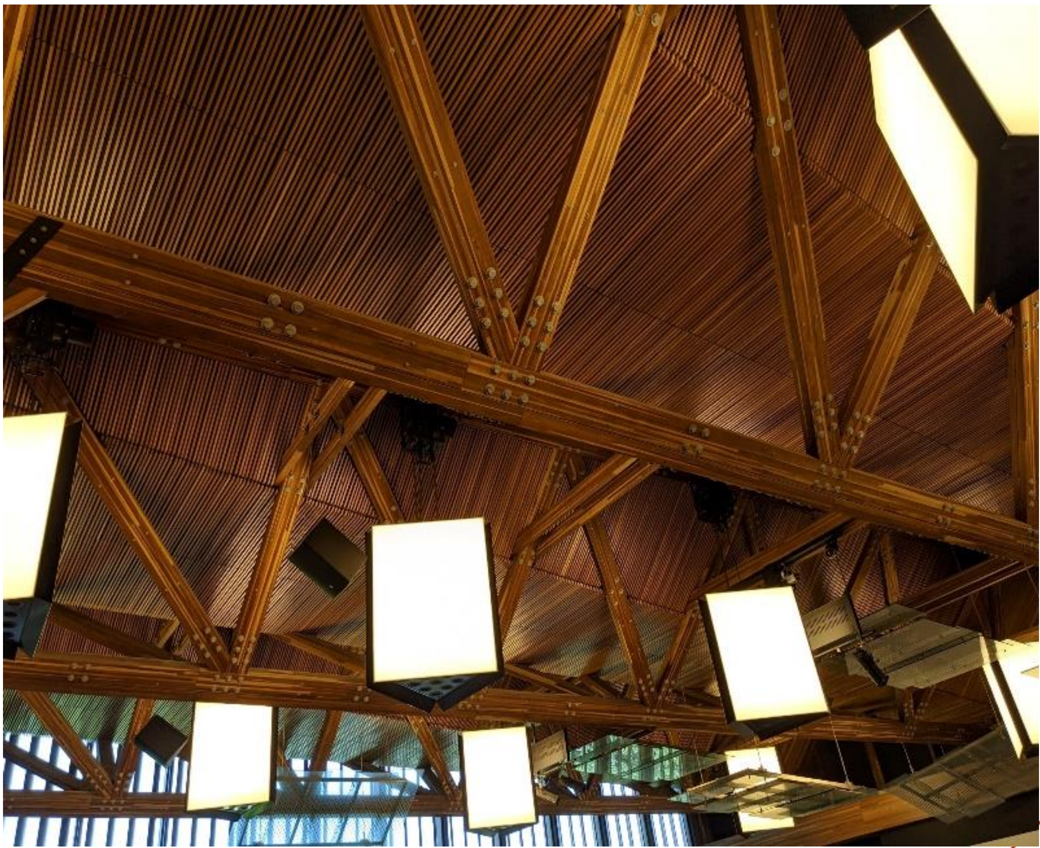
Manufacturing Competitiveness

This report was commissioned by the South & Central Queensland Regional Forestry Hub with funding from the Australian Government, Department of Agriculture, Fisheries and Forestry.

Adhesive Research for Softwood and Hardwood EWPs

Final Report – MS3

11th of August 2022



Queensland Government

This report was commissioned by the South and Central Queensland Regional Forestry Hub with funding from the Australian Government, Department of Agriculture, Fisheries and Forestry.
This report has been compiled by A. Faircloth, A. Outhwaite and reviewed by W. Leggate and R. McGavin of Forest Product Innovations, Department of Agriculture and Fisheries.

The Department of Agriculture and Fisheries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

Executive Summary

The objective of this project was to report on the current state of knowledge relating to commercially available and currently used adhesives in the Australian engineered wood product (EWP) industry with a focus on the South and Central Queensland (S&CQ) region. This report presents a cross sectional representation of the S&CQ and the greater Australian timber industry, its current outputs regarding adhesive-based EWPs, key species being used across the country, and the knowledge and therein gaps in understanding, concerning adhesives use in EWPs existing within the industry.

The objective of this report was aimed at addressing the key concerns of the S&CQ Forestry Hub members where the core knowledge required for adhesive applications in EWP manufacture is either (i) not available, (ii) difficult to obtain, or (iii) varies across sources. Through reviewed literature, industry engagement, and expert knowledge and opinion, the following report has been developed. The EWP types covered in this report consist of structural and non-structural, indoor and fully exposed/ outdoor applicable products manufactured from sawn timber, timber veneers, timber strands, fibres and particles. The report also presents challenges specific to both hardwood and softwood species of the S&CQ resource.

Industry engagement and reviewed literature identified adhesive usage and selection as being driven by standard requirements (e.g., for formaldehyde content), bond integrity, and visual aesthetic appeal (clear glue-lines for example). Although, for some EWP producers shifting to other adhesives requires advancements in the corresponding adhesive systems. Adhesive systems are more challenging for some products than others based on the material type. An example of this is through wood adhesion in softwood-based particleboard being well established, however the gluing of high-density hardwoods for glulam is much more difficult and demanding. Due to the applications of particleboard and minimal complexities with the current adhesion process, alternate adhesives systems are not currently of great concern. Although, advances in particleboard manufacture being made from an R&D point of view have focused on coupling softwood particles with other waste material types such as car tyres (rubber) or treated wood waste; all of which will require alternative adhesive systems research.

Australia’s primary LVL producer has established protocols for the manufacture of LVL using a blended construction strategy of softwoods and hardwood veneers and a formaldehyde type adhesive system. Through the industries adoption of blended species, adhesion systems for bonding of high-density hardwood and softwood veneer-based products has been highlighted as possible and commercially suitable. The same however, cannot be said for sawn-based EWPs using high-density hardwoods and softwoods for applications such as cross laminated timber (CLT) and glulam. Based on the respondents to the consultation phase detailed in Section 6 and Appendix A, a 50/ 50 division was reported for respondents working with hardwood and softwood species in their respective EWPs. Furthermore, of the participating manufacturers, it was found 100% of the hardwood sawn board producers would like

to see improvements in adhesion for face laminating their products, adding that difficulties in obtaining an adequate bond according to the Australian standards was of primary focus. Several of the softwood EWP producers also noted adhesion to be an issue for high-density Queensland softwoods such as Southern Pine (*Pinus caribaea/ Pinus elliottii*). These responses are consistent with reviewed research on high-density hardwoods and softwoods in both face laminating or finger jointing applications which defines the lack of adhesive penetration as one of the main causes of poor bonds.

EWP manufacturers were asked to provide their thoughts on areas of focus for future R&D. While LVL and plywood producers are commercially adopting adhesive systems for bonding high-density species, the majority of these products are developed using formaldehyde-based adhesives. Development of enhanced adhesion systems for native hardwoods using polyurethane adhesives for both LVL and plywood would enable the possibility of a shift away from formaldehyde as a reliable adhesive for these more difficult to work with species. Industry consultation revealed that changing resource (34%) and the increasing competition (25%) are considered high risk in the current economic climate. Australian EWP manufacturers have seen a fluctuation to their product demand with some experiencing increases while others have seen a decline due to resource based constraints. This change in demand has seen increases of up to 200% for some EWP types across Australia. A shifting resource for producers has provided new opportunities for product development and innovation enabling S&CQ regional manufacturers to consider methods in which the available resource can be optimised.

Additional interviews were conducted with a number of industry experts who advised that a better understanding of the design parameters to their product (such as log resource, intended EWP type, and product applications) was a critical and often overlooked part of EWP manufacturing set-up. Governing bodies and certification organisations were contacted to provide another level of detail on product performance issues noted in EWPs, expected challenges for the future industry and recommendations for future research focus. The feedback received from these experts and consultants outlined the lack of training schemes available to industry personnel specialising in EWP manufacture. Both producer and industry expert results presented through Section 6 are based on the respondents to the questionnaire and should not be considered an accurate representation of the whole of Australia's EWP sector.

Contents

1 Introduction

The work described in this report has been conducted by the Forest Product Innovations (FPI) team at the Salisbury Research Facility (SRF) – a group within Agri-Science Queensland, Department of Agriculture and Fisheries (QDAF). This project forms part of the South and Central Queensland (S&CQ) Regional Forestry Hub, with funding from the Australian Government, Department of Agriculture and Fisheries and Forestry. QDAF has been contracted by the S&CQ Regional Forestry Hub to conduct a review study and industry consultation into the use and knowledge that exists relating to adhesive based engineered wood products (EWPs). While there exists a great deal of literature regarding the development, evaluation, and use of EWPs in Australia, it has been indicated by the Queensland timber industry that this knowledge is not applicable at an industrial scale, nor easily accessible. Therefore, a need to consolidate this information into an industry relevant report was identified. Appendix C provides a detailed review of the literature that was found to be applicable to the context of this report.

The focus of this study has been to review and report on glued EWPs due to their high presence on the EWP market in comparison to non-glued EWP types (nail laminated panels, dowel-based connections, etc.). This report reviews published work as well as expert opinion from researchers, academics, industry consultants, and processors on the knowledge capacity surrounding EWP manufacture and the understanding of timber adhesives and wood species. Most EWPs that are comprised of sawn boards, veneers or wood particles involve the use of adhesives during their manufacture. The products' performance is therefore heavily reliant on the adhesive systems and gluing protocols in place to provide a strong, and at times, durable bond [1]. Appendix B discusses the processes that are used as standard practices across the globe for the manufacture of EWPs along with reviewing the uses for the completed EWPs.

Forest and Wood Products Australia (FWPA) reported that softwood timber sales from local producers have increased to 3.06 million m^3 at the end of the 2021 financial year; up 3.2% from the previous year. Based on softwood timber surveys and volume, FWPA predicts that production of sawn softwood is nearing capacity. With this in mind, the way is paved for EWPs to form a larger part of the construction sector through reducing the reliance on sawn boards and pivoting to more efficient, dimensionally stable, and stronger alternatives. Different EWPs are suitable for different applications, and it is through correct structure design and consideration of the application that these products can be efficient alternatives to sawn boards or other non-wood products.

EWPs are currently used across Australia in a variety of structural and non-structural applications from materials sourced locally and internationally. Local manufacturing has the benefit of working with Australian species within expected environmental conditions and therefore has an added understanding of the product in-service requirements. Although, compared to international EWP producers the local EWP sector in S&CQ and Australia is still in the process of developing the skills needed to appropriately work with some of the available resource and as such has been the reason behind the development of this report.

Australian producers face different challenges dependent on their location with access to and the type of resource differing greatly. It is also well known that Queensland has some of the most difficult species to work with as a result of high density and extractive content of some species [2]. This coupled with drastic climate condition variations throughout the year, across the country, requires EWP manufacturers to have a deep understanding of the resource, the adhesives they use, and the product application to be successful.

This report aims to provide information specific to these challenges as well as identify additional areas of interest as specified by the EWP industry. Appendix D discusses EWP performance evaluation, bond evaluation methods and EWP product development. Within Appendix D the adhesion difficulties with Queensland hardwood and high-density softwood species are discussed highlighting that assembly complexities, timber extractives, timber wettability, dimensional change and timber permeability are some of the factors that are contributing to the difficulties in getting EWPs manufactured from Queensland species into the market. Appendix E follows on from Appendix D listing some EWP applications and gluing qualities of key Queensland softwood and hardwood timber species.

1.1. Objectives

This project and its scope of objectives has been initiated through the S&CQ Forestry Hub steering committee meetings and round table discussions with participating processors. The focus of the review consists of identifying adhesive-based challenges a processor/ manufacturer would need to address, when considering entering the glued EWP manufacturing sector and producing marketable products. The report also identifies challenges and perceived risks current producers are facing or anticipate facing in the future. The objectives of the study were to conduct a comprehensive review of:

- The current state of knowledge regarding commercially available adhesive systems and protocols specific to the Queensland and wider Australian market for EWP manufacture.
- Potential use of identified adhesives for the listed EWPs with a particular focus towards their applicability to Queensland's specific log resource.

1.2. Methodology

Based on the objectives described above, the methodology for the study was developed to address and discuss the following key components:

- A review of the commercially available and used adhesives in Australia for the manufacturing of EWPs (solid and wood-based panels),
- Current state of knowledge, gaps in knowledge, and further opportunities for future research, with an emphasis on:

- Determination of the most appropriate adhesives for use in the production of EWPs (finger jointed lengths, glulam, solid timber panels, wood-based panels), with applicability to Queensland's specific log resource and current or expanding manufacturing sector.
- Technical information on the evaluation of EWP workability, surface finishing, service life, and product performance requirements (mechanical properties, product durability and bond integrity).
- Commercial evaluation of some EWPs, including the target market growth rates, industry competition (strengths, weaknesses, opportunities, and threats – SWOT), supply chain, and possible applications.

As detailed in the planning report (MS1 [3]), these points had been separated into three phases. Phase 1 of the study aimed at conducting a comprehensive literature review of available information specific to the Australian manufacturing industry for EWPs. Furthermore, a review of published work where relevant has been included and is detailed in Appendices B, C D, and E. Phase 2 was conducted in parallel to the literature review as this phase aimed at gathering information from a selection of processors, manufacturers, adhesive suppliers, and product conformance evaluators. This industry consultation aimed to get feedback from the manufacturer on challenges they have faced as well as ones they see in the future for continued growth. This information has been arranged and presented in Section 6 with the industry consultation questionnaire presented in Appendix A.

The third phase collated the outputs from phases 1 and 2 and provides some discussion on the expected benefits this information should have, as well as providing a recommendations section based on industry and expert driven consultation. The external contributors, industry collaborators, experts and consultants who contributed to this study have ensured the details within it provide a well-informed cross-sectional view of the EWP industry, the current spread across the country, and the perceived challenges.

2 Review of adhesives

2.1 Background

Since their origin, adhesives have played an important role in enabling wood product market development, in both a structural and non-structural context. With increases in the use of some EWPs and an expansion into mass timber products (another EWP type), ensuring the bonded interface is strong and durable for these products is highly important. In an answer to the requirement of a stronger and more durable bond, the manufacture of adhesives shifted from natural adhesives to synthetic types developed using polymers derived from petrochemicals and natural gas [4].

Natural, referred to as bio-based, adhesives are still in use today and are becoming a more attractive topic for research as society shifts towards more environmentally friendly alternatives for a range of product and material types. However, bio-based adhesives remain too expensive, are limited mainly to non-structural applications and are too variable to be widely used in the EWP manufacturing environment in today's market. Further research and development is required to refine their use and formulation to respond to some of their limitations [4, 5].

Synthetic polymers can be made stronger, more rigid, and durable than the wood from most timber species, and generally have much greater water resistance than adhesives based on natural polymers. The synthetic adhesives group has historically been made up of two main classes, the *amino* and the *phenolic* resins, with more recent developments such as the *epoxy* and *isocyanate-based* adhesives [4].

2.2 Adhesive classification

Adhesives can be classified into two categories as either thermoplastic or thermosetting relating to the type of changes they undergo during and after cure [6]. Most structural adhesives are thermosetting. In the timber industry thermosetting adhesives can be used in structural and non-structural applications with thermoplastic adhesives being restricted to non-structural applications due to their lower strength, tendency to soften on heating, degradation under long term environmental exposure and poor creep resistance when subjected to static loads.

Conversely, thermosetting adhesives' ability to resist creep, heat, and moisture makes them more suitable for use in structural applications. An adhesive's ability to resist water and heat are critical for determining its suitability for use in outdoor (external) applications. Figure 1 presents the categorisation of some adhesive types based on their application and classification.

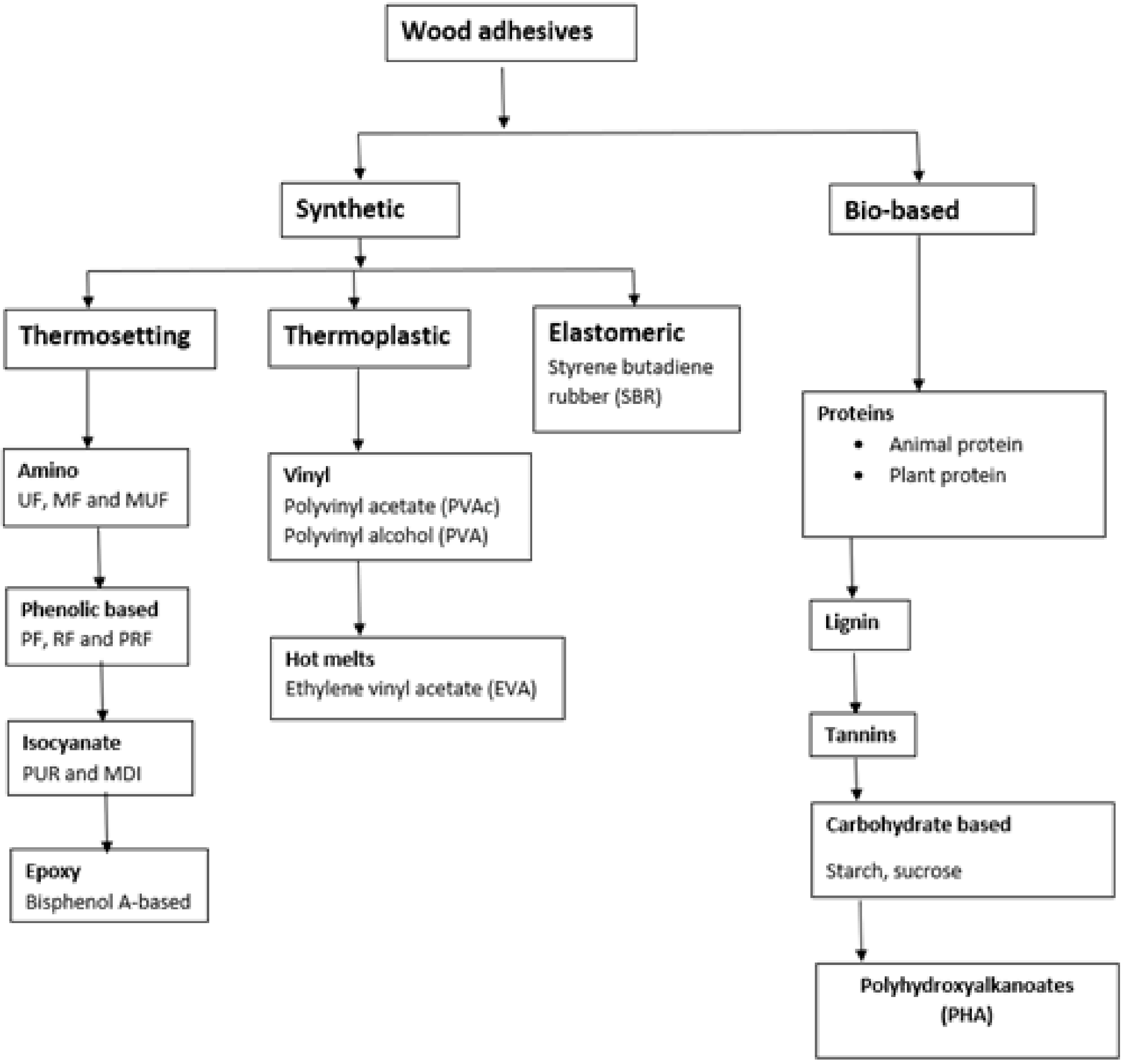


Figure 1: Classification of wood adhesives [5].

2.2.1 Thermoplastic

Thermoplastics are adhesives that once they set hard, will soften becoming malleable again upon heating and harden once cooled. Polyvinyl acetate (PVA) and hotmelt glues are examples of thermoplastic adhesives. Hotmelts are a form of thermoplastic adhesive that start as a solid, are then heated past melting point in the application gun allowing it to flow and make intimate contact over the gluing surface, and then harden once cooled. It is this flowing over the adherent surface and hardening that creates the adhesion. PVA is an example of a thermoplastic adhesive that has the solid dissolved in a solvent to produce a flowable solution that hardens on evaporation of the solution. PVA is generally dissolved in water as an emulsion. Figure 1 shows the adhesive types in their respective manufacturing origins and cure characteristic groups [5].

2.2.2 Thermosetting

Thermosetting adhesives commonly require a catalyst to promote curing due to an irreversible chemical reaction at room or elevated temperatures [6]. Once they have set, they will not soften when re-heated. The amino, phenolic, epoxy and isocyanate based adhesive groups are all examples of thermosetting adhesives. Thermosetting adhesives may be sold as multiple or single component systems.

Multiple component systems (most epoxies and resorcinol formaldehydes - RF) have their reactive components separated. Multiple part adhesives generally have longer shelf lives and are generally cured at room temperature or more rapidly at elevated temperatures [7]. Research has indicated that some multiple component systems can achieve a higher cure strength when cured at elevated temperatures.

Once the components are mixed, the working life/pot life is limited. Single component adhesives have all the reactive components mixed in a single package. The result of this can be a shorter shelf life, sometimes requiring refrigeration. Some single part systems may require heating to obtain a full cure (phenol formaldehyde - PF), while other adhesives may cure at room temperature by chemical reaction with the moisture in the air or on the timbers surface (single component polyurethane - 1C-PUR), by exposure to radiation (radio frequency, UV, etc), or by catalytic reaction with a substrate surface (1C-PUR).

2.2.2.1 Amino resins

The amino resins consist of urea formaldehyde (UF) adhesives and the slightly more expensive melamine formaldehyde (MF). UF is one of the cheapest adhesives for timber use on the market having high usage in particleboard, fibreboard, and plywood manufacture. MF and melamine urea formaldehyde (MUF) adhesives are used in the same products as UF with some usage with sawn boards in glulam products [4, 6].

2.2.2.2 Phenolic resins

The phenolic resins, phenol formaldehyde (PF), resorcinol formaldehyde (RF), and phenol-resorcinol formaldehyde (PRF) have for many years been regarded as the “platinum standard” in wood adhesives used widely in particleboard, plywood, and glulam product manufacture with their high strength characteristics matching that of many timber species [4]. This high strength is retained after the product exposure to high moisture levels and heating. However, a downside to phenolic resins is a dark red/ brown glue-line and higher cost than UF.

2.2.2.3 Isocyanate-based adhesives

Isocyanate-based adhesives have been known and used for over 65 years after being discovered in the late 1930’s [8]. The main types of isocyanate-based adhesives are polyurethane (PUR), aqueous polymer isocyanate (API), emulsion polymer isocyanate (EPI), methylene diphenyl diisocyanate (MDI), and polymeric MDI. API and EPI adhesives are a water-based polyvinyl acetate (PVA) solution that use isocyanates as a cross-linking solution. A review of literature and product specifications has revealed that API and EPI are essentially the same adhesive type that are named either API or EPI by the manufacturers [9].

2.2.2.4 Epoxy adhesives

Epoxy adhesives are less commonly used in the manufacture of EWPs because of their greater cost and, at times, lower durability than the previously mentioned adhesive types [10]. However, they are sometimes used for the on-site repair of timber structures due to their rapid, clear cure properties. Their main use on timber components has been in the boat building industry where they have been used successfully for over 50 years as adhesives and sealers.

2.3 Bio-based

Due to societal changes such as rising population, living standards and environmental awareness, developmental work that focuses on the removal of reliance on petrochemical based synthetic adhesives will lead to a cleaner EWP market sector [5]. The raw materials used in biobased adhesives are derived from biomass which is mostly produced by the agriculture and forest silvicultural processes.

Therefore, these materials are climate-neutral, and the finished bio-based adhesives have a greatly reduced effect on the environment. The major limitations to biobased adhesives include the availability of tannins, lack of adhesion for starches, high production costs for Polyhydroxyalkanoates, poor water resistance, and low strength properties mainly limiting their use to non-structural applications [5]. The availability of biobased and biodegradable adhesives for use in the packaging industry is growing with biobased adhesives already in use to manufacture cartons and plastics.

Weiss Chemicals have polyurethane assembly adhesives (Cosmo PU-100.900) and epoxy adhesives (Cosmo EP-200.110) available for use in door and window construction and by building trades. These adhesives are currently available on the market and are said to have a percentage of their make-up originating from natural renewable resources.

3 Common adhesive types in Australia

There are many types and variations of commercial adhesives to choose from for any specific application. The following paragraphs and Table 1 have been included to give an understanding of applications for adhesives used in the timber industry in both structural and non-structural applications. The information presented through this section has been extracted from both expert opinion as well as the work of Leggate *et al.* [1].

3.1 Urea formaldehyde (UF) adhesives

UF resins are commonly used adhesives in the veneer and particleboard industry for non-structural, interior applications. A type of amino resin, UF adhesives have several advantages and disadvantages as listed below:

Advantages:

- Relatively inexpensive,
- Cures at ambient temperature or can be accelerated by further heat application,
- Light colour and produces light colour glue-lines,

Disadvantages:

- Restricted for indoor use only,
- Glue-line weakens when exposed to long term high temperature and elevated moisture content,
- Potential to emit formaldehyde overtime although policy and testing is in place to restrict this occurrence,

3.2 Melamine formaldehyde (MF) and melamine urea formaldehyde (MUF) adhesives

MF and MUF adhesives have increased water resistance when compared to UF adhesives and therefore are commonly used for the manufacture of semi-weather exposed and some fully weather exposed products (supporting beams and trusses). A type of amino resin, MF/ MUF advantages and disadvantages are listed here:

Advantages:

- Common applications in paper sheet impregnation for plastic laminate backing,
- MUF provides a low-cost alternative to MF types,

Disadvantages:

- High cost of melamine limits use of MF adhesives,
- Consequence of low cost MUF is lower bond durability,
- MUF adhesives more expensive that UF,
- More understanding required regarding durability, fire, and creep performance,

3.3 Phenol formaldehyde (PF) adhesives

PF adhesives are widely used in the veneer industry. They have outstanding bond durability due to good waterproof properties and therefore are favoured for the manufacture of structural products, especially weather exposed areas. PF adhesives can be blended with either lignin, soy flour or tannin adhesives to make a partially organic based adhesive. Some advantages and disadvantages of PF adhesives are as follows:

Advantages:

- High bond durability,
- Can be used in structural products,
- Good tacking properties which provide some advantage during manufacturing,

Disadvantages:

- They can emit formaldehyde and therefore need to be tested regularly for emissions,
- High curing temperature needed and longer press time than UF,
- Produces a dark glue-line from the dark adhesive colour,
- Requires low veneer moisture content,
- pH of adhesive highly alkaline making the adhesive corrosive and a workplace hazard,

3.4 Resorcinol formaldehyde (RF) and phenol resorcinol formaldehyde (PRF) adhesives

RF and PRF adhesives are very widely used in the construction of glulam worldwide, however with some of their market recently being lost to PUR adhesives. RF and PRF have been the go-to adhesive for difficult to glue timber species due to their outstanding bond strength. RF and PRF adhesives are discussed together through this document as PRF adhesive behaves more like an RF adhesive than a PF adhesive. Some advantages and disadvantages of RF/ PRF are listed below:

Advantages:

- High bond durability,
- Can be used in structural products,
- Chemically stable once set,
- High resistance to heat,
- Room temperature or elevated temperature curing,

Disadvantages:

- Two component system requiring mixing and preparation,
- Poor gap filling characteristics,
- Long initial (cold) pre-press periods,
- Produces a dark glue-line from the dark adhesive colour,
- RF expensive due to cost of formaldehyde,
- Mixing can require use of powder hardener agent which becomes a OH&S hazard,
- Several days to achieve full cure,

3.5 Polyurethane adhesives

PUR adhesives have been adopted for use in EWPs manufactured from sawn timber, however, are not yet widely used in the manufacture of veneer products. They have been adapted for some veneer applications, particularly in Europe, and are gaining in popularity. Single component polyurethanes (1C-PURs) can be manufactured with differing reactivity times. The different reactivity time effects the adhesives allowable open time as well as the cure times. 1C-PUR reaction times can range from as little as 5 minutes to 70 minutes. Some advantages and disadvantages of PUR are listed below:

Advantages:

- Most are thermosetting,
- They work efficiently within a range of timber moisture contents,
- Used mainly as cold setting adhesives,
- Suitable for products used in weather exposed applications while having good ultraviolet (UV) and water resistance,
- Range of systems available with varying curing times for flexible production,
- Produces a clear/ white glue-line,

Disadvantages:

- Limited shelf life, especially after being opened and exposed to atmosphere,
- Requires the use of solvents for cleaning residual adhesive,
- Curing times can vary considerably due to the adhesive's sensitivity to humidity, temperature, and veneer moisture content,
- The bonds produced on high density (>750 kg/m^3) can be inefficient,
- More understanding required regarding durability, fire, and creep performance,

3.6 Polyvinyl acetate and derivatives

PVA and its derivatives are a very cheap and common thermoplastic adhesive used in woodworking. They lose moisture and solidify to form a tight bond between two surfaces, producing a durable and strong bond suited for use in interior and conditions that may experience some moisture as they provide some water resistance but do not pass cyclic wet/dry testing. Some advantages and disadvantages associated with PVA are:

Advantages:

- Large stress bearing zone,
- Excellent fatigue strength,
- Dampens vibration and absorbs shock,
- Smooth contours with no visible fasteners,
- Often less expensive and faster to use than mechanical fasteners,

Disadvantages:

- Requires careful surface preparation,
- Strength of bonded interface and joints difficult to determine without destructive testing,

- Provides attractive strength to weight ratio,
- Low water resistance,

There are four requirements that most adhesives need to meet to reach a cured state. The requirements are *heat*, *pressure*, *time,* and *catalyst*. Some adhesives may require more than one of the four requirements and others may require only one.

For example, a 1C adhesive like PVA requires *time* to achieve its full strength, whereas 1C-PUR requires *pressure*, *time,* and a *catalyst*, where the catalyst is the moisture in the timber and surrounding environment. An adhesive like PF requires *heat*, *pressure,* and *time* to achieve full adhesive cure. Table 1 provides an overview of the properties of commercially available adhesive types.

Table 1: Adhesive Properties and Uses [6].

Adhesive Type	Type	Form and Colour	Preparation and Application	Cure	Strength Properties	Typical uses
Melamine Formaldehyde (MF) or Melamine Urea Formaldehyde (MUF)	Structural, Indoor, moisture resistant.	Powdered and liquid forms with blended catalyst, white to tan in colour, transparent glue-line.	Mixed with water, sprayed, rolled, curtain applicator.	Heat cured required in press 120° - 150°C suited for fast cure.	High dry strength and durability once cured, resistant to water and damp atmosphere.	Softwood and hardwood plywood constructions, blockboard, end jointing, scarf joining, edge gluing, face lamination, CLT.
Urea Formaldehyde (UF)	Structural, Indoor.	Powdered and liquid forms; white to tan in colour, transparent glue-line.	Powder mixed with water, hardener, filler, and extender by user.	Some types cure at room temperature, others require press under heat of 120 °C.	High dry strength once cured, moderately durable under damp atmosphere, moderate to low resistance to wetting and temperatures greater than 50°C.	Interior use plywood, blockboard, MDF, and particleboard.
Phenol Formaldehyde (PF)	Structural, Outdoor.	Liquid, powder, and dry film; dark red-black glue-line.	Liquid blended with extenders and fillers by user; film inserted directly between laminates, liquid or powder applied	all formulations cured in hot press, at a temperature range of 120 – 150 °C.	High dry strength and durability once cured, high resistance to moisture and damp atmosphere, highly resistant to high	Primary adhesive for exterior durability in plywood, blockboard, OSB and hardboard (Masonite).

			directly to wood in composites.		temperature and chemical aging.	
Resorcinol Formaldehyde (RF) and Phenol resorcinol formaldehyde (PRF)	Structural, Outdoor.	Liquid resin and liquid or powder hardener, phenol may be copolymerised with resorcinol, dark red glue-line.	Resin mixed with hardener at 4:1 or 5:1 ratio, can be applied through brushing, spraying, rolling, or curtain coater.	Can cure at room temperature or at elevated temperatures of up to 90 °C.	High dry strength and durability once cured, highly resistant to moisture and damp atmosphere, highly resistant to high temperature and chemical aging.	Adhesive suitable for glulam and finger joints that must withstand severe service conditions (outdoor environmental conditions).
Aqueous Polymer Isocyanate (API) Emulsion Polymer Isocyanate (EPI)	Structural, Exterior in some countries. Not currently used in Australia.	Water based polymer with isocyanate cross linker (hardener), white in colour, white glue-line.	Polymer mixed with crosslinker at a ratio of 100:15 or 100:20, can be applied through brushing, spraying, rolling, curtain coater, or bead extrusion.	Room temperature cure.	High dry strength and durability once cured, resistant to water and damp atmospheres.	Adhesive suitable for glulam and finger joints in external conditions.
Polyurethane (PUR)	Structural, Exterior.	Low viscosity as a liquid to high viscosity as a mastic, supplied as	Adhesive applied directly to one surface, reactive to moisture in timber and in atmosphere	Room temperature cure. Rate of cure will be accelerated	High dry strength and durability once cured, resistant to water and damp atmospheres, good gap-filling	General purpose home and shop adhesive, a suitable construction adhesive for wall and flooring panels, as well

		one-part (1K) or two-part (2K) systems, colour varies from clear to brow, transparent glue-line.	producing CO_2 gas (foaming).	in hot and/ or humid conditions.	characteristics, widely used in Europe for structural applications. Currently do not comply with applicable Australian standards for Veneer products.	as glulam, finger joints, non-structural LVL and plywood.
Isocyanate (MDI), e(MDI), p(MDI)	Structural, Exterior.	Liquid containing methylene diphenyl diisocyanate, light brown liquid and clear glue-line in colour.	Adhesive can be applied by spray or spreader, reactive with water and produces CO_2 gas (foaming).	Elevated temperature cure.	High dry strength and durability once cured, highly resistant to water and damp atmospheres, can reduce moisture swelling of timber, adheres to metals and plastics.	Suitable for use in particleboard, fibreboard, and OSB manufacture.
Epoxy	Non-structural (in timber industry).	Liquid resin and hardener supplied as two parts, clear to amber in colour, translucent glue-line.	Two parts mixed by user with a limited pot life after mixing, large mixed quantities can cause fires due to exothermic reaction. Film adhesive available with high temperature cure.	Room or elevated temperature curing. Low press pressures required.	High dry strength once cured, formulations for timber can resist water and damp atmospheres, delaminates with repeated wetting and drying.	Commonly used for repair of glulam beams and other visual components, general home and workshop use. Used widely in several industries other than EWP manufacture.

Poly vinyl Alcohol / Acetate (PVA / PVAc)	Non-structural.	Liquid, ready to use, white to tan colourless glue-line.	Liquid applied directly to surface.	Room temperature.	High dry strength once cured although low resistance to water.	Suitable for furniture, doors, general purpose in homes and workshop applications.
Lignin, soy, or tannin incorporated into phenol formaldehyde	Undefined at this stage due to early market entrance.	Liquid, powder, and dry film; dark red-black glue-line.	Liquid blended with extenders and fillers by user.	All formulations cured in hot press, at a temperature range of 120 – 150 °C.	Good dry strength once cured, durability improved by blending with phenolic adhesive.	Very small markets as of 2020, but significant potential.
Elastomeric Mastic (construction adhesive)	Non-structural.	Putty-like consistency, synthetic or natural elastomers in organic solvent or latex emulsions, tan, yellow, grey, or black in colour.	Extruded in bead form to framing members by caulking gun.	Room temperature cure. Often nailed or screwed to add extra pressure during cure and while in service.	Strength develops slowly over several weeks, strength once cured weaker than conventional adhesives, resistant to water and moist atmosphere, tolerant of outdoor assembly conditions, good gap filling characteristics.	Suitable for sawn boards to plywood adhesion, as well as particleboard or plasterboard in floor and wall systems.
Elastomeric contact	Non-structural.	Viscous liquid, typically neoprene or	Applied to both surfaces, partially dried after	Roller pressing at room temperature	Strength develops immediately upon pressing, increases slowly over a period of	Suitable for rapid bonding of decorative benchtops, factory lamination of wood,

		styrene-butadiene.	spreading and before pressing.	produces instant bonding.	weeks, weaker than conventional adhesives once cured, low resistance to water and damp atmospheres, creep under static load.	paper, metal, and plastic sheet materials.
Animal Protein	Non-structural.	Clear, tan, or dark in colour, thick liquid consistency.	Often heated to apply.	Curves once cooled through loss of moisture.	Strong once cured, typically not water resistant.	Suitable for Furniture applications.
Soybean protein	Non-structural.	Powder form with added chemicals, white to tan in colour in both pre and post cure state.	Mixed with cold water, lime, caustic soda, and other chemicals.	Applied and pressed at room temperature.	Moderate to low strength once cured, moderate to low resistance to water and damp atmospheres.	Historically used for interior plywood.
Cross-linked soybean	Non-structural Limited exterior exposure.	Creamy viscous liquid. Tan/ white in colour.	Soy flour mixed with water and cross-linking chemicals to provide wet strength.	A temperature range of 120 – 150 °C is commonly used.	Good strength once cured, moderate durability performance.	Interior use for plywood, timber flooring, with potential for use in particleboard and fibreboard.

4 Utilisation/ Application

Based on the information presented through Section 3 and Table 1, adhesives can be commonly categorised based on their utilisation. A utilisation-based classification defines adhesives as being either structural or non-structural. The definition and exemplar utilisations of both types of applications are defined below.

4.1 Structural

Structural adhesives are materials of high strength and permanence. Their primary function is to resist high loads without deformation at the bonded interface. Structural adhesives are generally presumed to survive the life of the application, such as the service life of the structure or product. For an EWP to be used in structural applications it must be able to withstand the calculated design loads and forces, moisture and ultraviolet (UV) exposure, and chemical and saline environments throughout its design life. To enable this, structural EWPs have standardised design properties that must be adhered to according to Australian standards [11], as well as Australia's building and construction codes [12].

In Australia, adhesives are assessed for use in structural applications by testing the adhesive qualities in accordance with AS/NZS4364 [13] (Glulam) and/ or AS2754.1 [14] (Ply and LVL). The adhesives are tested for anti-fungal properties, pH of cured form, shear strength, wood fibre failure assessment, delamination, and creep resistance. For an adhesive company to sell an adhesive as structural that product must be certified as passing the requirements of the relevant standard for the product type (AS/NZS4364 [13] and/ or AS2754.1 [14]).

A finished, glued product is assessed through a range of product performance tests (as detailed in Appendix D) which cover both mechanical testing as well as bond integrity evaluation. The rigour and intensity of the bond evaluation process is dependent on the intended application of the product [15]. The applications, similar to structural and non-structural, are separated into 3 categories or service classes. The service classes (as represented in Figure 2) are representative of the expected environmental conditions and exposure ratings for temperature and humidity ranges. AS1720.1 [11] and AS/NZS1328.1 [16] specify that glulam products manufactured in Australia must meet the requirements of a service class 3 exposure rating for their initial qualification testing.

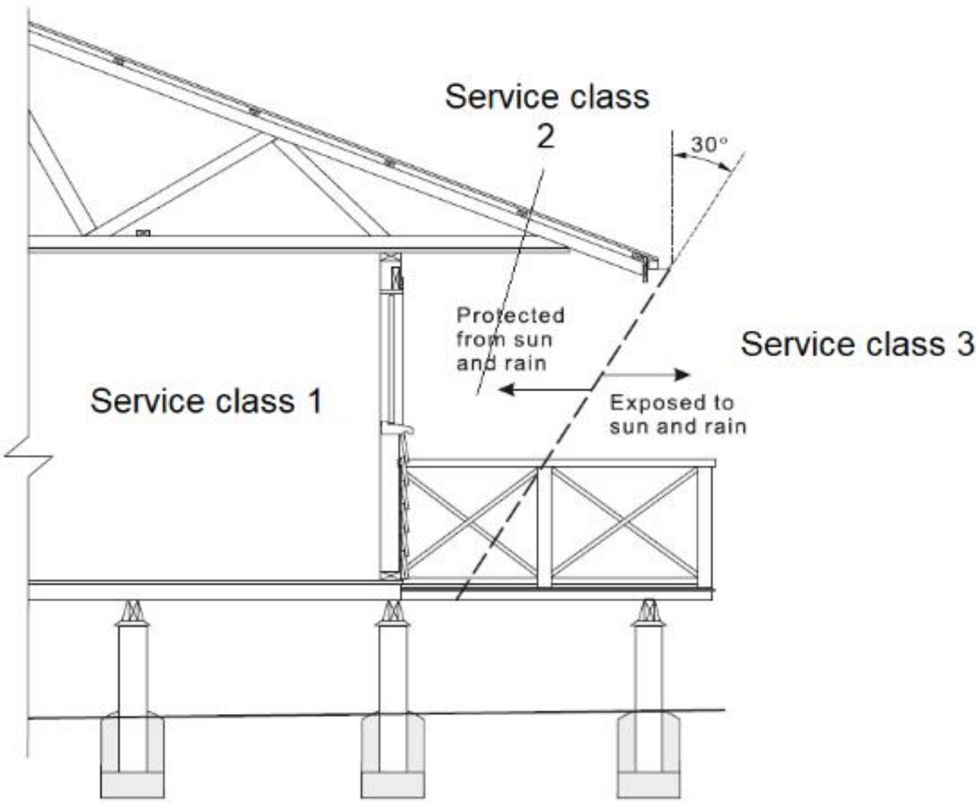


Figure 2: Service class exposure scenarios [15].

4.2 Non-structural

Non-structural adhesives are not required to support substantial loads, they are only required to hold light-weight materials in place. Examples of non-structural items are furniture, weatherboards on a house or decorative screening. Non-structural adhesives are sometimes used in combination with other types of fasteners. In these applications, the adhesive bond is considered a secondary fastener. The use of non-structural adhesives in combination with mechanical fasteners may permit a reduction in the number of mechanical fasteners that would normally be used and provide additional value in the assembly such as vibration, damping, and joint sealing.

However, for long term market acceptance some items such as finger jointed decking and weatherboards will need to be made using an adhesive that can withstand exposure to the elements if they are to be used in external locations. Most structural adhesives have been tested for environmental exposure leading to more information being available regarding bond durability driven from moisture changes than non-structural adhesives. No Australian standard covers the requirements for adhesives in non-structural applications where the bond is not required to permanently provide high mechanical properties like those subjected to load bearing applications [17].

5 Occupational health & safety

There are several potential occupational health and safety issues in using adhesives. A series of risks exist in using these chemicals regarding their contact with skin causing irritation as well as inhalation that can lead to respiratory tract-based risks. Some people may experience burning sensations in the eyes, nose, and throat, resulting in coughing, wheezing, and skin irritation if they are exposed to Formaldehyde at levels exceeding 100 mg/m^3 in the air.

Formaldehyde was listed as a human carcinogen in 2011 by the National Cancer Institute [5]. The Australian Government's National Occupational Health and Safety Commission (NOHSC) [18] has defined the national exposure standards for components found in adhesives to be as shown in Table 2.

Table 2: Exposure limits for a sample of chemicals found in adhesive products [18].

Component	Time Weighted Average (mg/m^3)	Short Term Exposure Limit (mg/m^3)
Formaldehyde	1.2	2.5
Isocyanate (All)	0.02	0.07
Melamine	None	None
Methanol	262	328
Phenol	4	None
Resorcinol	45	90
Urea	None	None

The risk in using these materials arises when the proper handling techniques and personal protective equipment recommendations are not followed [19]. There is an increase in exposure risk when the chemicals become airborne by volatizing the adhesive or creating an aerosol of the adhesive (or particulates contaminated with the adhesive) by, for example, spraying. Such conditions are likely to exist when this adhesive is used in the manufacture of MDF, particleboard or OSB.

Such a risk is significantly reduced when it is used in the manufacture of EWPs where it is typically applied as a liquid [20]. Recent studies have indicated that the level of isocyanate present when used in these applications is well below the levels recommended by the NOHSC [18]. These risks can be further reduced by introducing the appropriate occupational health systems and practices when these adhesives are used.

6 The Australian market

This Section of the report contains the information collected from the industry consultation conducted to define wood adhesive-based products and procedures being developed or currently in use across Australia. Figure 3 presents a visual representation of the location for some of the EWP manufacturers, processors of timber products (boards, veneers, particles), as well as the location of some performance testing facilities. Of the mapped locations, 25 Australian EWP producers participated in this study.

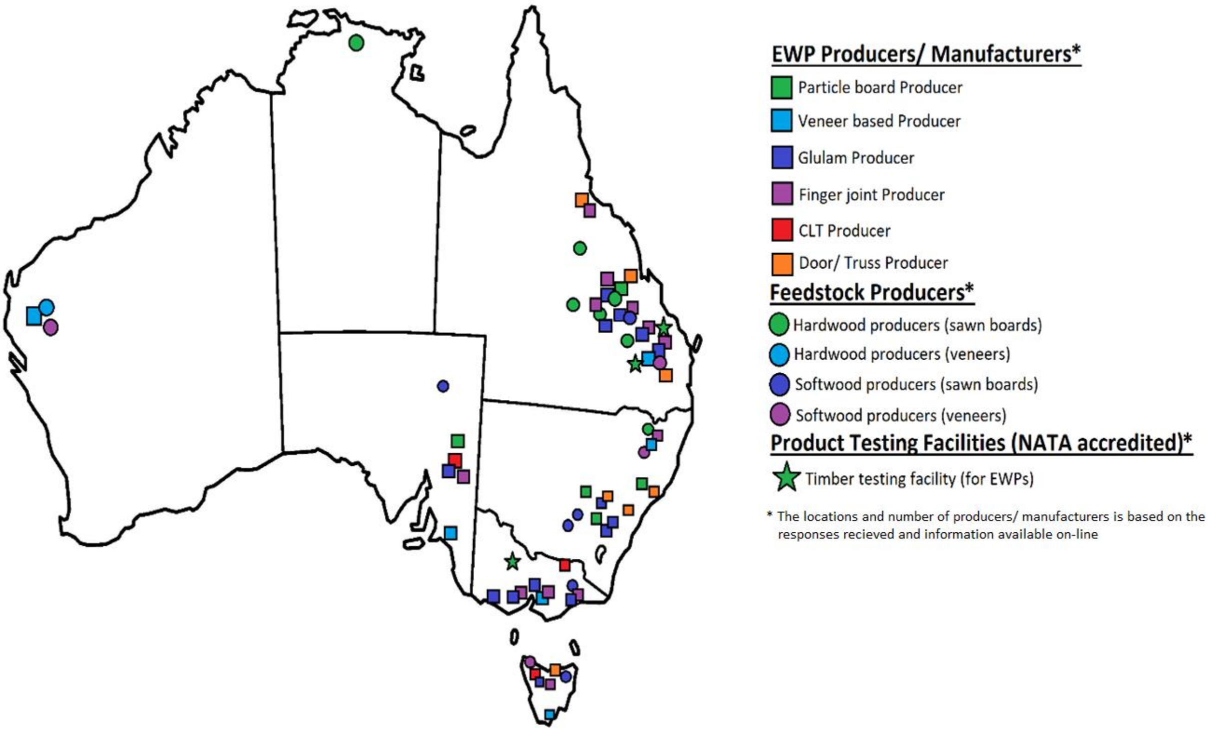


Figure 3: Country map of producers, processors, manufacturers, and testing facilities for EWPs, (bottom) breakdown of respondents.

In addition to the EWP manufacturers participating in the review, several consultancy companies, certification bodies and testing organisations also contributed. The information presented in the map is based on the authors knowledge, industry consultation, and available information online of the EWP sector in Australia and therefore should be considered accordingly.

Figure 4 presents the distribution of respondents who were willing to participate in the consultation and their regional location. Majority of the feedback and therefore information contained in this section is specific to the Qld industry followed by NSW, Victoria and Tasmania. It should be noted that these are not the only timber processors and EWP manufacturers in Australia, although the selected interviewees have been contacted to provide a representative view of the EWP sector in Australia across a range of adhesives, timber species and product types.

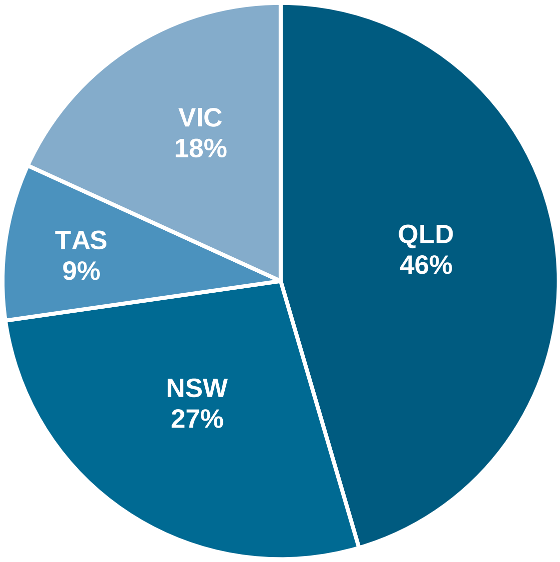


Figure 4: Breakdown of respondents and their location.

In addition to surveying manufacturers of EWPs, a series of selected industry experts and testing facilities were consulted to provide information regarding observations made through past research and development activities and details on the influence the bond integrity can have on mechanical and durable performance. Their participation involved responses to a series of questions which were aimed at providing:

- A generalised view of the EWPs available on the Australian market,
- The timber species and adhesives used across the country,
- Changes in market demand for their products, and
- Market opportunities that are being missed due to limited adhesive-based knowledge,

The result of these discussions with the targeted audience presented a range of detailed responses which have been amalgamated into some key observations and findings identified by the authors as detailed in the following section. The specific responses from the contributing companies have been kept confidential for the purpose of this review.

6.1 Consultation outcomes

6.1.1 Current EWP producers

Manufacturers of EWPs were targeted to gain both an accurate representation of the current EWP industry across Australia and detail products and challenges for both softwood and hardwood timber species. DAF reached out to 25 EWP manufacturers Australia wide. The manufacturers consisted of 3 CLT plants, 13 glulam plants, 5 Ply /LVL manufacturers, 3 particleboard producers and one (1) door manufacturer. Some of the participating manufacturers produced more than a single product type in most cases and where possible have been questioned on all their product range.

This was carried out to gain insight into the current activities Australian EWP producers were conducting and to determine any underlying trends or difficulties they note when using adhesives. Due to the larger number of sawn board type EWP manufacturers in Australia, the industry responses returned results that were biased on the side of sawn timber EWPs (64%). The responses detailed below present the results of this section of the study through their varied use of Australian resources and adhesives for a variety of EWPs. Some of the key observations were as follows.

6.1.1.1 Adhesives and EWP type

Figure 5 displays the information received from industry responses regarding the types of EWPs produced and the adhesives used to make them. It was observed that the most common adhesive-based EWP was the finger joint (33%). Furthermore, the most common adhesive used across the EWP types in Figure 5 (b) was PUR (33%) due to its single component nature and the ability to tune adhesive reaction times to processing and environmental requirements.

The results presented in Figure 5 are not volume specific, the chart presents only the number of manufacturers questioned that were using these adhesives and the number of these manufacturers that were producing these products.

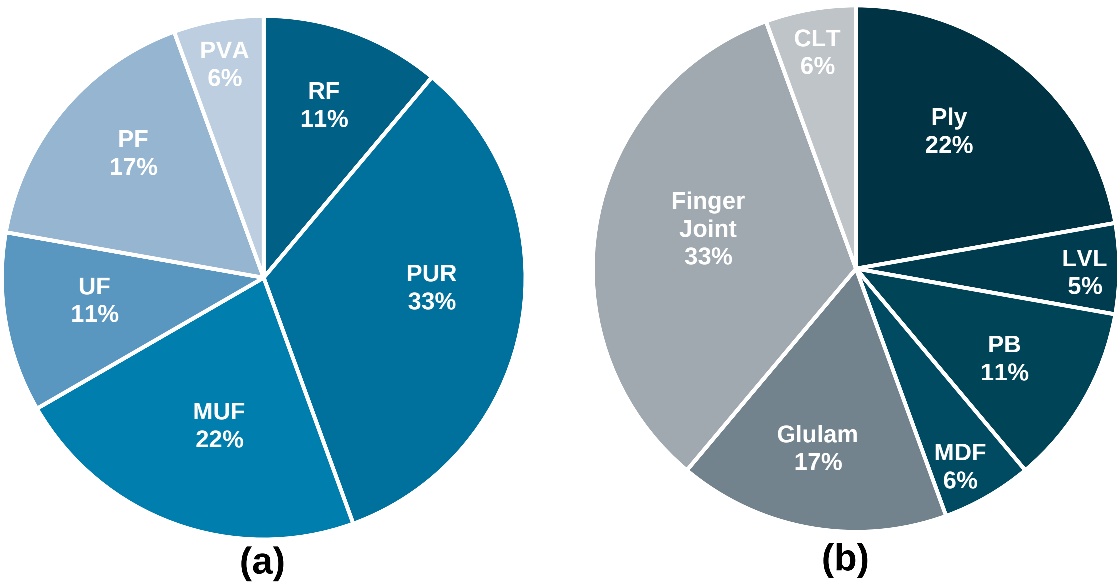


Figure 5: Distribution of (a) Adhesive types used, and (b) EWPs manufactured in Australia from survey respondents.

6.1.1.2 Species currently in use for EWP manufacture

The next outcome of the consultation was regarding the species currently being used across the EWP sector. The responses showed that a wide variety of Australian species (Figure 6) are currently being used to produce EWPs with both softwood and hardwood species and are being used to produce both veneer and sawn based products. The manufacture of particleboard is currently being carried out using softwood only in Australia. Spotted gum and blackbutt were shown be the two highest use hardwoods. Spotted gum is currently being used in both glulam and veneer-based products while blackbutt is currently being used in veneer-based products, finger jointed decking and glulam products. From the information presented in Figure 6, 45% of the commonly used species originate within or close to the S&CQ region.

The results presented in Figure 6 are not volume specific, the chart presents only the number of manufacturers questioned that were using these species for their EWP product types.

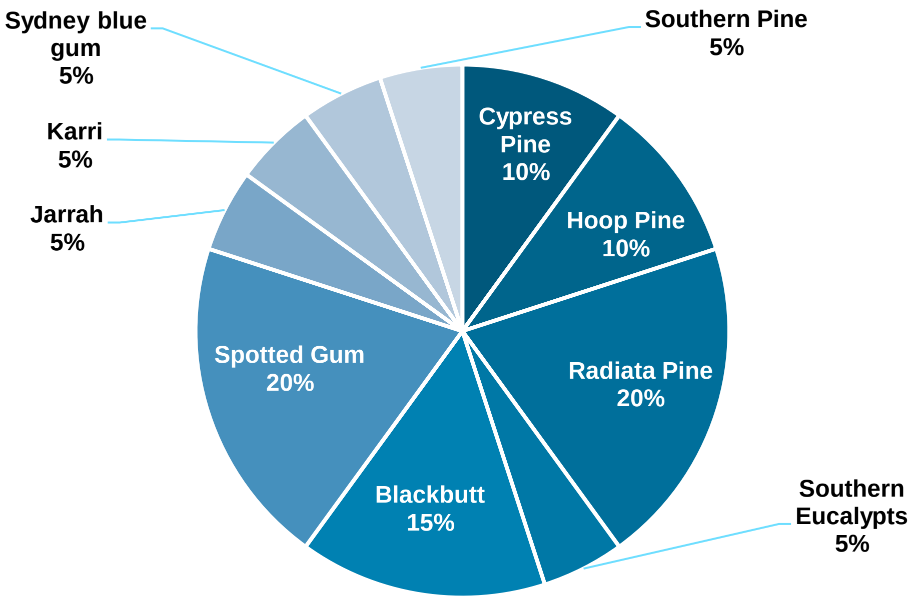


Figure 6: Common species used in the manufacture of Australian EWPs from survey respondents.

6.1.1.3 Increase in demand over the past two years

With several supply chain impacts occurring internationally, Australian manufacturers of EWPs have seen an increase in demand for their products over the past two years. Manufacturers were questioned as to the magnitude of demand change over this period with some interesting findings reported.

For some manufacturers, the demand is greater than their ability to supply given the shortage of trained labour and limited forest resources available. It was reported that one producer had seen a reduction in demand, but the amount was not described. This was due to a change to a lower volume and higher value product (a shift in business model). Two of the respondents reported an increase in demand, however they were unsure if the increase was due to the market changing or increased awareness of their products. The data presented in Figure 7 indicates the increase in market demands as a multiple value (1x = 100% increase, 0.75x = 75% increase, etc).

As presented in Figure 7 many manufacturers in Australia (65%) reported some demand increase with increases of 2 to 4 times normal demand reported for 25% of the manufacturers.

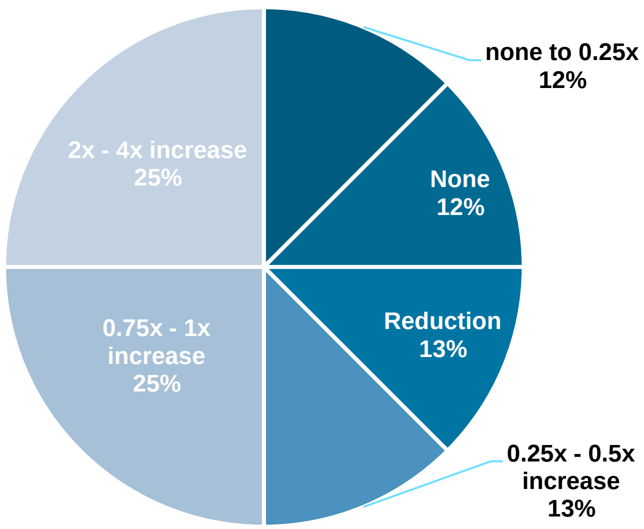


Figure 7: Increase in product demand over the last two years for current EWP producers surveyed.

6.1.1.4 Perceived risks to the Australian EWP industry

To understand some concerns of EWP producers, they were asked what they perceived as risks to their business and wider industry. The most common response was concerning the available log resource (34%) security and government policy on native forest logging (Figure 8).

This highlights one of the intricacies of the Australian timber industry where the most common concern was wood resource availability with competition national and international markets making up 25%. A further 17% of the responses considered adhesion in general as a risk outlining the bonding of some species to be difficult for certain applications.

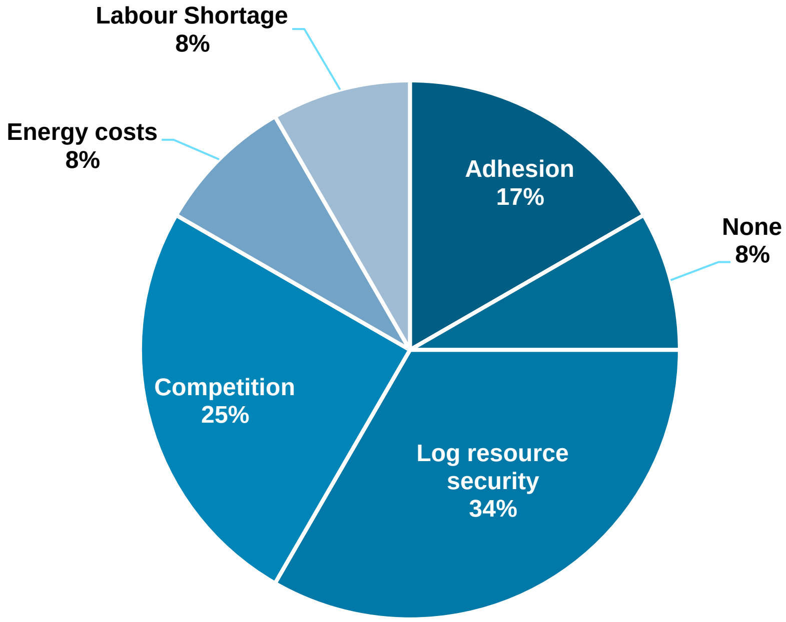


Figure 8: Australian EWP producers perceived risks to the EWP industry from the surveyed respondents.

6.1.1.5 Concerns regarding the use of adhesives

Following the concerns presented in Figure 8, it was made apparent that some EWP manufacturers have concerns regarding the use of adhesives. Two of these concern areas are safety related (formaldehyde emissions – 36% and isocyanate exposure – 14%). One concern was regarding formaldehyde emissions from the cured adhesive and the other regarding health concerns for manufacturing staff involved in the application of isocyanate adhesives. Others were concerned about adhesion problems specific to native, high-density hardwoods (29%) and fire performance (7%) of adhesives.

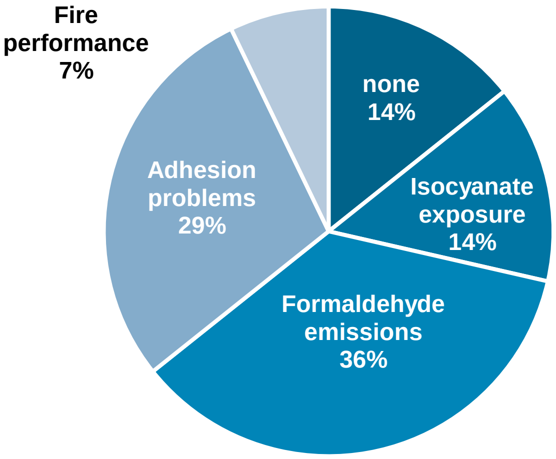


Figure 9: Australian EWP producers concerns regarding adhesives from the surveyed respondents.

6.1.1.6 Focus areas for future research

The respondents recommended 6 research areas that would benefit the wider EWP industry. Glulam producers would like to see solutions to the adhesion problems that are common with Australian high-density hardwoods along with a standard that better accommodates hardwood glulam compliance (Figure 10). One producer is seeking a release agent to assist in clean-up of equipment after adhesive application activities. With others wanting more insight and information on the fire performance of all adhesive types.

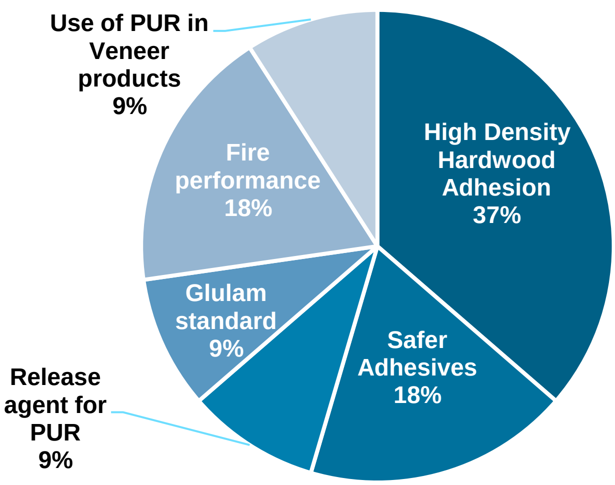


Figure 10: Australian EWP producers recommended areas for further research from the surveyed respondents.

Additionally, development of enhanced adhesion systems for native hardwoods using polyrethane type adhesives for both LVL and plywood would enable the continued shift away from formaldehyde as a reliant adhesive for these more difficult to work with species. Due to the application and minimal complexities with the current process of manufacturing particleboard, alternate adhesives systems are not of great concern. Although, advances being made from an R&D point of view are investigating means of coupling waste materials with the product to enable a more circular economic material to be greated.

6.2 Expert responses

In addition to seeking manufacturer responses as presented in the above key topics, during this review several industry experts and consultants were approached to provide their unique perspective and opinion on the aims and objectives of this study. The results of these discussions led to the following key discussion points:

- *Understanding your resource*: From responses presented in the previous charts it became apparent that industry had concerns regarding their current and future wood resource availabilities. This was further reinforced by the expert responses which detailed the importance of understanding the resource.
  This includes defining grading expectations, plantation availability, and market demand for material(s) by both industry and the intended consumer. Through defining these at an early stage it will enable the stakeholder to plan and manage the available resource effectively in the future.

- *Available training facilities*: A question the authors were interested in getting feedback from is in relation to available training for EWP producers and their staff. From consultation with industry, it became apparent that most companies rely on ‘on-the-job’ training which while this has its advantages, it was deemed an important point as part of this review to note the availability of training courses specific to EWP manufacture.
  Consulted industry experts indicated the lack of course based training available to the industry for EWP manufacture, indicating a heavy reliance on industry to train their staff on the job. It was noted by the consulted industry experts that a course on EWP manufacture, whether this be as part of a degree through a tertiary institution or a technically specific manufacturing course, would be advantageous to industry.

- *R&D capacity and activities*: During manufacturing EWPs there are a range of specifications and tolerances that must be worked within to ensure a consistent product and adequate adhesive bond. These include variables that can be controlled and ones that cannot. Variables such as environmental temperature and material variation are difficult to control whereas open times, press-pressures and spread rates can be controlled. R&D can play a crucial and important role in assisting industry to comprehend the effects these controllable and uncontrollable variables have on their products should these tolerances be exceeded.

R&D organisations can act in a supporting role where investigative studies on a laboratory and semi-industrial scale can be conducted into the effect of these manufacturing tolerances on quality impact. R&D conducted by either Universities or other research organisations should be considered more often by industry as a supporting system for manufacturers. The skills and abilities within some of these organisations provide an efficient network of experts that can assist with manufacturing issues.

- *Changes to demand and prices*: With the numerous national and international adverse events that have occurred over the past several years (COVID-19, changes to Australian log exports, conflict in Europe) the Australian timber market and supply chain (like many industries) has been impacted.
  Through increased demand and reliance for several Australian EWPs, local manufacturers have had to adapt new methods for optimising the available resource to meet these increases in market demand. This increase in demand has led to the increase in costs of products for consumers and raw materials for producers.

- *Common mistakes*: Another key point of discussion with the industry experts related to product performance testing. Ensuring there are correct manufacturing practices in place is an optimum way of maintaining consistency across products. However, having a quality assessment and assurance process in place provides manufacturers with a means of validating their production practices. This QA process allows for the detection of poor manufacturing processes or inconsistencies during production. Some commonly observed examples consist of:
  - *Dry out*: When hot veneers are processed too soon after drying (adhesive applied) the adhesive can dry out prior to pressing leading to targeted spread rates either not being met (leading to poor bonds) or to counter this issue, an increase in adhesive amount (leading to excess adhesive being used).
  - *Pre-cure jams*: In an automated feeder for pre-pressing, unevenly layered veneers or shifting panels during transfer can become stuck and require un-jamming. This can lead to the open and pre-press times being exceeded in some instances along with the pre-cure of panels loaded in the hot press awaiting the application of pressure.
  - *Wash out*: Results from veneer moisture content (MC) being too high or the spread rates used are too high. A high MC in veneers for panel products can also lead to blow out when pressed at high temperature.
  - *Thickness variation*: Variations in the thickness of veneers or boards can lead to uneven panels or beams, resulting in uneven pressure distribution across the product.

7 Challenges and future development

Australia's future for the use of EWPs is bright, prosperous, and rapidly unfolding. With the construction industries adoption of mass timber construction as a suitable and at times superior alternative to conventional materials, manufacturers will be pressured to meet this demand. An increase in their use will lead to reinforcement of the need for the knowledge capacity regarding EWP manufacture and correct adhesion practices specific to the Australian timber species.

Australia has the unique and at times difficult opportunity to be home to some of the world's most high-density hardwoods These high-density species have several complexities regarding adhesion. Furthermore, resource limitations have led to smaller log diameter sizes and lower qualities and industry's need to consider methods to optimise this new resource type; a constriction that is not forecasted to change soon.

These challenges provide key opportunities for research and development to occur in direct collaboration with industry partners. In addition to the above, industry and expert consultation outlined the need for national design and construction standards (Australian standards and building codes) to be updated to reflect the growing popularity and new applications EWPs are being classed as suitable for. Technical consultation is needed between researchers and industry to provide detailed information to standards committees to build knowledge and understanding regarding fire performance of EWPs, allow better standards covering anatomical and wood property differences between softwoods and hardwoods for jointing and face lamination quality assurance, and update design standards to reflect new adhesive types and knowledge generated from their testing.

8 Conclusions & recommendations

The aims and objectives of this review have been to report on the current understanding and knowledge capacity that exits within the Australian timber industry regarding adhesive-based EWP manufacture. Through consultation and collaboration with EWP manufacturers, industry experts and consultancy companies/ certification bodies this review provides details regarding the knowledge that exists within industry, the requirements for product design according to the relevant Australian standards, and perceived gaps in knowledge.

Furthermore, the consultation phase has presented several considerations for R&D focus in the future. The literature review section (Appendix C) of this report provides information regarding prominent Australian species being used in EWP manufacture and the corresponding adhesives. The tabulated data in Appendix E presents the species and what they are being used for in Australian EWPs, their adhesion attributes, and some further notes on their use.

For the adhesives that are listed in Section 3, information specific to the advantages and disadvantages of their use regarding several factors have been detailed. These factors include environmental impact and OH&S, differences regarding softwood or hardwood gluing attributes and their use, product performance testing differences, and visual product requirements as specified by the manufacturer.

The received responses from the industry consultation provided an insight into the EWP manufacturing market and knowledge capacity. The results discussed here are based on the responses received from the selected EWP manufacturers. Based on the engaged producers only, 1C-PUR adhesives appear to be the dominant adhesive with 33% of interviewees stating its use. This is closely followed by MUF and PF adhesive types with 22% and 17% of respondents claiming their use respectively. This could be a result of the bias in the review towards sawn board products such as glulam and finger joints which are commonly manufactured with PUR type. Products manufactured by these reviewed producers make up 7 EWP categories with the prominent EWP type being finger joints with 33% stating they are part of their range. This is followed by plywood and glulam with 22% and 17% respectively. This survey results detailed a shift away from the common resorcinol-based adhesives towards clear glue-line producing, single component and minimal environmental and health adverse adhesives such as the 1C-PURs.

Perceived areas for further development noted by the industry consisted of three main responses being the availability of wood resource with 34% reporting a change in availability due to the diminishing native forest resource supply for many hardwoods. The second being the increase in competition within the Australian industry with 25% of respondents aware of the increase in EWP production capabilities in Australia, leading to an increase in the number of manufacturers. Lastly, a number of producers noted adhesion systems as being areas for further development with 17% considering this a risk to Australian EWPs. It was also reported as a concern of 29% of the respondents that adhesive systems require further development to allow for a shift away from formaldehyde-based adhesives.

This industry growth, combined with the changing resource availability has led to established manufacturers to expand their EWP portfolio into more novel territory, as an attempt to create a marketable point of difference. It is suspected that the increase in demand (63% of respondents report increase in demand) may offset some of these competition concerns although without the available resource to process competition will continue to be a threat to companies using similar resource or manufacturing similar products. Increased research into the readiness of additional plantation resources or government support to grow the nations stock of plantation materials would be beneficial to industry growth.

The aims of R&D activities are to further advance the field of science with a specific focus towards the use and application of the research outputs. By ensuring research activities align with the aims and areas of interest of the industry, R&D activities will maintain the impact of the research being conducted. Some of the primary areas determined for further R&D include advancements in hardwood adhesion systems (noted by 37% producers as a primary area of interest), adhesives that are more environmentally friendly and sustainable (18%), further understanding of the performance of some EWPs and adhesive systems to fire performance (18%), and refinement of the current standards for glulam design and evaluation (9%).

While the aim of this review has been to develop an understanding of the knowledge and capacity of the industry regarding adhesive-based EWPs, it has also aimed at providing information on the processes involved with EWP manufacture and quality control. This document and its various appendices are hoped to be used as an informative guide and reference for new and existing groups within the industry to refer to for adhesive, species, or product specific details for the S&CQ and Australian based manufacturing for a range of EWP types.

9 Acknowledgement of contributions

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Further acknowledgement is extended to the industry partners who contributed to this study. To keeping their contribution confidential no person or company has been named, although their willingness to partake and share their insider knowledge has ensured this review reflects the opinions and knowledge of the EWP manufacturing sector.

The responses received from a series of timber experts in all fields relating to the supply chain are gratefully acknowledged. The feedback from these individuals has provided expert technical and market knowledge concerning various adhesive types, product performance specifications, product design and manufacture for EWPs developed from Australian species.

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Appendix A: Industry Questionnaire

List of questions for Industry:

Company name: ____

Location: (Town)_________________(City)_____________________(State)____________

Contact person: ____

Contact details: (Phone)_________________________(Email)___________________________

1. What are the EWPs you manufacture at present (both structural and non-structural)?

____

____

2. What timber species do you work with at present and based on what reasoning?

____

____

3. What adhesive(s) do you use and based on what reasoning (does not need to be brand specific)(adhesive cost)?

____

____

(Link adhesive with products from previous answers)

4. Have you always used this style of adhesive system, or have you changed? E.g., Formaldehyde to PUR.

____

____

5. What was the reason behind the change?

____

____

6. Are you aware of any negative attitudes towards any types of timber adhesives? (Formaldehyde emissions, fire standards)

____

____

7. Have you ever investigated the use of bio-adhesives?

____

8. How much materials (both timber and adhesive) would your company consume per annum?

____

____

9. (Link with adhesive and timber types from previous answers)

Linked to previous question, has this changed since previous years? if yes by how much?

____

____

10. What is the volume demand currently being experienced by your company across your EWP product(s) range?

____

____

11. Linked to previous question, has this changed since previous years? if yes by how much?

____

____

12. Are there market opportunities currently being missed or considered but are limited due to an adhesive based issue?

____

____

13. What are the perceived risks to your company (resourcing, material costs, market competition)?

____

____

14. What makes you stand out from the competition?

____

____

15. Are you a distributor of EWPs purchased from other suppliers and why?

____

____

16. Linked to previous question, if yes, who are these suppliers?

____

____

17. What areas would your company like to see focused for future R&D into adhesives?

____

____

____

18. Is there anything else you would like noted in this review?

____

____

Appendix B: Definition, Manufacturing and uses of EWPs

Across the Australian timber sector, the manufacturing industry currently produces a wide range of engineered wood products (EWPs). An EWP is defined as a timber composite product developed using various timber products (as well as non-timber products) in combination with adhesives [21].

These timber components within an EWP can consist of sawn boards, veneers, strands, particles, flakes and/ or fibres that are combined together with adhesives [21]. There are many types of EWPs that are commonly categorised based on the input materials used within them. The EWPs presented in this section have been detailed based on their use and/ or manufacturing capacity within the Australian EWP sector.

All EWP gluing operations use the application of pressure as part of the manufacturing process. The application of pressure brings the laminates or particles into close contact, consolidating the panel, reducing void size, and controlling glue-line thicknesses. Some pressing operations can be carried out at room temperature (single component polyurethanes and resorcinol-based adhesives) and other pressing operations are carried out using heat and pressure (phenol or urea-based formaldehyde adhesives, etc.).

As reported by GVR [22], from all the EWPs produced globally plywood dominates the market with a volume share of 29.5%. The plywood sector is predicted to see the greatest increase in production in the 2019 to 2025 period. Figure 11 illustrates the market share percentage of some EWP types as reported in 2018 [22]. Furthermore, GVR [22] predicts increases in particleboard production by 4.2% between the period of 2019 to 2025.

GVR [22] outlined the Asia Pacific region as accounting for the largest revenue share for purchasing EWPs with 46.7% in 2018. This is anticipated to continue to grow due to population growth in the regions as well as increased demand for affordable housing, structural EWPs, and low-to-medium cost furniture (flat packs) [22]. Figure 11 presents the limitation of reviewed products not including the full spectrum of EWP types and the differentiation between structural, outdoor, or furniture based.

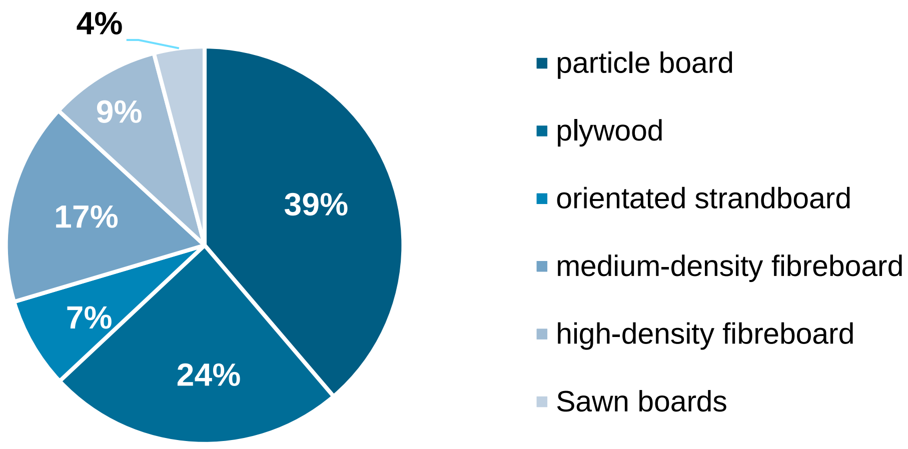

Figure 11: Market volume share of EWP types produced worldwide [22].

Sawn timber-based products

Sawn products play a large and crucial role in high strength, mass EWP types by enabling large sections and lengths from laminating or jointing material together. Some of the more common sawn EWPs are listed and detailed below.

Glued Laminated Timber (GLT or Glulam)	*<u>Definition</u>*: GLT or glulam is a type of EWP manufactured by laminating or gluing boards together through face lamination [23]. The result of this construction enables large sections of timber elements that can be used in a range of applications to replace the use of large cross-sectional dimensions of solid timber. This can include supporting columns and structural cross beams. They can also be either straight or curved in nature [23]. Large cross sectional solid sawn timber products, as is required occasionally for large spans, suffer disadvantages regarding drying. This leads to high demand and cost for these sections in a seasoned state. Face laminating smaller cross section sawn boards together using adhesives provides a cost-effective method of creating larger cross sections for large span applications.
Finger Jointed Products	*<u>Definition</u>*: Finger joints are a method of jointing used commonly on short length timber pieces to form boards of greater length. The wedges or fingers formed on end matched pieces are pressed together with adhesives to form a tight, ridged and durable bond [24]. Following on from the previous limitations of sawn boards, the presence of defects is often dealt with during the processing stages where defects (such as knots, splits, resin pockets) are removed from the board through docking. This results in shorter lengths often not acceptable for construction and therefore decreases the products value. Finger jointing provides an efficient and rapid method of longitudinally jointing lengths of timber together using adhesives. Examples of finger jointed products being currently utilised is through finger jointed framing boards, finger jointed laminates for GLT and cross laminated timber panels, as well as finger jointed decking lengths used in outdoor and exposed conditions.

Cross Laminated Timber (CLT)	*Definition*: Cross Laminated Timber (CLT) is a mass EWP similar in its construction to a very large plywood panel [25]. CLT combines the cross directional construction method of plywood with the techniques established from glulam and finger jointing where sawn boards are layered, and face bonded to create a stiff and strong mass panel product. CLT allows for large spanning applications due to the cross directional layering while enabling higher ceilings than conventional joist flooring systems. CLT also lends itself to modular construction strategies and virtually unlimited manufacturing size – due to the ability to finger joint lengths together to increase board length. A series of CLT composite structures in Qld alone include 25 King Street in Brisbane (completed in 2019), Monterey apartments in Kangaroo point (completed in 2021), and the Maryborough Fire Station (Currently under Construction).

The typical processing required for glulam manufacture is presented in Figure 12 and consists of the following. First logs are sawn into green boards which are then dried to a target moisture content. Boards are then graded which can consist of either visual or mechanical type grading. Visual grading is a concept used commonly by industry although more common for the hardwood resource. Mechanical grading is used for some softwoods depending on the application and processor; the system measures the individual stiffness values for each board using one of the various grading systems available (metroguard, calibre, etc.).

Following this jointing (if required) is conducted, this allows for defects to be removed from the materials or to create a longer laminate length [24]. From here boards are then dressed to their desired thickness and adhesive applied (as per the adhesives' technical data sheet). The beam is then pressed for a period of time as specified by the adhesive type and then dressed again post-curing.

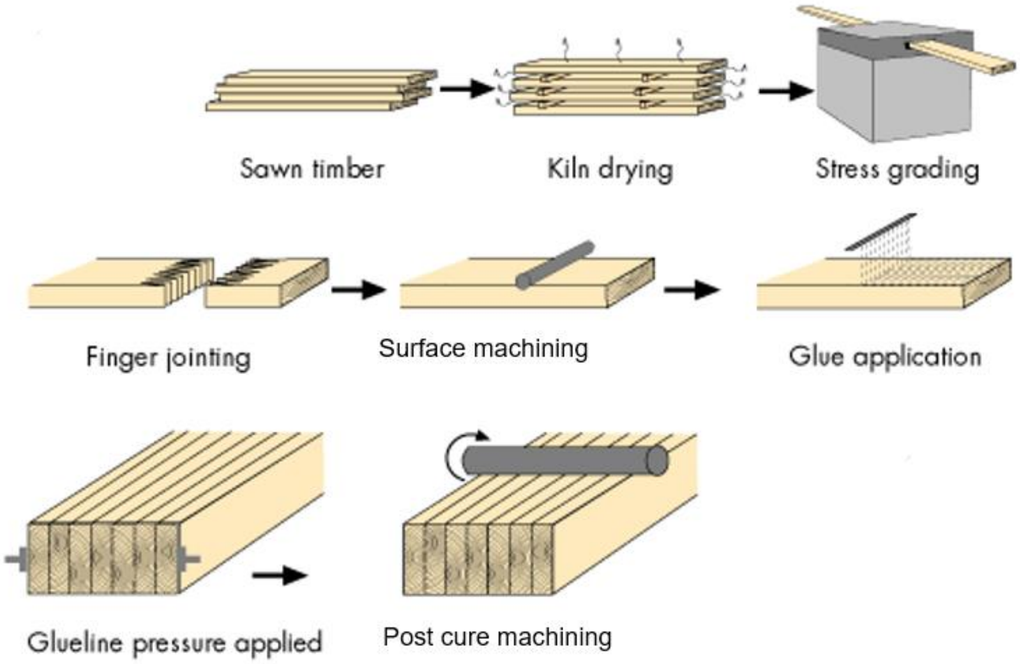

Figure 12: Glulam manufacturing process (www.plywoodinspection.com).

The stages presented in Figure 12 are in essence similar for the manufacture of edge glued panels, blockboard, glulam and CLT with variations in the material lay-up and equipment required. The pressing equipment required for glulam and CLT differ greatly as can be seen in Figure 13 (a glulam press) and Figure 14 (press for CLT production).

Figure 13: Glulam press: Rotopress by Ledinek. Glulam beam Capacities: Height 120 – 1050 mm, Width 80 – 310 mm, length 4 – 8 m (Ledinek systems).

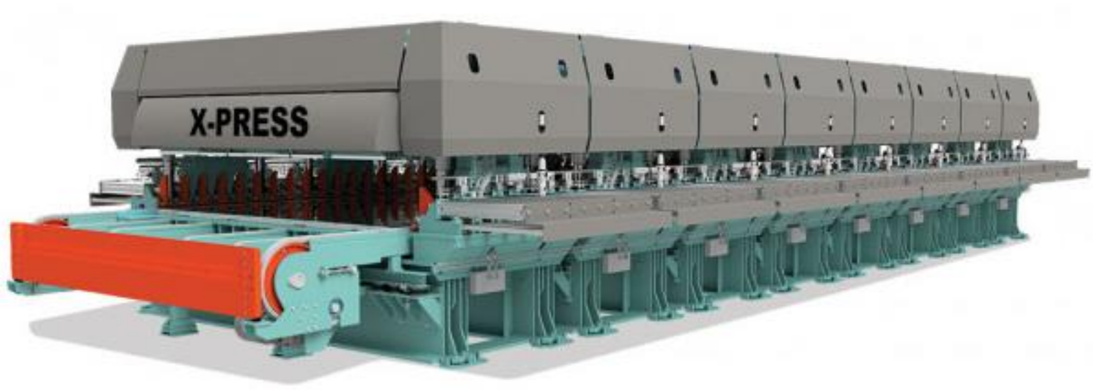

Figure 14: CLT press: X-press by Ledinek, Panel capacities: Width 2450 – 3500 mm, Thickness 60 – 360 mm Length 8 – 18 m. Press pressure 0.8 MPa (Ledinek systems).

Veneer based products

Veneer-based EWPs provide an alternative opportunity for manufacturers to increase recovery rates compared to EWPs based on sawn board feedstock. The generation of veneers used in the manufacture of laminated panels is carried out by either peeling or slicing, however most veneer-based EWPs are derived from peeling systems (rotary veneer peeler or lathe). A method by which optimal recovery can be ensured is through a spindleless lathe [26].

Plywood	*Definition*: Plywood is made up of veneers bonded together under heat and pressure to produce a panel. The lay-up of plywood consists of veneers layered on top of each other with each layer perpendicular to the proceeding veneer [1]. The cross lamination of the veneers gives the plywood sheet strength and stiffness in both axial directions along with dimensional stability from changes in moisture content.
Laminated veneer lumber (LVL)	*Definition*: LVL is also made up of wood veneers bonded together under heat and pressure to produce a panel product which is then commonly sawn into board-like products; it is commonly seen as a replacement for sawn boards [1]. However, LVL differs to plywood as the veneers are layered with the grain direction running parallel to the length axis of the panel/ board [1]. LVL can also be produced with a small number of veneers running perpendicular to the rest. These are known as cross-banded LVL.

Particle/ fibre-based products

The processing of particle and fibre-based EWPs is commonly manufactured using residual waste generated from other processing plants. The particles and fibres are then sorted, mixed with adhesive, laid out in an even thickness, and pressed to enable the adhesive to cure and the panel to form its desired shape and dimensions.

While the processes deviate slightly for the commonly used particle and/ or fibre-based products, an example of the process stages for particleboard is detailed in Figure 15.

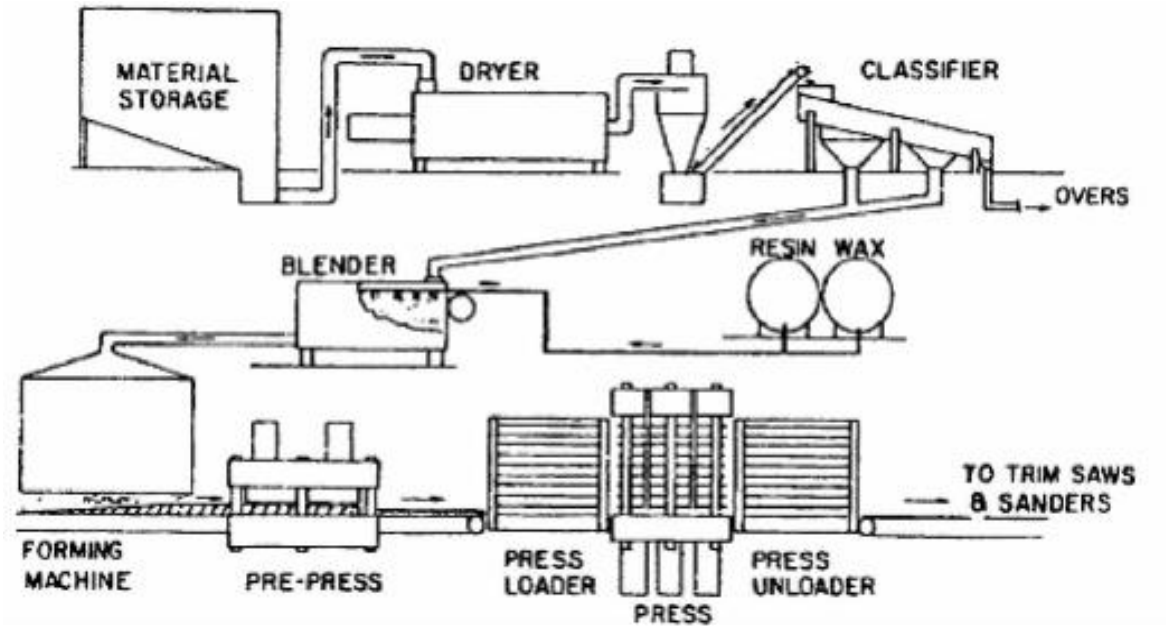

Figure 15: Particleboard manufacturing process (Invogue Building Material Solutions).

Particleboard	*<u>Definition</u>*: Particleboard is a reconstituted wood panel product manufactured from wood particles and/ or other residues (such as agricultural and non-agricultural materials); it is also commonly known as chipboard [27]. Wood particles and the adhesive are combined in a mixer and then spread out and cured using heat and pressure [27]. Particleboard is used in a range of different applications which is dependent on grade such as: • Structural or non-structural product uses, • Standard or moisture resistant panels, • Common applications consist of furniture and cabinetry with structural particle board panels being used in flooring,
Medium density fibreboard (MDF)	*<u>Definition</u>*: MDF is another reconstituted wood product made from hardwood or softwood particles bonded with adhesive [28]. The feedstock is chipped and then broken down to fibres in a defibrator. The fibres are then mixed with resin and wax and formed into panels using heat and pressure. The wax adds a level of water resistance. MDF has a higher density than that of particleboard through a finer particle size and more compact product configuration.

Orientated strand board (OSB)	*Definition*: OSB Is a structural panel made from thin wood strands bonded together with adhesive [29]. The strands on the outer layers are generally orientated with their grain in the panel's longitudinal direction. The inner core strands are orientated perpendicular to the outer strands. OSB has similar properties to plywood, is more cost effective, and stronger than particleboard. OSB is not currently produced in Australia. Applications of both OSB and MDF are similar in nature to particle board with each product having both benefits and advantages to their use.

Hybrid products

A hybrid EWP is a material that uses a combination of EWP types or combines them with sawn timber in its construction to produce a final product. Furthermore, the term hybrid for a product comes from the use of the term in a construction context [30].

Smart design involves considering the materials available and selecting the most appropriate product type for the intended application [30]. These can also include timber and non-timber materials. Figure 16 presents some examples of hybrid product types.

Blockboard	*Definition*: Blockboard is a sandwich panel that has a core made from strips of sawn timber boards that have been edge glued together and covered with an outer skin of veneers [31]. Blockboard can be produced for internal or external specifications depending on the adhesive used during manufacture. Information specific to the manufacture of blockboard can be found in the Australian standards for non-structural plywood (AS2271 [32]).
I-Joists	*Definition*: I-joists are strong and lightweight 'I' shaped EWP products [33]. I-joists are a structural beam that can be used to support flooring and roofing systems. I-joists are made up of upper and lower flanges and a connecting web. The upper and lower flanges are often made from solid timber or LVL. The web is often produced using plywood or OSB. An example of an I-joist is shown in Figure 16 (A).
CLT with plywood laminates	*Definition*: CLT can be produced using plywood laminates within the layers of the CLT. The plywood can be used as an outer

	laminate for aesthetic appeal or as an inner laminate to add support to the panel. This combination is also advantageous for fastener withdrawal capacity due to CLT's low performance when compared to veneer-based products. An example of this is shown in Figure 16 (B).
EWPs with fibre reinforced plastics	*Definition*: Research has been carried out on the use of fibre reinforced polymers in EWPs. The reinforcement can increase stiffness and potentially increase the performance of the product during fire testing. This also provides a means of incorporating low grade material in an application that requires high stiffness [34].

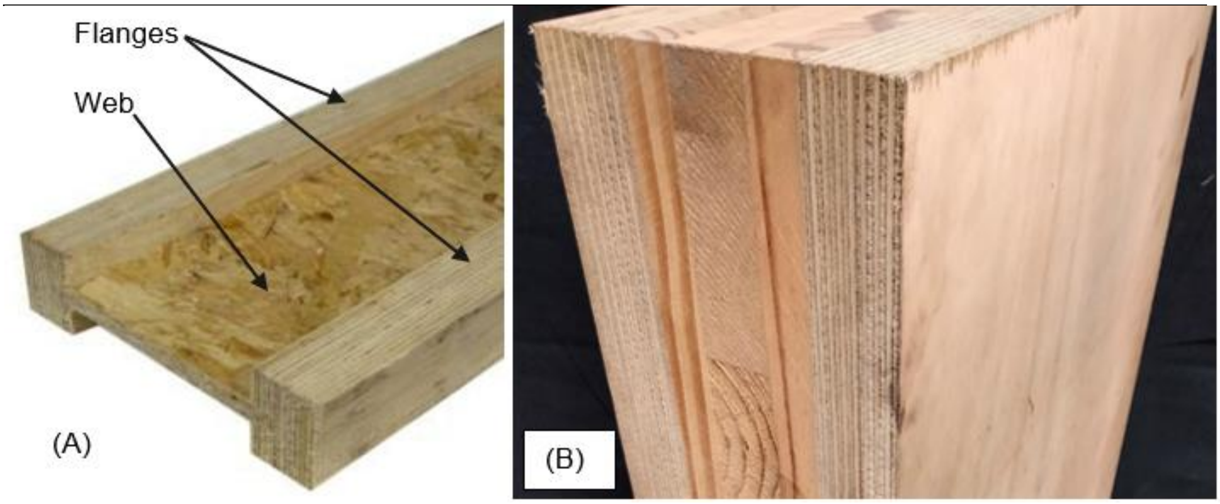

Figure 16: Images of hybrid EWPs. (A) I-Beam with LVL flanges and OSB web. (B) CLT panel with plywood outer laminates.

Appendix C: Literature Review

Background

The use of EWPs provides a means of reducing variation (such as properties and defects), something that is inherently common in sawn boards and a known limitation when working with timber. Factors such as density, board position from within the tree, percentage of latewood, moisture content, and knots all contribute to the performance variation measured from sawn boards.

Through peeling, docking, jointing, reducing board cross section, and/ or face laminating to reach required dimensions, defects can be removed, and variation reduced. This section of the report details a selection of published works on glued EWPs as well as observations made by industry experts and the research team on specific product performance. The increased use of EWPs is reported to positively affect the construction industry through the environmental benefits available with timber [35].

- Increased use of log resource through use of small dimension feedstock,
- Lower carbon emission during processing when compared to concrete and steel,
- The use of timber in buildings locks carbon away, offsetting carbon produced during EWP manufacture.

A life cycle assessment (LCA) conducted by Lu *et al.* [36] compared 5 construction materials for their potential effects towards global warming. The materials consisted of 3 variations of laminated veneer lumber (LVL_m – mid-rotation hardwood plantation resource, LVL_h – mature hardwood plantation resource, and LVL_s – mature softwood plantation resource), steel, and concrete. Lu *et al.* [36] reported all three constructions of the LVL to have considerably lower global warming potential (GWP) as well as significantly lower life cycle costs (LCC) compared to both steel and concrete.

Resource optimisation

Mcgavin *et al.* [37] with the Department of Agriculture and Fisheries (DAF), Forest Product Innovations (FPI) team carried out a project researching the feasibility of using plantation hardwood thinnings to produce laminated veneer lumber (LVL) and plywood. The project encompassed all areas of veneer product manufacture including recovery, grade, strength, and performance of glued products with species that included but was not limited to, spotted gum, Gympie messmate and Dunn's white gum.

The veneer peeling and grading of plantation thinnings was successful, showing that peeling is a viable option for this resource. Gluing trials did not immediately produce results that would allow use of the product in an external structural application. However, it was determined that the economic feasibility of the products needed to be further investigated to commercialise the investigated LVL and plywood for structural applications.

The new "mid-rise timber" construction sector provides significant market opportunities for a wide range of structural EWPs. More specifically, opportunities for higher structural performing EWPs may provide attractive opportunities for many of Australia's high-strength and high-density hardwood species to be incorporated.

DAF FPI, McGavin *et al.* [38] demonstrated that LVL produced from spotted gum (SPG - *Corymbia citriodora*) and a blend of SPG and hoop pine (HP - *Araucaria cunninghamii*) was technically feasible, producing superior structural properties, compared to many LVL products currently on the market. Another finding of this research was that LVL products comprising of either 100% cypress pine (CYP - *Callitris glaucophylla*) or 100% SPG were revealed to be resistant to subterranean termite attack.

McGavin *et al.* [38] discussed economic factors that are expected to be key drivers in the decision-making process of companies considering entering EWP manufacture. Although the report predominantly covers the manufacture of veneer-based EWPs, the economic factors can still be considered appropriate for the manufacture of other EWP varieties. The economic factors discussed consist of but are not limited to: (i) the product being manufactured, (ii) the scale of processing, (iii) log procurement strategies, and (iv) facility location and distance from the resource origin.

An EWP cannot be manufactured without adhesives or mechanical fasteners (nail laminated beams) and appropriate manufacturing processes. EWP's such as HP plywood, radiata pine (RP - *Pinus radiata*) glulam, and particleboard (commonly made from HP and RP in Qld) have adhesive systems and manufacturing processes that are well established and proven.

Whereas EWPs manufactured with native high-density hardwoods still require additional developmental research in producing appropriate adhesive and manufacturing procedures that will produce a durable end product. The manufacture of LVL using small diameter logs from Australian hardwood plantations and native forests was carried out with positive results in EWP strength and termite resistance [39].

McGavin *et al.* [39] identified that LVL manufactured from previously un-utilised resources could provide an economic and mechanically suitable product. Evaluation also identified the benefits towards blending high density species with low density and stiffness species to include the under-utilised resource and produce an economically beneficial LVL panel.

Hardwoods and softwoods

Softwood research

Collaborative research between DAF and the University of Queensland (UQ), engineering and built environment (EBE) department focused on manufacturing tolerances for press pressures, spread rates, and uneven timber surfaces in CLT manufacture with PUR adhesive [40].

Using southern pine, Davies *et al.* [40] with the DAF FPI team investigated product performance variations when coupled with these variables. The research showed that the following factors effected panel performance:

- Glue-line voids from poor machining or board alignment,
- Insufficient or excessive adhesive spread rates,
- Insufficient or excessive press pressures,

Trials need to be carried out to determine the best adhesive application and curing procedures for any producers' product type and manufacturing facilities environmental conditions.

Hardwood research

Several studies have targeted one of the densest Australian species available SPG [2, 41]. Leggate *et al.* [2] with the DAF FPI team highlighted the challenges faced when attempting to obtain a durable bond for some of these high-density Australian species in a sawn board EWP. The main challenge and recommended focus of future research is in enhancing the adhesive penetration into the material to enable a deeper interlock mechanism.

It was concluded from the study that without a cost-effective solution to increase penetration of the adhesive, other solutions to promote adhesion are unlikely to succeed [2]. Widsten *et al.* [42] investigated a series of Australian timber species, including SPG for their gluability attributes and the reasons for poor bonds to occur in sawn products. This study investigated the bonding performance of SPG and other species using a single component polyurethane (1C-PUR).

The results of the study confirmed SPG to have the highest extractives content of the 9 reviewed species as well as having one of the highest densities. Although this was inconsistent with the tensile strength of the test pieces as the SPG produced one of the lower tensile strengths perpendicular to the sample face. This is most likely a result of poor adhesive penetration. The outcomes of this study led to recommendations that work specific to the surface preparation of some of the more difficult to adhere species was continued and expanded on [42].

The work of Burch [43] investigated SPG and Gympie messmate (*Eucalyptus cloeziana*) across a range of pre-preparation techniques to increase gluability when bonding veneer obtained from the species to produce plywood. One means of correlating gluability of a materials surface is through its response to liquids that come in contact with the surface, this is referred to as wettability. Wettability refers to the ability of an adherend (such as wood) to attract a liquid (such as an adhesive).

The contact the liquid droplet makes with the specimen surface refers to the contact angle, where a smaller contact angle refers to a high surface wettability which is hypothesised to indicate good adhesion properties. Testing was conducted for a range of pre-treatment methods such as heat treatment, and heat and chemical combined treatment techniques. Adhesion testing was not conducted during this study although it provides further support that these high-density, complex species require appropriate surface or sample pre-preparation to achieve a suitable bond [43].

Adhesion based challenges and solutions have been researched across the prominent EWPs such as CLT, glulam, finger jointing, and veneer and particle-based panels. Some of the current and completed project work identified by the authors have been reported here.

Many gluing trials focusing on sawn board laminates for use in glulam products have been carried out to try and find a surface preparation/treatment process that improves the gluability of Queensland's native hardwoods [2, 44, 45]. DAF FPI and Outhwaite *et al.* [45] commenced comparing different surface machining methods, planing, planing followed by sanding and face milling. It was found that the increased surface roughness and surface area created by sanding post-planing and face milling increased adhesion with face milling producing the highest and most consistent results [45-47]. The improvements brought about by face milling were not enough for spotted gum and Darwin stringybark glulam samples to consistently pass the bond line durability test in AS/NZS1328.1 [16].

To try and further improve the gluability of these species other parameters were trialled including high and low board moisture contents, elevated temperature curing, varying press pressures and cure times, surface scrubs, primers, coupling agents, solvent surface wipes, penetration enhancers and surface washes [45]. Through this work a board preparation process that is commercially viable and that consistently results in a bond durable enough to pass AS/NZS1328.1 [16] was not found. Work is still underway at DAF to develop surface preparation and adhesive application processes that create highly durable adhesive bonds for Queensland's high density timber species, particularly spotted gum [2].

Adhesion based research has long been focused on enabling a satisfactory bond strength for Australia's more dense hardwoods in accordance with the current glulam standard [16]. As noted previously in this review and as is detailed in some of the mentioned completed and ongoing works, these investigations have provided key information as to the surface preparation techniques, adhesive performance characteristics, and change in strength values.

Although as these advancements are made, there is little understanding of the glue laminated products performance during the various stressing periods that make up the testing for AS/NZS1328.1 [16]. As such, research into the strain development within the glue-line of a glulam beam during wetting and drying cycles using a range of techniques is being conducted [48]. Preliminary results are providing detailed information as to the product distortion and small to large changes in the product from drying stresses for several species.

Blended species research

Based on the value assessment study by McGavin *et al.* [38], a further study by DAF FPI and McGavin *et al.* [39] manufactured a series of LVL panels from the surveyed and collected resources. The resource consisted of SPG, white CYP, and HP which was used in several constructions and blends to develop LVL products. Using a melamine urea formaldehyde (MUF) adhesive, the LVL panels were made, and mechanical tests were conducted to validate their quality and performance.

It was found that in all methods, the 100% SPG LVL was superior although results also indicated that comparable strength values can be obtained through blending SPG with other species of a lower stiffness (such as HP or CYP). The minimal inclusion of SPG as only face veneers with a HP core resulted in higher mechanical performance than a 100% CYP and HP LVL panel. This study indicated the benefit of EWPs in value adding to available resource enabling more opportunities for market access for under-utilised Qld hardwood resource.

During a similar body of work, Mohamad *et al.* [49] conducted a series of assessments (mechanical properties and bond quality) on 3 species types (Merpauh – *Peninsular Malaysia*, Jelutong – *Dyera Costulata*, Sesendok - *Brunei*) of glulam with 3 different configurations (using sawn boards). These species were laminated into either glulams containing either 100% of each of the species or blends of 2 species within a single beam design. Mohamad *et al.* [49] found a blended glulam of Merpauh (hardwood - HWD) and Sesendok (softwood - SWD) produces higher stiffness and strength values than the 100% Merpauh composite. Furthermore, bond quality assessments indicated low total delamination levels for the 100% SWD (Jelutong and Sesendok) and SWD/HWD (Sesendok and Merpauh) composite glulams when tested in accordance with [50]. Delamination was high for the HWD species. All beams were manufactured with a phenol resorcinol formaldehyde (PRF) adhesive type.

Manufacturing and evaluation methods

Standards review for Hardwood inclusion

Based on the referenced literature presented through [2, 45, 46] many attempts to bond high-density hardwood species for sawn EWPs results in delamination and poor bonds. It has been argued by a number of industry experts, researchers and EWP manufacturers that the requirements for bond verification outlined in the Australian/New Zealand standard for glulam products AS/NZS1328.1 [16] are not suitable for hardwood use.

Furthermore, the qualification testing specified in AS/NZS4364 [13] for new adhesive types, requires evaluation using species common to European or American regions due to the standard origins. These species are considered lesser known in Australia; hard maple (*Acer Nigrum*), lodgepole pine (*Pinus Contorta*), black spruce (*Picea Mariana*) and Douglas fir (*Pseudotsuga Menziesii*). This leads to adhesives being classified for use in Australia while not being assessed against Australian species.

In collaboration with adhesive companies and the timber industry the FPI DAF Shirmohammadi *et al.* [51] recently completed a review of AS/NZS1328.1 [16]. The review highlighted issues with the current glulam standard and provided recommendations to build a better standard with greater usability whilst validating the requirements within the standard.

It has been highlighted in Europe that the current glulam delamination test methods do not suit hardwoods. Research is underway to create a European standard that will better suit the characteristics of European hardwoods.

Effects of treatability on softwood and hardwood EWPs

Research is underway by the DAF FPI team into the use of 1C-PUR adhesives on radiata pine treated to a H5 level with copper chrome arsenic (CCA), alkaline copper quaternary (ACQ) and micronized copper azole (MCA) [52]. Initial delamination testing [16] showed that glulam can be successfully manufactured using radiata pine treated with CCA, ACQ and MCA.

Another batch of samples are undergoing six months of temperature and humidity cycling at the end of which they will be delamination tested. This will provide some indication of the effects the preservative treatment has on adhesive bonds when subjected to continuous moisture content and dimensional change. Fire performance is another key design factor for mass timber structures and therefore the materials used within them.

Robinson *et al.* [53] with the DAF FPI team has been investigating improving the durability and fire performance of sawn wood and veneer-based products for low durability Eucalyptus species. This work has involved trialling a range of commercial preservatives, preservatives and penetration enhancing agents, differing treatment schedules and pre-treatment methods to improve penetration and retention under vacuum pressure impregnation cycles. The team has identified that treatment of thinner dimension material can improve penetration and retention of some species however thinner dimensions have a narrower application in the market. In response, the treatment work has been expanded to include veneer-based products and the viability of treated veneer and veneer-based products. This work has also investigated the fire performance of veneer and veneer-based products treated with interior and exterior fire retardants.

Fire performance

During the industry interviews, several participants noted fire performance being an issue for the future regarding standard requirements. The UQ Fire Safety Engineering Research group has a large capacity for fire performance testing of timber and timber composite products and has conducted an R&D project on investigating the fire performance of several prominent EWP types. They are also researching the self-extinguishing mechanisms of timber EWPs. Research growth in this space will ensure future policy and governance is appropriately informed of the materials performance.

Novel advancements

Finger jointed hardwoods for decking

Finger jointing has long been a method of extending the longitudinal span of short length timber pieces through a tooth-like profile of a nominated length, bonded with adhesive. With the high-density hardwood resource in Queensland and Northern NSW, it has proven difficult to obtain an adequate bond integrity for high moisture areas and outdoor applications such as outdoor decking, in accordance with the relevant testing standards [54].

The manufacture of finger joints using spotted gum and Darwin stringybark was investigated for a series of joint geometries and adhesive types by the DAF FPI team. While results presented good indicators of the species to be used for jointing, the testing highlighted the inadequacies of the current standard at the time of writing (AS 5068) in relation to fibre failure measurements for hardwoods.

Rubber waste panel production

Kumar *et al.* [55] and the DAF FPI team are investigating the potential for rubber crumb sourced from end-of-life tyres (EOLT) to be incorporated in the manufacture of wood-based composite panels. In Australia, 56 million EOLT, equating to 450,000 tonnes, are generated each year.

The project could potentially create positive economic, social, and environmental outcomes such as a recycling opportunity for a large volume of EOLT, additional feedstock to enable particleboard manufacturers to meet growing market demand and potentially enabling new substitutive and sustainable materials. Adding rubber crumb to particleboard could offer several product advantages including increased noise dampening, shock resistance, surface grip, swelling resistance, and durability.

Bio-based adhesives

From the advancements in EWP manufacture referenced through this review and growing applications noted across the timber sector in Australia, more attention has been drawn to the environmental impacts of some adhesives. Kumar *et al.* [5] with the DAF FPI team conducted a review into available bio-based adhesives available for use in either structural or non-structural EWP applications.

Bio-based adhesives have been used for hundreds of years, however their low strength and durability limited their use to internal applications only [5]. Although research into their use and application is developing, there are still several limitations that need to be addressed prior to the adhesives' adoption by the industry sector.

Kobeticova *et al.* [56] investigated the biodegradation of a bio-adhesive 'bone glue' for its potential as a bonding agent when used with straw. Kobeticova *et al.* [56] identified the combination of bone glue and sodium lignosulphonate produced a stable, natural, bio-based adhesive using the straw. The Wood Biology and Wood products group at the University of Göttingen [57], Germany are researching bio-based polyurethane adhesives using technical kraft lignin and liquefied bark as natural renewable polyols instead of synthetic ones, thus allowing the reuse of these industrial by-products and wastes that are available in large quantities.

Appendix D: Product Performance Evaluation

The developmental stages of structure design are crucial for material selection, cost analysis, and trade selection. Through this process there is a wide scope of stakeholders (engineers, architects, trades) who all have an influence on the material types used in the structure; their perception of some materials can influence the materials' inclusion in designs [58].

Several studies have evaluated the perception of trades and engineers regarding EWPs with results indicating an understanding of the benefits of EWPs with a need for robust design in the early stages of development. A surveying study was conducted to investigate the perception of EWPs as a material by architects for both structural and non-structural purposes. Igin *et al.* [58] found that while 90% of the respondents reported using structural timber where possible for residential purposes, only 20% used structural timber for non-residential applications.

This appeared to be linked with perceived challenges regarding maintenance of exposed timber products in office, industrial, or public scenarios and a lack of knowledge for durability performance. The referenced review by Igin *et al.* [58] identifies a clear and consistent gap across many continents that there exists a lack of knowledge and understanding regarding product performance characteristics, criteria and evaluation methods.

This section of the report details the general product performance criteria for EWPs. As presented in Figure 17, the generalised product performance criteria have been summarised into 5 main categories of mechanical performance, bond integrity, formaldehyde emissions (if applicable), durability and surface finish and visual grade.

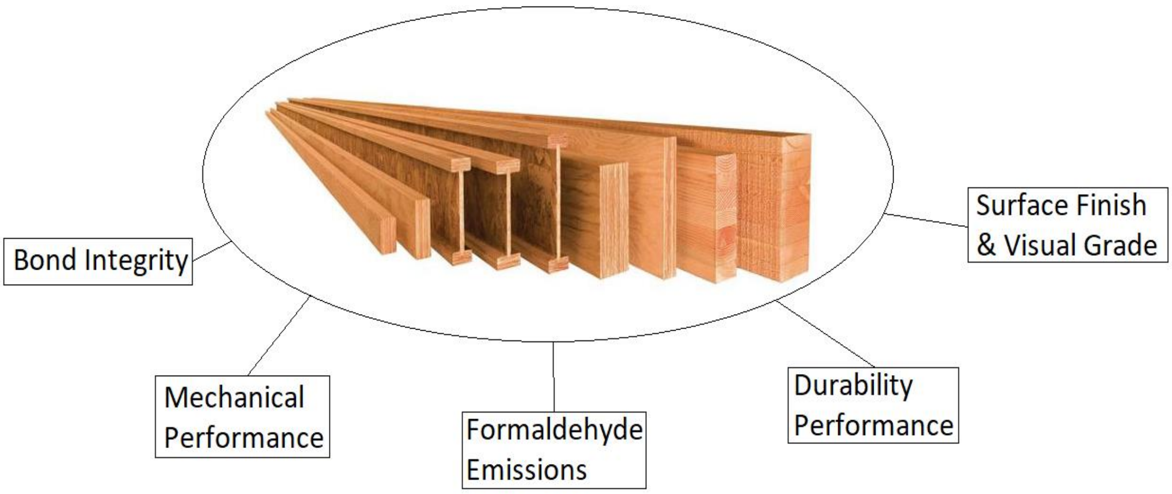

Figure 17: EWP performance criteria and evaluation methods.

Mechanical properties	Across all structural EWPs, the performance regarding the characteristic properties is a key design criterion. Based on the standardised testing method and design standards for the material type in question, the characteristic value is obtained through experimental static testing for several specimens (as detailed by the standard). The testing is commonly governed by either the products intended application or the design standard although some general properties include: • Bending stiffness (MOE) and strength (MOR), • Shear strength (including beam shear, block shear, panel shear and planar shear), • Tensile strength, • Compression strength (including bearing strength, and compression strength parallel and perpendicular to the grain direction),
Bond integrity	The approach used to determine the bond integrity of the glueline between bonded wooden materials varies between veneer-based, board-based, or particle-based products. While this variation results in different testing methods, the aim remains the same which is to provide an appropriate representation of the performance for a glued interface under some form of stress. AS/NZS1328.1 [16] states "*the adhesive shall be capable of producing strong and durable joints which maintains the bond integrity through the intended lifetime of the structure*", where this statement provides an accurate generalisation of the purpose of all EWPs.
Formaldehyde emissions	Formaldehyde has been classified as a known carcinogen by both the National Pollutant Inventory (NPI - [59]) and the International Agency for Research on Cancer (IARC - [60]). While the cancer-causing properties of formaldehyde are only evident in very high concentrations it is still important to measure emissions from some building products. Formaldehyde emission testing is required across several countries using a variety of methods. Formaldehyde emissions are more commonly measured from veneer-based or particle-based products due to the number of glue-lines compared to a sawn board product such as glulam or CLT. The levels commonly found within plywood/ LVL is often hundreds of times lower than a dangerous amount [61].

Durability performance	As timber is a natural material, it is susceptible to fungal decay and degradation by pests. As moisture is still present within the timber product(s) after processing, this can provide a means for decay to begin, furthermore the moisture content of the timber products will vary with the environmental conditions (seasons and weathering). To increase timbers decay and pest resistance, preservative treatment is suggested although as is the case with formaldehyde, some treatment chemicals are not suitable for certain products and product applications.
Surface finish & visual grade	An important attribute of timber is its visual appeal and ability to produce pleasant architectural features that bring natural warmth and comfort to a structure. The quality of surface veneers and boards used in timber elements where appearance matters highlight that quality must meet the market expectations. The appearance quality has been documented within Australian standards for plywood and glulam including appearance grades and requirements for glulam and plywood in situations where aesthetic appearance is an important factor.
Fire Performance	While timber is a combustible material, its inherent insulating properties, known burn rates and burn predictability can be used during structure design phases to allow for increases in fire safety. When exposed to fire, the timbers surface goes through thermal breakdown converting its surface to charcoal. The charcoal acts as a sacrificial part of the timber as it protects the inner material and slows the fire as time continues [62].

Table 3: Sources of structural design properties and criteria for EWPs [63].

EWP Type	Manufacturing Standard	Design Properties	Design Factors/ Criteria
GLT	AS/NZS1328.1 [16]	AS1720.1 [11] or proprietary (limited)	AS1720.1 [11] and GLTAA
LVL	AS/NZS4357.0 [64]	Proprietary	AS1720.1 [11]
Plywood	AS/NZS2269.0 [65]	AS1720.1 [11]	AS1720.1 [11]
OSB	EN300 [66]*	Proprietary	Proprietary
Particleboard	AS/NZS1860.1 [67]	Proprietary	Proprietary
I-Beams	Proprietary	Proprietary	Proprietary

* Where an Australian standard is not available, the international equivalent has been referenced.

Bond evaluation methods

While it is important to ensure manufacturing processes and procedures are followed correctly, quality assurance and verification that these processes are being followed is equally important.

This section briefly expands on the test requirements as introduced for the bond integrity of EWPs in accordance with the relevant Australian or international standards. Table 4 presents this information.

Table 4: Bond quality evaluation standards and their definitions.

EWP Type	Assessment Method	Description of method
GLT	AS/NZS 1328.1 (1998), Appendix C	One of the required tests for glulam bond integrity assessment consists of water impregnation and low humidity drying cycles being conducted on a section of glulam. The testing is followed by measured changes or delamination in the bonded interface or glue-line between laminates in the glulam block. The method specifies the acceptable tolerance for delamination that occurs.
LVL	AS/NZS 2098.2 (2012), AS/NZS 4357.0, AS/NZS 2269.0 (2012)	The process of evaluating the bond quality for LVL and plywood is identical which is through forcibly separating the veneers to expose the glued interface or glue-line. The amount of wood fibre left behind during this process is visually assessed and a percentage assigned. This percentage value is what determines the quality of the bond and whether the sample will pass the specifications of the standard.
Plywood	AS/NZS 2098.2 (2012) and AS/NZS 2269.0 (2012)	
OSB	EN300 (2006) [66]	The process for evaluating the performance of Particleboard and OSB uses the same testing methods with differing performance criteria. Performance is assessed through one of two ways; using either the internal bond test or a swelling thickness assessment. Internal bond testing consists of a tensile load being
Particleboard	AS/NZS 4266.1 (2017) [68]	

		applied perpendicular to the face to a section of the manufactured particleboard. The load reached at the time of failure is used to determine the tensile force required to obtain failure in the sample and thus determine the quality of the bond between particles. The second test consists of submitting the samples to a water bath or boil process for a period of time and measuring dimensional change (specifically thickness changes). The samples' ability to resist moisture uptake will be a result of the adhesive used and thus thickness swelling will indicate the performance of the bond.

EWP product development

Solid wood & sawn timber-based EWPs

Queensland is home to some of the most high-density, high strength and highly durable hardwood timber species on the planet. These are commonly used as either sawn or veneer-based products for both structural and non-structural applications [2]. Unfortunately, with the high density and high durability comes a high degree of gluing difficulty. Hardwood sawmills are challenged with overcoming this adhesion difficulty to allow for the manufacture of a marketable EWP made from sawn feedstock [2].

As specified by AS/NZS1328.1 [16] Appendix C, sample sections of structural glulam products are tested using evaluation Method A which allows for qualification of the product against a service class 3 exposure rating. Glulam samples that undergoing the Method A procedure are subjected to water impregnation and dry cycling. At the conclusion of these cycles, the glulam specimen is then assessed at the glue-line for areas experiencing delamination or separation specific to the bonded interface.

According to AS/NZS1328.1 [16] the samples are given a pass or fail result based on the amount of delamination recorded from the tested specimen. Leggate *et al.* [2] showed that high-density hardwood timbers such as spotted gum and Darwin stringybark frequently produce high percentages of delamination, with glue-line delamination exceeding the requirements of the standard. The key reasons Leggate *et al.* [2] identified the frequent glue-line failures are summarised as:

- <u>*Mechanical properties*</u>: Through conducting block shear tests of sections of the glulam specimen before and after cycling there appeared to be a greater proportion of the samples failing with low wood fibre percentages versus visible glueline percentage, indicating a lack of bonding and penetration.

- *Assembly complexities*: Difficulty was had in bringing the species into close contact during product assembly and pressing. It was also found difficult keeping the boards in correct alignment during this process.

- *Extractives*: As noted during assembly difficulty, surface penetration of the tested species was difficult to obtain (as also noted from the mechanical testing). This was found to be a result of a high content of extractives that can interfere with the gluing process.

- *Wettability*: Through conducting surface water droplet experiments, a low wettability was reported for both species evaluated, as indicated from previously referenced research this is most likely a result of extractive content.

- *Dimensional change*: During the cycling process and as has been reported through other sources [41], both species have an inherently high dimensional movement with changing moisture content. This can cause added stress to the glue-line during cycling.

- *Porosity and permeability*: Low porosity and permeability was measured for both species resulting in minimal adhesive penetration. This is likely to be due to an accumulation of factors as reported above.

All of these factors can contribute to what is seen to be poor adhesion or bond performance, especially when glulam is subjected to the severe stressing imposed by the water impregnation and dry cyclic conditions of the test method [16]. Many of these issues are not just confined to high-density hardwood timbers, for example, the latewood content in southern pine can exceed densities of 900 kg/m^3. Furthermore, the species high resin content introduces adhesive challenges compared to other common softwood timbers [2, 44, 46, 69]. The problems encountered with gluing higher density softwoods becomes particularly pertinent when it is the high-density material that is preferred for structural glulam applications due to increased stiffness [2, 44, 46, 69].

To work through the adhesion problems with high density species, the DAF Forest Product Innovation (FPI) team completed fundamental research in the benefits of different pre-gluing surface machining methods. The surface machining methods investigated were planing, planing and sanding, and face milling. Planing is currently the industry standard in pre-gluing surface machining and usually produces acceptable results on low density softwood and hardwood species like radiata pine and shinning gum (*Eucalyptus nitens*).

It was found by FPI that surface machining methods that increase surface roughness and open the cellular structure on the timbers surface result in increased bond line durability. Figure 18 shows images of a face milled (A), planed and sanded (B), and planed only (C) samples after delamination testing with a 1C-PUR adhesive. From the images presented, face milling produces the best performing result and passes the standard, planing alone results in the poorest performance of the three.

Planing followed by sanding gave a vast improvement over planing, however, did not perform as well as face milling, marginally failing the delamination test.

Figure 18: Samples of machining methods tested by Forest Product Innovation: (A) face milled (B) planed and sanded (C) planed

To gauge the extent of the increase in timber/ adhesive interaction, microscopic investigation was carried out by DAF-FPI on cured glue-lines. It was found that on shining gum the use of face milling resulted in deeper and more uniform penetration of the 1C-PUR used in the research.

Figure 19 shows two microscope images where the difference in adhesive penetration can be seen between a face milled (A) and planed surface (B).

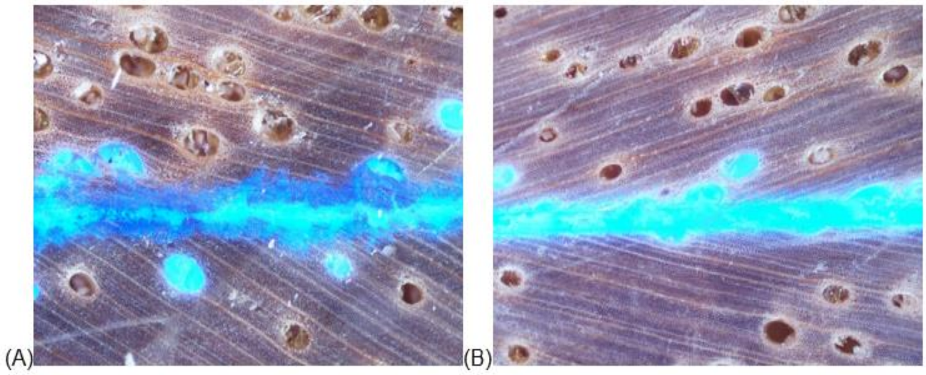

Figure 19: Microscope images showing adhesive penetration in samples prepared with 2 surface machining methods: (A) face milled (B) planed.

The use of face milling as a pre-gluing, surface machining approach, gave improvements on lower density Australian hardwoods that enabled them to qualify for use as structural glulam.

Unfortunately for the higher density species such as spotted gum the benefits of face milling were not great enough to consistently qualify them for glulam use, although it did improve results.

The qualification of high-density Australian hardwoods for use as structural glulam products will not come from advances in surface machining processes alone. For these, extra research work will need to be carried out to evaluate:

- Means of improving adhesive penetration,
- Methods to increase board dimensional stability,
- Systems to reduce or overcome the effects of the extractive content of the timber,

Veneer-based products

With a shortening in supply of native forest log resources and a need to find an alternative it is likely that the development of improved adhesive systems and application processes for veneer-based EWPs from high-density Australian hardwoods will receive increased attention. A driver for this activity is privately owned hardwood plantations that produce low-grade small diameter logs. Due to their size and a high percentage of unpredictable juvenile wood, these logs are often not suitable for traditional sawmilling. However, they can potentially provide plantation owners a return on investment by being peeled into veneers and turned into a high-grade product.

One way to combat the increase in demand for timber products and a decrease in supply and size of the log resource is through the use of veneer-based products due to their key advantage over sawn timber-based EWPs in maximising the yield of material from the log.

For the product to function as structural, the veneers produced will need to be consolidated into a panel (plywood or LVL) or beam (LVL) using the adhesives currently referred to in Table 1 while conforming to the Australian standards. The adhesion challenges for veneer-based products are not as great as those for sawn-board products such as CLT and glulam. This is due to veneers having the benefits of:

- Greatly decreased dimensional movement,
- Veneer checking created during peeling providing increased surface area for adhesive interaction, penetration, and keying in,
- Veneer malleability allows intimate contact of veneers during pressing,

Key evaluation factors for veneer-based products include bond quality and formaldehyde emissions testing (if applicable). Similar to the process explained for sawn products such as glulam and CLT, bond integrity is assessed dependent on the expected application of the product according to AS/NZS2098.2 [70].

Sections of the veneer-based panel are exposed to a weathering process, after which the topmost veneer is forcibly removed to expose each of the proceeding glue-lines. Visual assessment is used to quantify the amount for wood fibre left behind after removal of the veneer. A score based on the total percentage of wood fibre is made for each veneer and for the product on average and is given a pass or fail based on the criteria in AS/NZS2269.0 [65].

Similarly, formaldehyde emission testing is conducted using a section of the finished panel by conditioning the material in a sealed chamber for a period of time alongside a dish of water. At the conclusion of the conditioning period the dish is removed, and a portion of the solution evaluated for the formaldehyde content in the water. This recorded formaldehyde content is considered the emission amount as absorbed from the veneer-based panel. The results are also given a pass or fail based on the specifications of AS/NZS2269.0 [65] and AS/NZS4357.0 [64].

Wood particle-based products

The production of particleboard is well established with adhesive use and pressing processes being proprietary information. However, there is the potential for a change in the manufacture of particleboard to a non-synthetic adhesive bonding process that uses heat, pressure and sugar containing lignocellulosic materials, such as sugar-cane bagasse, as the bonding agent [71].

Furthermore, particleboard provides a means of recycling and reusing timber materials once processed. Particle-based composite panels could provide a means of reducing waste and land fill content of timber products such as treated products, hardwoods, and even non-timber materials such as rubber or plastics.

Wood welding

Wood welding is a novel process of joining two pieces of timber together using pressure and vibration. The combination of the two forces creates friction between the pieces, heating the surfaces up. When the surfaces reach 170°C to 280°C the lignin in the timber melts [71]. Upon cooling the lignin will harden again resulting in the pieces being joined together.

The joint is said to be as strong as an adhesive bonded joint. The application of wood welding was validated for a laboratory scale under controlled conditions. Further research is needed to investigate the methods ability to be upscaled to an industry level adoption [71]. It should also be noted that to the best of the authors' knowledge, there are no commercial operations based on wood welding in Australia.

Surface finish and sealing of timber and EWPs

One drawback to EWPs is the comparison of their durability when compared to low maintenance structures made of steel and concrete which offer up to 20+ years of maintenance-free performance. Although, various wood preservation practices can provide similar or longer time frames for structural durability performance the long-term aesthetic performance (appearance) of timber products particularly in outdoor exposure and weathering situations is a major challenge.

The development of timber surface finishes that will provide EWPs with maintenance free periods similar to steel and concrete will help to limit this negative factor in the use of EWPs. Currently clear coating type finishes are available to protect EWPs against environmental damage in exterior applications. They are commonly solvent, or water based acrylic and polyurethane coatings with added UV absorbers [17].

Over time these coatings lose their flexibility and begin to crack from the stresses of the continuous shrinking and swelling of timber surfaces, allowing moisture and environmental contaminants to penetrate the coating through to the timber interphase region and begin to break down the bond between the coating and the timber.

A collaboration between CSIRO, Melbourne University and Swinburne University realised the issues with timber surface coatings and ran trials using automotive and aerospace polyurethane coatings that have a warranted life of in automotive applications of 15 – 20 years [17]. The polyurethane coatings were used in conjunction with a range of surface preparations on Victorian ash (*Eucalyptus Regnans* and *Eucalyptus Delegatensis*), blue gum (*Eucalyptus Globulus*), tallow wood, and blackbutt that resulted in estimations of clear coatings on external timber elements lasting up to 15 years [17].

Wood modification

Thermal modification

Wood modification techniques are processes in which low-value wood species can be tuned into high-value resource. These techniques are known to greatly improve the durability and dimensional stability of softwoods. These techniques include processes to gain property improvements, increase gluability, are non-toxic, and non-biocidal [72].

Examples of this process being currently used and successfully by the EWP sector is thermally modified wood (ThermoWood®) which uses Australian grown plantation Radiata Pine. Due to its success in New Zealand, its approach has been adopted and established in Australia. The product needs to consider the changing resource available, material costs against similar market ready products, and compliance with Australian building codes and regulations to become a marketable option [72].

Chemical modification

Through a combined review of the timber market and literature several commercially available chemically modified timber products were found. All chemical modifications found were initially directed to enhance the durability and dimensional stability of softwood species.

The low permeability of hardwoods may reduce the effectiveness of these treatments in stabilising the entire cross-section but perhaps stabilisation of the surface a few cells deep will help increase the durability of adhesive bond lines and surface finishes.

- *Acetylation:* A process that modifies wood using acetic anhydride, making it resistant to degradation by water and fungal attack, therefore, improving the timbers durability and dimensional stability. Acetylation has been carried out on a commercial basis since 2007. The resulting product is acetylated radiata pine and alder (*Alnus spp,*) marketed as Accoya® [73].
- *Furfurylation*: A process that modifies wood using furfuryl alcohol (derived from sugar cane and corn cobs) originally discovered in 1959. The furfurylation process improves timbers resistance to biological degradation showing comparable durability to CCA treated softwoods along with improved dimensional stability and enhanced mechanical properties. Furfurylated wood is distributed in Australia under the Kebony® brand [73].
- *1,3-dimethylol-4,5-dihydroxyethyleneurea* (DMDHEU): A process used on highly porous pine species involving the injection of the reagent DMDHEU. A well utilised chemical in the textiles industry. Timber modification with DMDHEU has been shown to improve dimensional stability, durability and slightly improve water resistance. The impregnation modification process is presently marketed by BASF under the commercial name Belmadur® [73].

Densification

Surface densification is the transverse compression of the wood cells on the surface of the timber, thereby, increasing the density of low-density species. The densification action increases the timbers hardness and resistance to surface abrasion.

Further treatments are required after the densification activity is completed to prevent the timber returning to its original form [73].

Appendix E: Australian Species, EWP uses and gluing attributes

The following section presents a series of tables detailing a selection of commonly used timber species in the Australian EWP marketplace. The data presented details their current usages (applications) and notable gluing attributes. It should be outlined that while these species are not limited to the EWP applications listed, these are their current product uses based on the company questionnaire responses received and the authors' knowledge of the EWP sector in Australia.

The information specific to the gluing attributes has been generated based on expert knowledge, and hands on experience as well as collected information from industry. Table 5 presents the commonly used softwoods in the EWP sector whereas Table 6 presents the commonly used hardwoods.

Table 5: Prominent softwood species used and their common applications and attributes.

Softwood			
Timber	**Scientific Name**	**EWP Application**	**Gluing Attributes**
Hoop Pine	*Araucaria cunninghamii*	plywood	Minimal difficulty, relatively clear species (low number of defects) leading to minimal variation in boards.
Cypress Pine	*Callitris glaucophylla*	Glulam, CLT	Minimal difficulty, low density and unique cellular structure makes for suitable material for most EWP applications. Large number of features (defects and colour streaks) can lead to gluing difficulties.
Radiata Pine	*Pinus radiata*	Plywood, glulam, CLT, particleboard, MDF	Minimal difficulty, low-to-moderate density enabling its use in most EWP applications with most adhesive types.
Southern/Slash pine	*Pinus elliottii,* *Pinus Caribaea and hybrid of the two*	Glulam, CLT, veneer-based products, particleboard, MDF	Higher stiffness grades suffer from delamination in high density latewood bands. Appropriate surface preparation of the material prior to bonding has proven to alleviate this issue.

Table 6: Prominent hardwood species used and their common applications and attributes.

Hardwood			
Timber	**Scientific Name**	**EWP Application**	**Gluing Attributes**
Blackbutt New England Blackbutt	*Eucalyptus pilularis* *Eucalyptus andrewsii*	Finger jointing, glulam	Research is currently ongoing. Glue bonds that can pass AS/NZS1328.1 [16] may be able to be achieved using 1C-PUR with appropriate surface preparation methods.
Darwin stringybark	*Eucalyptus tetradonta*	Finger jointing, glulam, plywood, LVL	Research is currently ongoing. Glue bonds that can pass AS/NZS1328.1 [16] may be able to be achieved using 1C-PUR with appropriate surface preparation, pressing and adhesive curing methods.
Gympie messmate	*Eucalyptus cloeziana*	Finger jointing, glulam, plywood, LVL	Research has shown Gympie messmate to have similar adhesion qualities to spotted gum. Trials would need to be carried out to determine gluability of Gympie messmate sawn products. Manufacturing EWPs from veneers is possible with some work to establish gluing processes.
Ironbark (Red and Grey)	*Eucalyptus paniculata (grey)* *Eucalyptus sideroxylon (red)*	Finger jointing, glulam, plywood, LVL	It is noted to have a high density and a high dimensional change during moisture cycling. This can lead to difficulty in achieving suitable bonds with Ironbark species. Surface preparation research and quantifying the dimensional movement would be crucial to successful product development.
Rose/Flooded Gum	*Eucalyptus grandis*	Finger jointing, glulam, plywood, LVL	Density and shrinkage are similar to *Eucalyptus Nitens*. Has been reported to provide suitable bonds when used with a 1C-PUR and phenol adhesives.

Spotted gum	*Corymbia citriodora,* *Corymbia maculata,* *Corymbia henryi*	Finger jointing, glulam, plywood, LVL	High extractives content, high density, and high dimensional movement material. Both phenolic adhesives and 1C-PURs struggle to achieve suitable bond types when tested according to 1328.1 (1998). Companies producing EWPs from sawn products have carried out extensive R&D to determine suitable manufacturing protocols.
Tallowwood	*Eucalyptus microcorys*	Finger jointing, glulam, plywood, LVL	Has reported similar adhesion properties and dimensional change characteristics to SPG.

There are gaps in knowledge about the performance of adhesives when used on the high-density Queensland hardwoods. Further investigation is required to fill these gaps. Two of the known gaps include:

- Unknown level of stress applied to adhesive and adhesive bond during dimensional change driven by changes in moisture content,
- Effect of extractives found in native species on adhesive and adhesive bond during cure phase and service life.

The small amount of work carried out on the gluability of Queensland species so far has shown that each species glues differently and gluing trials will need to be carried out on a species basis to determine its adhesion characteristics.