# An inter-disciplinary approach to design

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**Abstract**: The doctoral research study referred to in this paper is the fusion of two disciplines that have both been instrumental in creating an environmentally conscious product. Inter-disciplinary studies in the field of materials science and industrial design converge with the aim to help push each discipline further in the pursuit for advanced knowledge in materials development and designed outcomes.

The above approach facilitated significant breakthroughs in both disciplines: in materials science through drastic improvement of adhesion properties of timber through rigorous scientific research and in product design through utilising product performance requirements for advanced industrial design as a means for innovation. An environmentally friendly water-based process for surface modification of timber, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was tested for its potential ability to enhance adhesion of timber products and then implemented into the product design process. The surface modification process applied to the outermost surface of timber neutralises natural extractives and chemically bonds adhesive promoting molecular chains to the timber's surface. The process is carried out to significantly increase the quality of adhesion of an applied decorative or protective coating. The ensuing testing confirmed a drastic increase in the bond strength for all timber species investigated in this project by an average factor of four-fold, with some species achieving a 10-fold strength increase.

The successful outcome of this scientific research is subsequently applied in the development of a timber window frame that utilises this new surface modification technology to create an environmentally friendly product outcome. Surface-engineered, sustainably produced regrowth timber used in this work provides the performance comparable, and in some cases better, than unsustainable hardwoods which currently dominate the timber window frame market.

The design segment of this research utilises a design process based on technology-led design strategies. Technology-led design requires that the existing and accepted design methodologies, based on user and producer design parameter paradigms, are reconfigured. While the needs of potential users for any new product have to be met, the design strategies are typically directed and restrained by the material's design limits and current manufacturing practices and considerations.

In this paper we discuss an innovative approach to the product design that removes or pushes the boundaries of materials properties limitations; the process which is led by design desires targeting enhanced materials with specific properties superior to those currently available.

***Key words: Timber, Design, Surface Modification.***

## Introduction

Over the last several years successful research on surface engineering of a variety of materials has been conducted at the CSIRO, Australia's premier research organisation. This research, funded by the Australian Government, has resulted in successful outcome in solving problems with sub-standard adhesion of glues and paints to many advanced and commodity materials including synthetic polymers and different timber species. This research has also been supported by the Cooperative Research Centre (CRC) Wood Innovations and Swinburne University of Technology (SUT) who provided funding and other assistance for this work.

The principal mission of the CRC was to develop and commercialise new wood-based materials and technologies as well as to extend relevant research that establishes wood as the sustainable material of choice. The CRC has been funded by the Australian Government, and involved leading timber and wood products companies and Australia's leading forest and wood researchers.

SUT has supported all design and development for this research. SUT has a strong reputation in Australia and overseas as a provider of career orientated education and as a university with a commitment to research. The University maintains a strong technology base and important links with industry, complemented by a number of innovative specialist research centres which attract a great deal of international interest.

The CSIRO is Australia's national science agency and one of the largest and most diverse research agencies in the world whose aim is to deliver breakthrough science and innovative solutions for industry, society and the environment. The CSIRO team led by a co-author of this paper has earlier developed successful technologies for surface engineering of synthetic polymers used by the automotive and aerospace industries, and subsequently investigated the applicability of similar approaches to enhancing the adhesion of surface coatings and adhesive resins to machined and sanded timbers. All development and investigation of our new concepts to enhancing adhesion to wood surface has been carried out using laboratory and industrial scale equipment and testing facilities of CSIRO who also provided financial support for this work.

Within the framework of the CRC Wood Innovations, the initial stage of this research provided a broad overview of the potential for new product developments within the timber construction industry. From this research, the project identified a need for innovative and more effective solutions that focused our research on the investigation of surface modified timber with the aim of improving its inferior weathering properties, its potential for outdoor use, and its use in new product development. The current research concentrates on new wood materials/processes, and their application in designed objects – all made possible through scientific advances made in CSIRO in the field of surface engineering of synthetic and natural polymers such as wood.

The design process was initially driven by parameters that were not yet fully identified or quantified. Due to the fact that one of the basic parameters in this project was to consider the performance characteristics of surface modified timber, the research focused on a new technology development which in turn, has led to a design process that centered on innovation within the window frame industry.

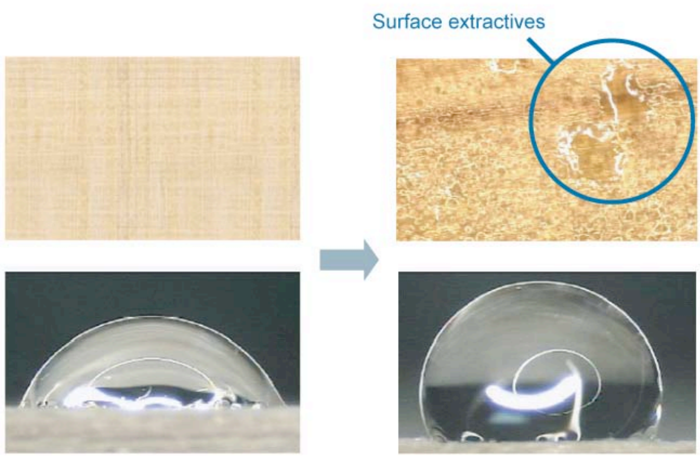
Fig 1. One of the major problems associated with timber use in outdoor applications – delamination of paint from the timber surface.

### Key problems with timber adhesion

The most significant issue regarding timber use for outdoor products is the poor characteristics this material has with regard to weathering over a prolonged period of time. Ongoing product maintenance is something the majority of consumers want to avoid, hence the domination of aluminium and Polyvinyl Chloride (PVC) in the window frame industry. Timber has numerous benefits over its competition such as sustainability, aesthetics, low thermal conductivity and ease of manufacture, but unfortunately its major weakness, a poor outdoor performance, is the main reason consumers are deterred away from this material

### Deterioration of surface wettability of timber by paints or adhesives

Extensive research indicated that extractives on wood surfaces are the principal, physical and chemical contributors to surface inactivation, hence to poor wettability by water-based adhesives and decorative and protective coatings. This is particularly true for resinous timber species. When subjected to high temperatures during processing, extractives diffuse to the surface where they concentrate and physically block adhesive contact with the wood cells surface. Furthermore, resinous and oily exudates are hydrophobic (repel water). Due to the fact that most wood adhesives contain water as a carrier, they do not, therefore, properly wet the surface and do not flow into the porous structure of wood cells (do not penetrate the extractive-covered surfaces [1]).




**After machining** **4 hours after**

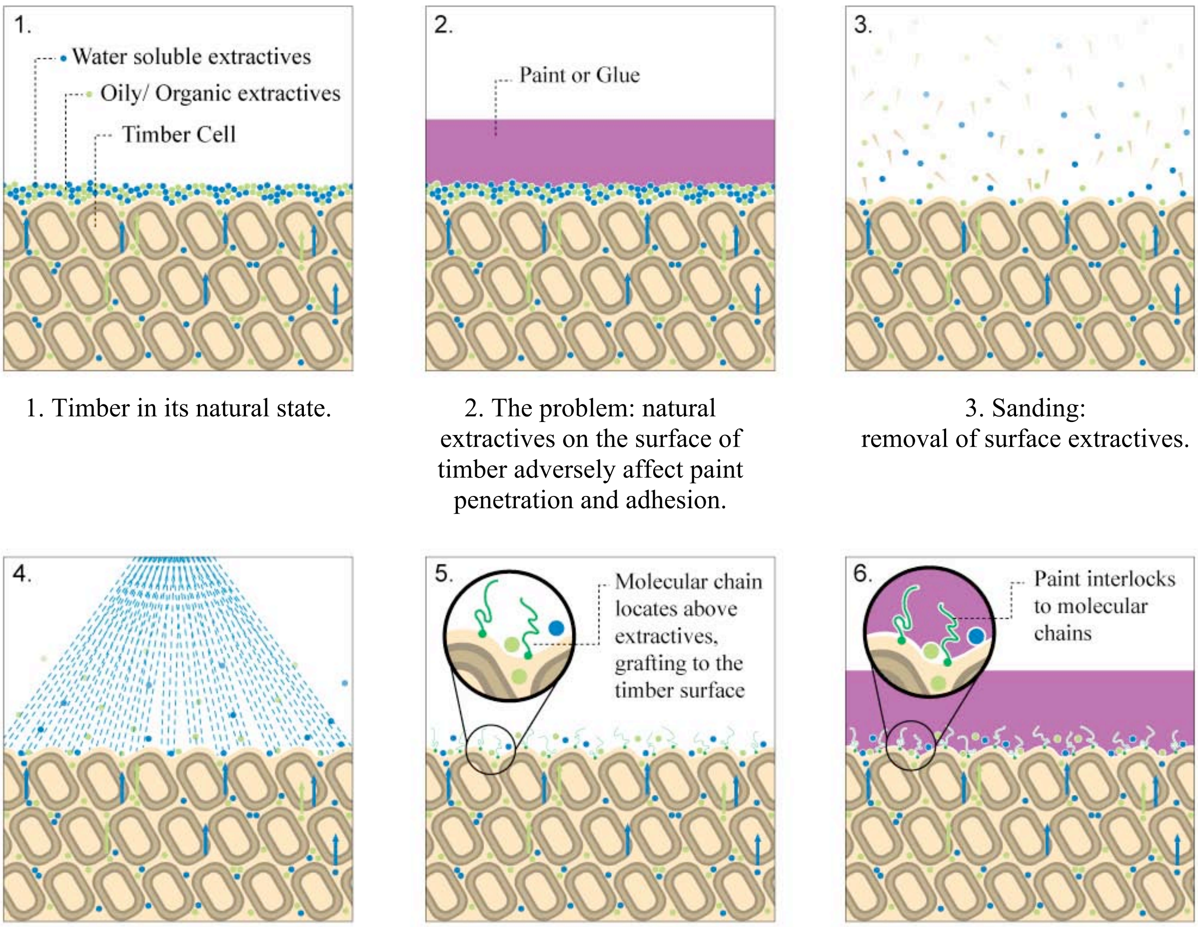
Fig 2. Microscopic view of timber surface showing the deterioration of wettability over a 4-hour period.

The severity of the problem is clearly illustrated by a sequence of photos presented in Figure 2. Two upper-row photos depict the kinetics of extractives migration to the surface of freshly machined and sanded wood which becomes covered by clearly visible resinous patches of extractives, if left unbonded or unpainted for 4 hours after machining. The two lower photos depict droplets of water deposited on the wood surface immediately after machining and that deposited on wood surface 4 hours after the sanding. These photos clearly demonstrate how the reduction of surface wettability of machined or sanded wood is reduced with the time elapsing after machining, and how this may adversely affect the surface wet-out by a water-based adhesive or paint.

## Timber surface modification process

The key reasons for poor adhesion of hardwoods are interference of extractives and moisture, absence of durable chemical bonds between the structural constituents of wood and glue or paints, and poor interlocking with cell cavities. The problem is aggravated by swelling and shrinkage of wood in response to humidity cycles. All of these lead to a gradual deterioration of adhesion during outdoor exposure. [1]

## The principles and schematics of timber modification process




1. Timber in its natural state.

2. The problem: natural extractives on the surface of timber adversely affect paint penetration and adhesion.

3. Sanding: removal of surface extractives.

4. Graft chemical spray to attach adhesion-promoting molecular chains. Removal and digestion of extractives.

5. Timber in its modified state. Chemically bonded molecular chains.

6. Desired outcome. Neutralisation of extractives by chemically bonded molecular chains to increase adhesive qualities for the timber.

Fig 3. A visualisation of the modification process of surface modified timber.

After machining, extractives migrate rapidly to the wood surface, creating a weak boundary layer which can seriously hinder adhesion. Deposits of extractives on the gluing surface can block the reaction sites, preventing the anchorage of adhesives. Incompatibility between the extractives and adhesives can result in inferior bonding and the extractives can either affect the curing and setting abilities of the adhesives or influence the wet ability of the wood surface so that penetration of a particular adhesive is adversely affected.

To alleviate this problem, CSIRO has developed a new surface engineering process for wood, whose sequence and underlying principles are schematically illustrated in Figure 3.

This research aims to alleviate the above problems by elucidation of the mechanisms of adhesion, the changes in wood chemistry after prolonged exposure, and surface modification processes. The latter typically involves grafting specific types of connector molecules which form durable molecular bridges between the surface of the timber's structural constituents and glues.

The above approach demonstrates a significantly improved bond strength (up to ten times, compared with untreated timber surface) of surface engineered timber species. The process involves a 'spray-on' application of a water-based adhesion promoter onto freshly sanded surfaces, which are bonded with Bostik's polyurethane adhesive (AV 515) subsequent to the following treatments:

1. No treatment (control)
2. Direct spray application of a water-based primer comprising of a surface-activating chemical, graft molecules and other functional additives.

After the adhesive cure, all bonded specimens are subjected to severe hydro-thermal stress corresponding to the realistic scenario of outdoor service conditions of structurally bonded timber component in tropical environment. This protocol involves exposure to constant load and condensing humidity at 60°C for 24 hours (Fig 5). After a 24-hour exposure time, the load level is incrementally raised until failure of the loaded sample (de-bonding, or timber fracture) is observed during a 24-hour cycle (Fig 6,7).

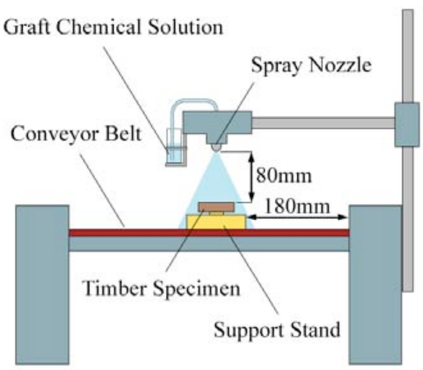



Fig 4.The method of applying chemical solution to the surface of timber.

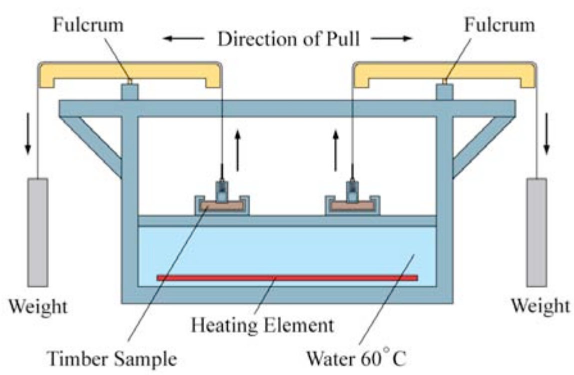



Fig 5. Conditioning bath for accelerated tensile strength testing of timber samples.

Fig 6. Negative test result showing adhesion failure (adhesive delaminating from wood surface) of non-modified sample.

Fig 7. Positive test result showing timber fracture of modified sample.

**Principal research outcomes**

Constant load testing has been performed on a variety of different timber species. This has been carried out to better understand the tensile strength performance of specific timbers modified with graft chemical solution at the CSIRO laboratories. Figure 8 shows the improvement in tensile strength of surface modified timber against non-modified timbers of the same species.

**Improved timber adhesion**

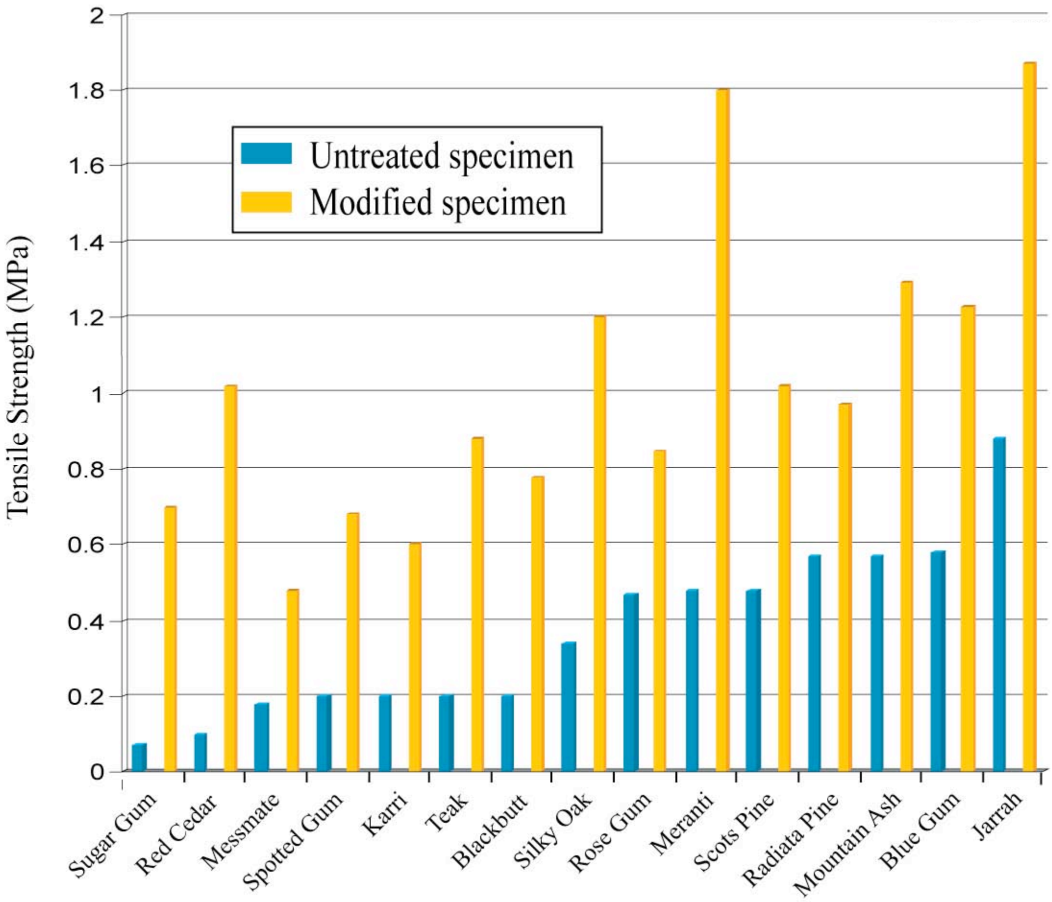



Fig 8. Results of constant load tests showing improved tensile strength between non-modified and modified timber specimens.

## Sustainable benefits

The positive outcome of this research shows that with sanding and surface modification of Scots Pine (European Redwood), a higher tensile strength of bonded joints is achieved compared with an un-modified Meranti. This is a significant practical outcome because Meranti is currently one of the most popular timbers used in the construction of timber window frames in Australia, but is unsustainable as it is not covered by the Forest Stewardship Council (FSC). The FSC is a governing body that controls the correct management of world forests and only accredits timber species that are managed as a sustainable resource. Therefore, by engineering surface properties of Scots Pine, which is covered by the FSC, to achieve the same tensile strength levels of adhesively bonded joints as with Meranti, a sustainable material can replace the need for an unsustainable material for the manufacture of timber window frames.

An extensive research program designed for different timber species used for a variety of outdoor applications has lead to the accumulation of a large and verifiable set of quantitative data validating the applicability of this novel scientific concept to different timber species.

This new knowledge in material science has been consequently transferred into a practical design outcome that demonstrates the fit of this successful science to ensuing commercialisation. The design outcome, in this case a timber window frame, will lead to the success of this technology in a genuine product application. Knowledge gained from this product development, can be transferred to other products of the same nature, such as outdoor timber furniture, cladding and doorframes.

## New design paradigm

The importance of the product design cannot be underestimated as a poorly designed product would undo the scientific advancements and be an unnecessary burden to the environment. Quality design is an essential tool that must be fully understood to ensure a positive sustainable outcome in any product development and commercialisation. While utilising the positive outcomes of scientific research that has improved the characteristics of timber for outdoor use, it is important to maximise the effect of these outcomes in a positive design application. Window frames are fully exposed to all weather conditions and timber window frames especially must be effectively designed to repel water and allow air circulation within the frame to reduce moisture buildup. The chemical modification process increases the bond strength of adhesive glues and paints which dramatically increase the tensile strength of adhesively bonded window frame joints and that of decorative or protective surface finishes. However, a detailed design protocol is required to maximise the quality of this engineered timber to ensure that water is directed away from internal components within the frame. A well resolved and thorough understanding of the design requirements to ascertain elucidation of these problems is vital to enable the window frame to function at its highest potential and to guarantee a longer life span. By creating better quality product and extending its life, this will create less of a burden on our environment through significant extension of the lifetime of such effectively designed product.

Successes with the science are incorporated into the design which has been tested to improve the material characteristics and enables materials that once have been perceived as unsuitable, whilst now, when suitably engineered can be seen as suitable. This not only is a benefit from an environmental point of view, being able to use sustainable timber instead of old-growth hardwoods, but also from a point of view of costs, as sustainable more abundant plantation timbers are cheaper than old-growth hardwoods.

In this research we believe it is important for design to lead or direct scientific developments firstly to identify specific performance targets for the science, and secondly to apply this newly developed science to design applications that were perhaps never considered by a scientist, or perceived impossible. This method can then be seen as a logistic circuit between the design and science disciplines through which scientific breakthroughs can also influence the design research pursuits.

This type of an interdisciplinary study is particularly valuable because it provides good collateral and constructive input into both, science and design, which also created a significant advantage for this doctoral research. Ideas and successful research methods diffusing into this process from both disciplines helped with constructing a better path for the research outcomes due to the fact that the knowledge has been built and gained from feedback provided by two different, but synchronized mind-sets; one technical from the fundamental and applied science platform, and the other from the applied and aesthetic design discipline.

In line with the above concept, design carried out within this research project has created a need for new scientific concepts targeting improved surface characteristics for timber use in outdoor applications. The success of this research has not only improved the characteristics of timber for outdoor applications, but has led to other advantages such as sustainable benefits for the construction industry. The outcome of this scientific research has re-established timber as a sustainable material of choice for the manufacturing of window frames.

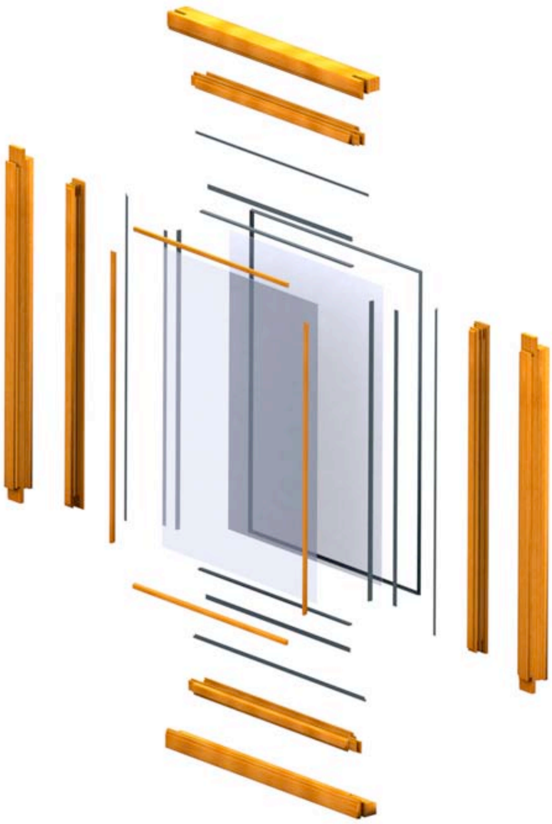


Fig 9. Digital CAD renderings of the final design outcome: Casement window.

The next stage of our quest is to push the development of science to create better timber characteristics to effectively compete with PVC and aluminium.

There is a lack of confidence among consumers of timber window frames in Australia due to a presumably poor manufacturing practice and trends employed by a majority of Australian timber window frame manufacturers. The lack of attention to a proper design code aiming to produce a durable, and hence successful timber-based product has steered consumers away from timber and towards more durable but also energy-intensive aluminium and PVC. This is due to the ongoing maintenance required in upholding the quality and ensuring longevity for timber window frames, which is something most Australians would aim to avoid. All window frames, no matter what material they are made of, require ongoing maintenance to uphold their appearance and extend the life of the product. The lack of design code within Australian timber window frames has seen a dramatic reduction of timber and a significant increase in aluminium for the manufacturing of window frames for Australian houses. This is outlined in Table 1, which shows the dominance of aluminium over timber for this industry sector. In fact, aluminium windows are third only to structural timber (12.35 per cent), and clay brick (9.05 per cent), for the percentage make-up of all materials used in residential house building in Australia [2]. Aluminium windows were also positioned third for the percentage contribution of materials used in the construction of buildings other than houses (5.70 per cent), behind mixed concrete (9.42 per cent) and structural steel (8.37 per cent). The contribution timber windows make to the materials used in building construction, other than houses, was a mere 0.15 per cent, second last out of 63 materials displayed, positioning itself in front of sand, aggregate and filling (0.10 per cent) [2].

Table 1. Percentage contribution of materials used in house building in Australia [2].

| | Sydney | Melbourne | Brisbane | Perth | Adelaide | Hobart | Weighted average |
|---|---|---|---|---|---|---|---|
| Timber windows (%) | 1.84 | 1.58 | 0.39 | 0.00 | 1.74 | 1.65 | 1.17 |
| Aluminium windows (%) | 7.91 | 5.49 | 8.87 | 9.06 | 7.68 | 7.18 | 7.60 |

## Conclusions

To date, there has been no study providing comparably successful modification of timber surfaces utilising a simple and effective chemical modification process. The proprietary chemical formulation is confidential to CSIRO and currently undergoing multi-national patent examination and approval. There has been no study from an Industrial Design perspective incorporating the successful results of this new material technology into a designed outcome. This study is an endeavour to utilise design as a catalyst for innovation within the scientific realm.

The subject of this research is revolutionary by demonstrated drastic improvement of adhesion of timber to adhesives and coatings which has been demonstrated through rigorous scientific developments, additionally utilising industrial design as a means for targeted product innovation. The surface modification process uses environmentally friendly, water-based chemicals applied to the surface of timber, which neutralize detrimental effect of wood extractives and chemically promote good adhesion through arrays of molecular chains firmly attached to the timber surface. This increases the bond strength and durability for all timber species tested in this project by an overall average of 4 times with some species increasing bond strength by 10-fold when bonded with a structural polyurethane adhesive (Bostik AV515).

The design segment of this project uses a design process based on technology led design strategies. Technology led design requires that the existing and accepted design methodologies, based on user and producer design parameter paradigms, are reconfigured. While the needs of potential users for any new product have to be met, the design strategies in this case are heavily directed by materials and manufacturing considerations. This is an innovative approach for designing that pushes scientific limitations, led by design thinking.

The significance of surface engineering sustainable timbers to the same tensile strength levels in adhesively bonded or painted products as that available with unsustainable timbers for adhesively bonded applications, not only facilitates effective limiting of the currently observed destructive deforestation of old-growth forests, but also saves the consumer money. Cost benefits of sustainable plantation timbers are significant when compared to the price of unsustainable hardwoods, which will become more expensive as they become scarce. Sustainable plantation timbers are also less expensive than aluminium and PVC, which are the materials that currently dominate the window frame market in Australia and have a much larger embodied energy than timber, establishing timber as a sustainable material of choice for the manufacturing of outdoor products.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Dr Gavin Melles. Swinburne University of Technology.


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