DEVELOPING A PREFABRICATED LOW-CARBON CONSTRUCTION SYSTEM USING CROSS-LAMINATED TIMBER (CLT) PANELS FOR MULTISTOREY INNER-CITY INFILL HOUSING IN AUSTRALIA

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ABSTRACT

Prefabricated engineered solid wood panel construction systems can sequester and store CO_2. Modular cross-laminated timber (CLT, also called cross-lam) panels form the basis of low-carbon, engineered construction systems using solid wood panels that can be used to build residential infill developments of 10 storeys or higher. Multi-apartment buildings of 4 to 10 storeys constructed entirely in timber, such as recently in Europe, are innovative, but their social and cultural acceptance in Australia and North America is at this stage still uncertain. Commercial utilisation is only possible if there is a demand and user acceptance.

This paper explores the opportunities offered by an innovative low carbon construction system using cross-laminated timber (CLT) panels to improve the design and delivery of urban infill housing. CLT construction has been developed around 1996 in Austria: layers of timber boards are glued crosswise in different directions to increase loadbearing capacity. The paper describes a multi-disciplinary research project into cross-laminated timber panels which aims to transform the Australian construction and development industry, involving a range of key partners. This project will introduce cross-laminated timber panels as a way to build with a lightweight prefabricated low-carbon construction system that is advantageous for urban infill and residential buildings in the range of 4 to 8 stories height. The challenges, research questions and advantages of this new engineered timber system are explained, and a detailed research methodology for further research is presented.

KEYWORDS

multi-storey infill housing, low carbon construction system, engineered timber, cross-laminated timber (cross-lam, CLT), modular prefabrication, construction waste

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1. INTRODUCTION

The traditional model of greenfield housing development in Australia and the U.S. is unsustainable because of the quantity of energy, materials and water used, land consumed, waste generated, and the greenhouse gas emissions that result from high consumption and inefficiencies. The flow of raw materials through the urban system has not received adequate attention because the topic of urban waste is unglamorous albeit extremely important. Reducing the consumption of materials in the construction sector is essential and even more important than recycling of building materials, as the construction of buildings and neighbourhoods using current methods require vast amounts of energy generated by fossil fuels and are based on linear one-way throughput of non-renewable materials.

Rethinking the way we deal with material flows and changing behaviour in regard to waste streams and waste avoidance, is likely to deliver significant improvements and curb the threat of environmental degradation and global warming. The research the sd+b Research Centre is involved with explores a wide range of topics around consumption and waste of materials, material flows, and solutions for better management of resources for urban development. The University understands itself as a platform for the exchange of knowledge and ideas in these areas, bringing together representatives from academia with industry, government and local communities.

We have borrowed from the planet for a long time, exceeding its carrying capacity, and if our society and economy are not transformed we risk descent into unhealthy urban conditions, loss of precious biodiversity, and depletion of virgin materials. Our current model of economic and urban growth is driving this unhealthy system, and, as a consequence, we have passed the limits of our planet's capacity to support us. Over the last 20 years, the amount of waste Australians produce has more than doubled, and it is likely that this amount will double again between 2011 and 2020 as the amount of waste generated in Australia grows by around 6 to 7 per cent per person, per year (National Waste Report, 2010).

The notion of 'waste' is based on the assumption that energy and materials, having once served the construction sector's immediate purposes, simply cease to exist in any functional sense, and that the only possibility is dumping these resources in landfills. Or, to borrow a word from Mumford and Geddes (1961), current construction methods are 'paleotechnic', representing unsustainable behaviour based on primitive, exploitative technologies rather than regenerative ones. However, the reuse of building components and construction materials would not only reduce the amount of waste created, but also allow for recycling and retrofitting of entire neighbourhoods or districts, once requirements have changed (Lattke and Lehmann, 2007; Zaman and Lehmann, 2011).

This paper describes a multi-disciplinary research project into cross-laminated timber panels which aims to transform the Australian construction and development industry and involves a range of key partners. This project will introduce cross-laminated timber panels as a way to build with a lightweight prefabricated low-carbon construction system that is advantageous for urban infill and residential buildings. The challenge, research questions and advantages of this system are explained below.

Wood is an important contemporary building resource due to its low embodied energy and unique attributes. The potential of prefabricated engineered solid wood panel systems, such as CLT, as a sustainable building material and system is only just being realised around the globe. Since timber is the only material that has the capacity to store carbon in large quantities over a long period of time, solid wood panel construction offers the opportunity to turn buildings into 'carbon sinks'. Thus the historically negative environmental impact of urban development and construction can be turned around with CLT construction on brownfield sites.

> *The energy budgets of products and buildings made of wood show that they may use less energy over their total life cycle (manufacture, use, maintenance and disposal) than can be recovered from the waste products of their production and from their recycling potential at the end of their life cycle: they are energy-positive. No other construction material is so comprehensively energy-efficient and therefore climate effective as wood.* (Wegener, Pahler and Tratzmiller, 2010, p.4)

1.1 Why transforming the current system of over-consumption is important

We are a wasteful nation. For instance, 40 per cent of all food is not eaten, it is thrown out; it is neither used for composting to return nutrients to the soil, nor in a biogas plant to generate energy (George, 2009). Our resources are limited and endless consumption and growth is impossible. If we cut down more trees than we grow, at some point we run out of trees. Passing the limits has consequences, as we see in increasing global warming, changing weather patterns, and a change in the way the whole system of 'Spaceship Earth' (Buckminster-Fuller, 1969) behaves.

Topics such as food security (is the solution urban farming?), water scarcity (stormwater harvesting?), rising energy costs (decentralised energy production on solar roofs and facades?), depletion of virgin materials (closing the loop of material cycles and resource recovery?), and traffic congestion (strong investment in public transport?) have emerged as major concerns. Researchers are looking into better ways for us to live together in the future, in more liveable and sustainable cities. Behaviour change has frequently been listed as the number one hurdle to reducing consumption towards a more energy- and material-efficient low-carbon future. If we could only plan better cities and design better buildings and products that needed less energy, water, materials and other resources (during production *and* operation), we could generate less waste and facilitate behaviour change simply through good design. For instance, enabling people to be less dependent on air-conditioning, or car driving could significantly reduce greenhouse gas (GhG) emissions (Lehmann and Crocker, 2012).

Extended Producer Responsibility (EPR) is an approach that seeks to designate responsibility for the impacts of products (or urban development) throughout their whole lifecycle. Applying this idea not only to mobile phones but also to the construction sector means when a building is made the consequences of its use and demolition (disposal) must be considered during its design. Adopting this approach across various industries would help to minimise waste and improve the efficiency of the resources used.

Homes of the 1950s Australian suburbs have mostly been built in fibro and timber sticks, while the 1960s houses were usually constructed in crème-coloured brick veneer construction; none of it particularly material efficient and limited to maximum two stories in height. Things are going to change in the construction sector too, as we must make every effort to future-proof the built environment by designing more resilient urban systems to cater for low-consumption, low-carbon lifestyles (this is, not air-condition dependent), and increase the longevity of buildings. We will increasingly learn from nature's complex ecosystems and natural ordering principles, redefining our industrial ecology and changing the way we design, produce and re-use products. As environmental activist Paul Gilding predicts, 'we will break our addiction to growth, accept that more stuff is not making our lives better and focus instead on what does' (Gilding, 2011).

1.2 Urban development and cross-lam (CLT) technology for infill

Over three-quarters of Australians live in its 18 major cities with over 100,000 people and the population of these major cities is predicted to grow (Commonwealth of Australia, 2010). Urban design and low carbon technologies have a key role in shaping the future of our cities. Planning strategies for Australian cities require a high percentage of new housing to be in existing urban areas—as an example, the *30 Year Plan for Greater Adelaide* estimates a growth of 560,000 people by 2040, requiring 70 per cent of new development to cater for this growth to be urban infill (Government of South Australia/DPLG, 2010). The Australian government through the Council of Australian Governments (COAG) is taking a much greater interest in the mechanisms whereby housing can be provided that is sustainable, focussing on its affordability, accessibility to services, and carbon emissions during construction and occupation. In Australia, the residential and commercial building sectors produce 23 per cent of the nation's GHG emissions, indirectly, as a result of materials used in construction, waste disposal, material inefficiencies and ongoing energy use (Green Building Council Australia, 2011). In addition, increasing cost of energy in Australia is driving the property and construction sector to look toward more energy-efficient products (Green Building Council Australia, 2011).

2. INTRODUCING MULTI-STOREY TIMBER CONSTRUCTION SYSTEMS

It is time to scale up our scholarship in low-carbon solutions to match the challenges we are facing in the construction sector—one of the most wasteful—and to support policy development. Improving collaboration across the sector is critical, as is guiding research agendas and legislation. At the same time it is important to educate communities to encourage a groundswell of support for this type of construction and hence influence the developers to build what people want. Our researchers are collaboratively working towards developing a responsive plan for the transformation of Australian cities as an important part of the solution. These efforts must support long-term planning and research in line with agreed national priorities, for holistic whole-of-lifecycle approaches. We therefore facilitate, support and continually evolve interdisciplinary, collaborative research and development capability in architectural and urban design and in sustainability knowledge for resilient urban systems and construction methods.

Low-carbon prefabricated modular construction systems, using load-bearing cross-laminated timber (CLT) panels (such as those manufactured in Europe) and 'design for disassembly' principles will offer significant opportunities for carbon reduction and waste avoidance, among other benefits. Introducing such innovative construction systems to the Australian construction industry and housing market has its challenges. Hence this multi-disciplinary research project has been developed, involving researchers at the Barbara Hardy Institute and the Research Centre for Sustainable Design and Behaviour (sd+b). The project's partners include: the South Australian government's Department of Communities and Social Inclusion; Housing SA; the Integrated Design Commission and Government Architect (Department of Premier and Cabinet); the Land Management Corporation, the government's developing body; Zero Waste SA, a government agency; a local city council;

a local construction company; the Property Council of Australia; two architectural firms; and one of Australia's wood product supplier. The composition of these partner organizations will ensure a broad impact of the research project. In terms of introduction of CLT construction to Australia, a 10 to 15 per cent market penetration within five years is seen a feasible by the team.

Timber has recently been used in a much more sophisticated way than previously. In recent years, approaches to timber construction in Central Europe have undergone innovative changes. In construction technology, we generally need to differentiate between wood, timber and lumber. Definitions used in this chapter are (Dehne and Krueger, 2006):

- Wood: the hard, fibrous, lignified substance lying under the bark of trees. It consists largely of cellulose and lignin. Wood is a natural material and is irregular by nature.
- Timber: the wood of trees cut and prepared for use as building material (e.g., beams, posts).
- Lumber: timber cut into marketable boards, planks or other structural members of standard or specified length.

Traditional approaches, such as block and half-timbered constructions and the balloon-frame and platform-frame constructions seen in North America, have given way to today's different types of construction: frame, skeleton, or solid CLT constructions. The main difference between these systems lies within the hierarchy of the load-bearing elements of the building structure as selective or linear elements. These constructions are characterised by the method of assembling prefabricated structural elements and the structure of the façade (envelope). General building systems consist of similar wall and ceiling elements, though these elements can also be used in combination to form a building structure; for example, the application of solid wood elements in ceilings of framework structures.

Modern methods of construction including prefabrication of CLT panels have gained attention in Europe, Canada and New Zealand. CLT panels are fabricated by bonding together timber boards (usually spruce, larch or pine) with structural adhesives to produce a solid timber panel with each layer of the panel alternating between longitudinal and transverse lamellae (Timber Development Association of NSW, 2011). The CLT panels are compatible with digital design and precision cutting techniques, enabling delivery of a prefabricated wall, floor or roof element for rapid on-site assembly; implementation shows that the system cuts construction times by more than half (Kaufmann, 2011; Waugh & Thistleton, 2011). Prefabricated CLT panels offer a number of advantages to delivering more sustainable buildings including modular, rapid on-site assembly (substantially faster and safer) which reduces cost, construction activity impacts and waste (Lehmann, 2010; Lehmann & Crocker, 2012; Lee, 2011). In New Zealand, research has also highlighted the opportunity that timber structures, assembled on-site through bolt fixings, provide for integrating 'design for disassembly' principles (John et al, 2009). Such principles are said to allow reuse of load bearing timber panels and entire components on alternate sites at the end of the building's useful life.

The presence of *radiata pine* softwood plantations in the 'Green Triangle' in the South East of SA, close to urban communities in South Australia and Victoria, led to a recent scoping study by the Zero Waste SA Research Centre for Sustainable Design and Behaviour (sd+b) at University of South Australia (Lehmann & Hamilton, 2011). The purpose of the scoping study was to identify the key factors preventing or enabling the adoption of CLT construction systems for infill development in South Australia and to identify the priority areas for research.

Designing timber buildings requires more careful detailing and precise planning than other construction methods. Generally, condensation can occur where moist air comes into contact with a surface of a lower temperature. Air always contains water vapour in varying quantities; its capacity to do so is related to its temperature—warm air holds more moisture than cold air. When moist air comes into contact with colder air or a colder surface (e.g., a timber element), the air is unable to retain the same amount of moisture and the water is released to form condensation in the element. The moisture from condensed water causes timber to decay, as the damp causes wet rot inside the walls. This is often hard to detect and may not be noticed until mould growth or rotting of material actually occurs.

Consequently there is a need for a precise, correctly layered and high-quality construction envelope to protect the timber structure from rain and water condensation. Only correct detailing will protect it from humidity and solve the question of surface treatment—to keep maintenance low and to 'pre-design' the ageing process and the appearance of the surface.

The project will introduce cross-laminated timber panels (CLT) to the Australian construction sector. These panels are lightweight, prefabricated, modular, produced off-site, recyclable and highly material-efficient. In addition, this construction method has significantly less embodied energy and enables 'design for disassembly' principles—buildings can be disassembled or adapted more easily as use dictates. CLT panels are a 'value-added' timber product that can substitute for concrete or steel, which are both very carbon-intensive. As layers of timber boards are glued crosswise (width of wood stripes usually varies between 80 and 240 mm, with thickness between 10 and 40 mm), the loadbearing capacity of CLT panels in different directions is increased for taking up compression loads, while the shrinkage and swelling as a result of humidity variations is eliminated. It allows for a high level of prefabrication, where buildings can be erected rapidly as openings for doors and windows are already included in the factory cutting process (KLH, 2011).

The project partners are committed to up-scaling the application (from prototyping to full-scale demonstration) and an inner-city pilot project will deliver useful preliminary information.

2.1 The future: a recyclable construction system with potential for carbon reduction

To identify holistic approaches, such as principles for disassembly and reusability of entire building components, requires researchers in disciplines including economics, design and materials, to work together to enable the systemic environmental restructuring of consumption and provision in energy, water and waste systems. In the context of this change process, designers—architects, urban planners, industrial, interior or product designers—play a major part. To advance design knowledge one has to engage in designing. In *Sustainable by design*, Stuart Walker (2006) outlines a new understanding of the complexity and potential of sustainable design, extolling the contribution of design to the creation of a more meaningful material culture.

Prefabricated modular CLT panels, when manufactured in Australia, should be available in sizes up to 16 m × 3.2 m (length x width; even greater lengths are possible, depending on machinery), and usual thicknesses from 50 mm to 250 mm, even up to 500 mm. These panels are made from three, five or seven layers of solid wood planks glued together in alternating directions for strength. Recently new adhesives have been developed that resolve the previous fire and off-gassing (VOC) issues. The CLT panels suit a wide range of prefabricated floor, floor-to-floor high wall and roof applications for both commercial and residential buildings. Utilising specialised computer-controlled machinery, these panels are manufactured, factory cut, bored and grooved to suit any end use, and delivered just in time for assembly on-site. CAD and CNC computerised technology delivers perfect precision and allows building designers to interface directly with production. Manufacturing elements for mass customisation of buildings (e.g., using a 'kit of parts') will develop a manufacturing assemblies industry similar to the automotive industry, using digital fabrication and systems design of components, realising prototypes and demonstration projects. Applied research will drive this off-site fabrication. The extent of factory prefabrication dramatically reduces construction time on-site. The panels can be used as:

- a complete construction system (modular and demountable);
- components in conjunction with complementary engineered timber products, such as glue-laminated timber and laminated veneered lumber (GLT and LVL); and
- hybrid structures in combination with concrete and steel.

A main concern with multistorey construction systems is fire behaviour. Design models of timber structures in fire usually take into account the loss in cross-section due to charring of wood. While little information is available on charring of CLT panels (and their adhesives for bonding), a recent extensive testing programme on the fire behaviour of CLT panels has been conducted in Switzerland, and results are very promising (Frangi *et al*, 2009). For instance, the spread of flame and therefore fire safety is comparable to other established construction methods. Building designs for timber structures require fire engineering to be embodied in the architectural and structural design concepts from the beginning—to ensure integrated solutions that are cost effective and meet the requirements of the building code and regulatory authorities.

Using resources more efficiently through CLT construction reduces the embodied carbon in materials and structures from around 550 kg CO_2/sqm to 300 kg CO_2/sqm, compared to conventional materials used for such construction. This is achieved by using a prefabricated timber construction system with lightweight facades with low-impact finishes. Timber is a significantly lower-impact material than steel or concrete, as it produces less GHG emissions, is fully recyclable and regrows sustainably. CLT panels have a high material efficiency, using around 0.75m^3 of CLT per sqm of apartment. Using local timber will allow the entire supply chain to be controlled, developed, and its impacts minimised across the whole life-cycle of a building.

FIGURE 1. Prefabricated cross-laminated panels are engineered load-bearing jumbo panels, consisting of a series of layers, bonded together timber boards (usually spruce, larch or pine) with structural adhesives, forming a solid timber panel with each layer of the panel alternating between longitudinal and transverse lamellae. CLT panels can be up to format 3.2 × 16 metres (approx. 10 × 45 feet) in size.

2.2 The project challenge and policy context

The transformation of production processes, green infrastructure and systems includes concepts of resource efficiency (especially material efficiency), decoupling (material use decoupled from urban growth), clean technologies, and design for sustainability, industrial ecology and lifecycle analysis. Industrial production and the construction sector as a whole have to be transformed. In their seminal book *Natural capitalism: the next industrial revolution*, Paul Hawken, Amory Lovins and Hunter Lovins (2000) described the path we must take to ensure the future prosperity of our civilisation and our planet. The book rocked the business and manufacturing communities with its authors' innovative approach—which fused ecological integrity with business acumen via the radical concept of 'natural capitalism'.

This project aims to develop systems and designs in timber to tackle the negative environmental impact of buildings through innovative uses of wood technology that offer new ways of constructing efficient and affordable structures that demand less of the environment while maintaining functionality and aesthetic appeal. This innovative study has the potential to transform the construction sector and change the way we design, build, maintain and recycle inner-city infill projects in Australian cities. Once carbon accounting is in place, existing building materials' carbon lifecycles will be assessed, underpinning future government policy initiatives in the construction sector. High carbon intensity materials (such as steel, aluminium and concrete) have already been identified, and the Federal Government's low carbon legislation will motivate industry to develop low-carbon, high-performance alternatives and systems. Hence, there is an increasing importance of research in recycled construction materials.

Legislation is already pointing this way, and South Australia's declining manufacturing industries could instead assemble green kit-buildings. A recent *Thinker in Residence* report published by the SA government's Integrated Design Commission (2011) recommends:

> *Manufactured assemblies for mass customisation of buildings. Expertise in the design and manufacturing of 'green' assemblies for mass customisation of buildings by transforming non-viable manufacturing industries into eco-innovation industries for diverse locations, populations and purposes in South Australia.*

Therefore, the research project combines:

1. low-carbon materials with low embodied energy;
2. design of prefabricated buildings: digital fabrication of modular floor-to-floor high elements;
3. initiating behavioural change in the construction sector to support a more sustainable style of living in new urban districts.

The project explores modular prefabrication and integrated solutions, using low-carbon materials and lightweight construction systems for sustainable buildings to significantly reduce construction waste and the consumption of resources and materials. The developed 'workplace and living' prototypes and guidelines will take passive and active solar principles into account, including international best practice for cross-ventilation and lifecycle assessment criteria. Today, digital design allows for 'digital prefab', which can lead to a new form of 'sustainable prefab'. The building of today is designed with digital tools and is produced by means of digitally controlled production. This might lead to a revolution in the conception, design and realisation of multistorey apartment buildings. Moreover, it prompts a whole new debate about what is appropriate in architecture: zero-waste construction becomes a reality.

A paradigm shift has taken place, from architecture based on mass production to architecture based on industrially produced made-to-measure components. Simultaneously, the role of the architect, or, to be precise, the expert formerly known as the 'architect', is changing as the context for development has entirely changed. This project aims to develop a better understanding of these changes and to help design professionals and decision-makers develop better models for Australia's transit-oriented developments (TODs) and urban infill with residential multistorey buildings.

The first CLT multistorey residential building in Australia will be 807 Bourke Street in Victoria Harbour (Docklands) in Melbourne, a 10-storey apartment building to be constructed entirely in CLT panels by Lend Lease in collaboration with KLH (Austrian panel manufacturer); construction is due to start in May 2012.

2.3 Exploring initial research questions

This project's questions go far beyond the simple one of recycling building components in the construction sector. John Tillman Lyle notes:

> *. . . among the most serious difficulties with waste management in the industrialised nations is the immense quantity of materials to be dealt with. The industrial economies' high emphasis on productivity necessarily results in large volumes of waste, which is the essence of the throughput system* (Lyle, 1994).

It became clear at early stage that the project should explore a wide range of issues, including:

- How can we quickly introduce this technology in Australia?
- Will timber construction apartments be embraced by consumers?
- Given existing building codes, how can we get approval for inner-city residential buildings in the range of four to eight storeys (i.e., resolving issues around fire and acoustics)?
- How can we ensure local supply chains, sourcing of appropriate timber (South Australian pine), investment and skills to build with timber?

Prefabrication ideas are, of course, not new (witness the ground-breaking systems research carried out by German architect Konrad Wachsmann in the U.S. in the 1950s; or the prefabricated self-built wood frame kit houses by Swiss architect Walter Segal in the UK in the 1970s), but with digital fabrication and advances in Building Information Modelling (BIM) it has returned in an innovative way that will avoid endless repetition of the same element; the system allows for individual mass customization (Ward, 2007).

2.4 The main advantages of the new engineered timber system

The research team is working towards low-carbon construction solutions that offer new ways of constructing affordable housing, which will benefit from the many advantages CLT panels offer. The advantages of CLT panels include:

- over 50 per cent reduction of construction time, significantly minimising construction costs;
- high material-efficiency, zero-waste construction is becoming a reality;

- less weight (lightweight, better handling on-site, smaller foundations. Timber has a weight of 500 kg/m^3, compared to concrete with 2450 kg/m^3);
- more safety (less dangerous manoeuvres on-site and less time on-site);
- independent of weather, made under high quality control in an off-site factory;
- significantly less noisy construction, convenient in urban centres, due to prefabrication off-site;
- earthquake resistant (ideal for all cities on fault lines);
- strong and durable, locally sourced, leading to distinctive architecture;
- thermally efficient, with low embodied energy;
- healthy, dry construction method, quick readiness for occupancy;
- simple construction techniques, easy to up-skill workforce, offering a complete system approach or components with high dimensional accuracy (see: Figure 1);
- lightweight, suitable for sites with poor foundation conditions and narrow lots (as urban infill), with slim load-bearing construction elements;
- recyclable and biodegradable, made from an abundant and fully renewable wood resource (sustainably harvested pine plantation forestry);
- adding economic value by processing our raw timber into specialised components;
- improving cash flow mechanisms for developers, while prefab delivers more security to financing banks; and
- negative net carbon emissions (the carbon storage capacity is likely to be recognised by government for carbon sink benefits), sourced from sustainably grown and harvested forest stock (using plantation timber that is replanted in a 12-year cycle). Wood is the only material with a negative CO_2 balance; each cubic metre of wood sequestrates an average of 0.8 to 0.9 tonnes CO_2.

European experiences of CLT construction over the last decade will allow for significant technology transfer. Timber's flexibility makes it much more affordable to saw-cut a large piece of CLT panel into a particular geometry or complex shape, compared to laser-cutting a comparable piece of steel. The precision is impressive, as well as the speed on construction site: Modular repetition is high and the elements are light-weight in comparison to concrete. For the 9-storey 'Stadthaus' project in London, the engineers estimated a 17 weeks' time saving (Waugh & Thistleton, 2011).

Further advantages of prefabricated modular, multistorey housing systems include integrated waste management, which is a significant factor in the design and delivery process, enhanced as a consequence of building in a factory environment where one can achieve reduced site waste and environmental impact by:

- designing to standard building material dimensions to minimise wastage (e.g., if a sheet comes in at 1.2 m wide, the product is designed at intervals of 1.2 m or 0.6 m, rather than 1.0 m and 0.5 m);
- continuously recycling and streaming waste (factory waste is sorted into metals, timber, general waste and cardboard to optimise recycling opportunities);
- minimisation of travel or transport emissions; and
- zero-waste construction and fast assembly on-site using mechanical jointing systems.

Engineers have calculated a reduction of CO_2 emissions by 50 to 55 per cent compared to conventional construction methods (Arup, 2008). Timber stores 0.8 tonnes of CO_2 within 1 cubic metre and is a replenishable material. In comparison, the production of concrete, aluminium and steel are one-way energy-intensive processes that release large amounts of CO_2 into the atmosphere (see AGO 2002; McKinsey 2008; BEIIC 2010; DCCEE 2011). CLT panels can be easily demounted for re-use, or used as an energy source at the end of the building's life. Overall, this technology offers construction systems for urban infill and narrow lots, where there is no or little storage space, therefore ideal for four-to-eight storey buildings.

3. A RESEARCH STRATEGY FOR LOW CARBON CONSTRUCTION SYSTEMS

Research in the field related to CLT buildings has so far frequently been part of a broader focus on examining the low carbon properties of timber buildings, their structural performance, their fire performance and how forest and wood products, including recent innovations in engineered wood products, may be used more widely in the construction of multi-storey buildings. A major focus of timber building research compares the environmental impacts of timber with that of steel, concrete and masonry. A 55 per cent reduction in GHG emissions (carbon dioxide) is reported to be achievable by using timber, compared to steel and concrete (Head, 2008), confirming that timber provides a lower carbon solution. For multi-storey buildings specifically, Sathre and Gustavsson (2009) compared two functionally equivalent four storey buildings, one framed in timber, the other framed in reinforced concrete, finding that the timber framed building used 28 per cent less primary energy for materials and emitted 45 per cent less carbon than in the concrete framed building.

Research in Australia (Carre, 2010), where *radiata pine* is widely used for timber framing, concluded that single detached housing constructed in timber uses less embodied energy than steel or concrete construction. CSIRO have developed an environmental impact assessment module (called eCO_2) for AccuRate which allows the embodied CO_2 in a proposed house design to be assessed, although this module does not apply to residential (Class 2) multi-storey buildings (Woodsolutions, 2011). It has been estimated that the growth and processing of timber in Australia also stores carbon, estimated to be 0.83 tonnes carbon dioxide (CO_2) per cubic metre of timber (Bootle, 2006; NSW Department of Primary Industries, 2008).

Researching the systematic retrofitting of existing building stock and entire districts is increasingly important, because the majority of carbon emissions and environmental impact comes from existing buildings. In the very near future, new low-carbon products and construction techniques will be developed and commercialised with industry partners to help industry reduce lifecycle carbon content and minimise embodied energy. The required market transformation will only be achieved when new government policy is implemented, underpinned by research into lifecycle carbon and the optimisation of local supply chains. This will transform the building construction, material supply chain, infrastructure and property development markets, such that there is consumer demand for low-carbon products and services, removing identified barriers (Garnaut 2008; PMEETF 2010). The ability of government at all levels to adopt new policy and planning settings will be vital to the success of these market transformations. It will also build the capacity and capability of industry such that the building and infrastructure design and construction industry is able to deliver the necessary low-carbon products and services.

The project focuses on appropriate uses of innovative and sustainable construction materials from a holistic standpoint of structural and environmental performance. Consequently, links with other university research centres are very important, especially in the field of building physics and construction management.

4. THREE RECENT EUROPEAN CASES TO BE ANALYSED

Since the late 1990s, construction with CLT panels in Europe has resulted in some groundbreaking demonstration projects which have been extensively analysed (Lattke and Lehmann, 2007; Lehmann, 2010). The measured insulation (R-value) and acoustic characteristics of the Austrian built cases are impressive: a R-value 0.45W/m^2K for external walls are easily achievable, and a superior acoustic value for external and internal walls, achieving sound proofing values of R_w 50 dB-A (Kaufmann 2011), suggesting that CLT will perform well in terms of acoustical and general environmental functions. Here a brief description of three European cases:

Project 1: Svartlamoen multi-apartment building in Trondheim, Norway, 2005 (Architects: Brendeland and Kristoffersen, Trondheim). This is one of the most remarkable timber constructions in Europe. Two buildings with an overall area of around 1000 sqm were built. The main five-storey building, which measures 6 m x 22 m, also contains rooms that can be used commercially, and the four upper floors contain units of 120 sqm. The entire construction was made out of solid CLT boards and clad with Norwegian larch. The untreated timber surfaces of the load-bearing elements are exposed on the inside. The use of prefabricated elements reduced total construction time significantly, to 9 months (about half the usual time). The efficient assembly of the timber elements allowed four workers to erect the main structure in just 10 working days.

Project 2: Am Muehlweg residential development in Vienna, Austria, 2005–2006 (Architects: Hubert Riess; Hermann and Johannes Kaufmann, Schwarzach/Vorarlberg Region, Austria). One hundred public-sector apartments were built on three interconnecting sites, with the emphasis on the optimum exploitation of the ecological and economic benefits of timber and mixed constructions. Terraced houses and an L-shaped building surround an internal courtyard, creating a communal area. The three-storey superstructures made from prefabricated CLT panels built on top of the concrete basement were constructed in 15 months.

FIGURE 2. Prefabricated cross-laminated panels, up to 16 m in length, are delivered just in time for assembly on-site; image of a European project under construction. The 4-storey built CLT quarter in Vienna, Am Muehlweg, shows that a very high quality can be achieved even for public housing (Photos: the author, 2010).

Project 3: Holzhausen multi-apartment building in Steinhausen, Switzerland, 2006 (Architects: Scheitlin-Syfrig and Partner, Luzern). The new fire protection standard in Switzerland, introduced in January 2005, permits the construction of timber buildings of up to six storeys with a 60-minute fire-resistance capability. This is Switzerland's first six-storey timber building, with a four-storey CLT panel construction on top of a concrete base. Each floor accommodates two spacious apartments of 150 sqm and 166 sqm.

5. RESEARCH METHODOLOGY, QUESTIONS AND NEXT STEPS

This research initiative is timely and significant, addressing the lack of research in this field. The presence of a source of CLT panels in the Asia Pacific region will increase the need for Australian regulators and building certifiers to develop knowledge, skill and capacity to assess CLT building designs to ensure that this construction technology is not unduly disadvantaged compared to traditional construction systems or other modern methods of construction based on steel and concrete prefabricated panels. In this context, research to address the key gaps in knowledge that restrict the broader uptake of the CLT construction system in Australia is becoming increasingly urgent.

The research will further address three significant environmental problems: Material consumption of common construction methods is contributing to (i) growing resource scarcity, (ii) pollution in the form of GHG emissions and inefficiencies, adding to (iii) a growing waste problem in Australia.

In an analysis of barriers identified by stakeholders to using CLT construction systems, Lehmann & Hamilton (2011) noted a number of aspects related to the lack of reference CLT in performance standards in building codes and regulations in Australia. One aspect relates to the permitted height of timber buildings generally, reflecting the expected performance of timber framed construction rather than engineered CLT construction. The National Construction Code (NCC) also focuses on the combustibility of timber, classifying buildings constructed in timber as Type A. There are no *deemed to satisfy* provisions relating to CLT products or performance standards for these products, requiring expert opinion likely to be based on destructive testing. The NCC and its building codes are performance based and are similar to codes adopted in most European countries. A recent review of building regulations for multi-storey timber buildings in Europe (Östman and Källsner, 2011) identified and analysed five building requirements: fire safety; acoustics and vibrations; stabilisation; seismic design; and durability design. They found that the main limitations from a regulatory perspective to the increase in use of wood for multi-storey buildings in Europe were fire and acoustic performance requirements. Östman and Källsner (2011) noted that issues raised by BRE (2004) were still being resolved in Europe in 2011. These issues relate to:

- regional differences in building regulations in some countries;
- a lack of codes and standards for many wood products, resulting in costly and time-consuming certification procedures for technical performance of these products;
- limited use of Euro Codes, although familiarity was increasing;
- uncertainty and lack of in-depth knowledge of regulations relevant to timber construction;

- limited external use of wood or wood products due to height of the building and distance between adjacent buildings—related to external spread of fire; and
- variation in the maximum number of storeys permitted.

While timber is combustible, it is predictable in fire and has a high degree of fire resistance; CLT panels are resistant to initial combustibility. The results of recent fire performance testing of CLT has provided sufficient evidence to force a review of Euro Codes and an update of building codes at a country level (Östman and Källsner, 2011). In respect of fire performance of CLT, the most influential fire research to date has been undertaken by Frangi et al. for the WoodWisdom-Net project in Europe. Their study found that the integrity of the CLT panels tested is reliant on both the rate of fire spread and speed with which the layer burns, and the type of adhesive used.

The research project will therefore address the following four key research questions:

RQ1. So far, CLT construction systems have mainly been used in temperate and cool climatic conditions in Europe and Canada. But how do we best adapt the method of CLT construction technology to urban infill development in a hot climate, such as in Australia?

RQ2. What quantifiable benefits (e.g. CO_2 reductions, carbon storage capacity, speed of construction, etc) accrue to the use of CLT compared to traditional steel, concrete and masonry for infill development?

RQ3. How exactly can adoption of this new, material-efficient, low carbon technology aid the transformation of the Australian construction industry, making it more competitive and environmentally sensitive?

RQ4. Which urban infill design is the most compatible with CLT construction methods in the Australian context and what is the impact of CLT construction on urban form/ urban infill, for instance for TODs?

The project will outline policy directions to define guidelines for urban infill and CLT construction in the near term (3 to 5 years), mid-term (10 to 15 years) and long term (beyond 20 years). Through four inter-related *Themes* the Low carbon CLT prefabrication project addresses four significant gaps, guided by the conceptual framework developed in the scoping study (inter-related areas and stages of research):

(i) mapping of key low carbon construction concepts and six relevant cases;
(ii) investigate how CLT systems can be applied to urban infill which stores carbon;
(iii) investigate design for disassembly and thus create energy and greenhouse gas benefits;
(iv) synthesise the above to develop a CLT system suitable for Australia and provide an evidence base for policy and decision makers to better understand supply chains.

The suggested project approach is structured around these four *Themes* addressing the research gaps outlined earlier and the four *Research Questions.* It is planned that at least six cases of recent 4 to 7 storey CLT buildings in Europe (in Vienna/Austria, Berlin/Germany, London/UK, Trondheim/Norway and Steinhausen/Switzerland) and Canada (UBC Vancouver) will be analysed in-depth to better understand the factors affecting building standards adopted, the influence of urban design features, suitable surrounding land-uses, location and community acceptance. Social and cultural acceptance plays a vital role during the implementation of any technology innovations. A detailed post-occupancy evaluation will be conducted for all cases, to develop an indicator matrix that allows recommending future standards for CLT buildings and their social acceptance, most suitable for an introduction of the technology in Australia (Lehmann and Fitzgerald, 2012).

The conceptual framework adopts an empirical approach whereby actual prototypes of CLT buildings will be subjected to tests and analysis. Using case studies proposed in Australian urban centres, guidelines for design of CLT buildings will be developed that adequately address acoustics, structure, seismic performance, durability, energy efficiency and fire performance. As *deemed to satisfy* (DTS) building regulations do not currently exist for CLT multi-storey structures in Australia, draft guidelines will be developed from empirical testing to inform Australian standards of design and construction for multi-storey CLT buildings. An explanation of the approach proposed follows:

- Five existing sites in four Australian cities earmarked for infill development will be identified and development rules and urban design guidelines reviewed to ensure better designs for multi-storey buildings of 4 to 8 storey are permitted development, in consultation with government agencies.
- Appropriate design criteria for CLT multi-storey buildings will be identified through a literature review, an in-depth analysis of case studies, and consultation with building approvals professionals.
- The factors important to industry and community acceptance of CLT buildings for infill development will be identified through consultative research methods (e.g. perceptions of durability and fire risk).
- Designs will be subjected to compliance testing for acoustic, seismic, energy and thermal efficiency performance standards using appropriate testing regimes and current Australian standards for multi-storey residential construction in urban infill locations.

FIGURE 3. The 'Forte' building in Melbourne Docklands under construction, in July 2012. The 10-storey residential tower with 23 apartments is entirely prefabricated, using an engineered solid wood panel construction system; the building stores around 1,400 tonnes CO_2 in its structure (Photos: the author, July 2012).

- A prototype of a CLT building component(s) will be designed and constructed using fully exposed CLT panels sourced from Europe and from a local wood products manufacturer.
- The prototype will be tested for fire severity and compared to the fire severity of an equivalent component constructed from non-combustible materials. The critical behaviour of adhesives used will be determined in these tests. The component openings and connections will also be tested for fire resistance.
- The need for fire spread prevention technology, expected to be a sprinkler system as a minimum, and will be assessed to determine the minimum standard for CLT multi-storey buildings.
- All fire testing will be documented through measurements, visual observation and video recording
- Test results will be analysed using current building code requirements, fire fighting standards and urban design objectives. Results will be discussed with appropriate regulatory bodies in each jurisdiction including building rules assessors and fire fighting agencies.
- Using the evidence of testing during the research, draft guidelines for the design of fire-safe CLT multi-storey buildings will be developed, submitted to an Industry Reference Group (IRG) for peer review.
- Revised guidelines will then be submitted to the Australian Building Codes Board for consideration.
- Regular Focus Meetings will be conducted including the Industry Reference Group.

6. CONCLUSION AND FURTHER WORK

New research agendas are emerging in response to the needs of our society to become sustainable. Conducting research is essential in the change process, as it will deliver more and better solutions to curb global warming. Universities are leading the search for solutions. In his seminal essay 'The metabolism of cities', Herbert Girardet notes that:

> *the linear model of urban production, consumption and disposal is unsustainable and undermines the overall ecological viability of urban systems, for it has the tendency to disrupt natural cycles. In the future, cities need to function quite differently* (Girardet, 2004).

Transforming the construction sector's building methods is an essential part of moving towards a better model with reduced material consumption, higher efficiencies, and carbon storage abilities. Timber is a wholly sustainable construction material for the developed world, as it re-grows, can be sustainably harvested, is fully recyclable, and stores carbon. Using certified wood ensures that the timber is supplied from sustainable forestry, and not from developing countries, where precious 'old-growth' forests are illegally logged.

No doubt, CLT can become an interesting alternative construction method in rapidly expanding, urbanising cities such as in the Asia-Pacific region (e.g. in China), where there is a need for inner-city apartment buildings and rapid low carbon construction technology. It also shows good performance against earthquakes (Ceccotti, 2008). Significant savings during the construction stage are achievable, as well as reduced CO_2 emissions in comparison with concrete or steel. The integration of sustainability in housing, combined with holistic problem solving, is of crucial importance for the development and re-development of all urban areas. When combined with innovative technological solutions for modular prefabrication, this drive for sustainability could lead to more affordable housing, if the advantage of repetitive modules is fully explored. This is particularly important for Australian cities; a recent international study ranked no Australian urban area as 'affordable' and 25 of Australia's 28 urban areas as 'severely unaffordable' (Demographia, 2011).

In conclusion, cross-laminated timber panels are a product extremely well suited for multi-storey urban infill buildings because of its versatility and many outlined advantages compared to concrete and steel. With lengths up to 16 meters and the possibility of extending with mechanical joints or glued connections, widths of up to 3.2 meters and thicknesses up to 500 mm, almost any necessary shape of element can be manufactured on the market today. Innovative possibilities and new applications using CLT are far from being exhausted. So far, the highest CLT building is the 'Stadthaus' in London Hackney, a 9-storey apartment tower; and 'Forte' residential tower in Melbourne Docklands, a 1-storey apartment building (in both cases also the elevator shaft is made of CLT panels); but there is potential for wood-concrete hybrids, composite structures, combining CLT elements with a concrete core and structural outriggers as a structural system for much higher buildings, e.g. using CLT structural wall elements in the facades in combination with a concrete core (van de Kuilen et al, 2011): very tall timber towers (up to 40 stories) have recently been developed by various architect plus engineer teams, e.g. in Europe by Kaufmann and TZG (TU-Munich), in the UK by Ramage and Ramboll (with the University of Cambridge), in Austria by Winter (TU-Vienna); and in Canada by Michael Green. However, for the time being these remain academic challenges, as long as fire safety and earthquake performance are still in research stage. In real construction, CLT has already proven to be very material efficient for multi-storey buildings in the range of 4 to 8 stories height; hence, ideal for the urban density Australian cities are requiring.

The construction industry of tomorrow will favor materials and systems with low embodied energy that can easily be recycled and re-used, based on green supply chains. However, the influence of embodied energy on the lifecycle balance is by many architects still not well understood (Wackernagel and Rees, 1996). 'Zero waste' means maximum material efficiency and resource recovery, without any construction waste to landfill; it also means that buildings are fully demountable and fully recyclable at the end of their lifecycle. This research project aims to evolve timber designs and manufacturing systems to reduce buildings' negative environmental impact through innovative uses of wood technology that offer new ways to construct efficient and affordable structures that demand less of the environment, while maintaining high functionality and aesthetic appeal. Research findings will be reported in a forthcoming book publication planned for 2013. The project's findings will apply to the lifecycle of sustainable multi-apartment housing projects, help ensure long-term viability of buildings, nudge the behaviour of stakeholders towards more sustainable outcomes, reduce resource consumption, and increase re-use of waste and building components. There is no CLT manufacturing in Australia yet (New Zealand and Canada have started manufacturing CLT panels in early 2012, but are still working out production issues). However, it is only a question of time, as the demand for CLT products in Australia and the U.S. are likely to reach the level to justify the investment in a domestic manufacturing plant; US-architects have also become interested in introducing this new way to build and have designed first demonstration projects using CLT construction (such as the recent project by Mark Mack Architects from San Francisco for a 4-storey multi-apartment building).

This paper has outlined why CLT construction systems are a relevant topic within the context of the current environmental debate and the use of sustainable materials and construction methods. This technology might even turn urban infill developments into 'carbon sinks'. Timber, the construction material of the past, is again re-considered as the construction material of the future; as a high-performance, low-carbon construction material, adequate for multistorey residential buildings even in an urban setting.

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