Rethinking Timber Buildings

Seven perspectives on the use of timber in building design and construction

ARUP

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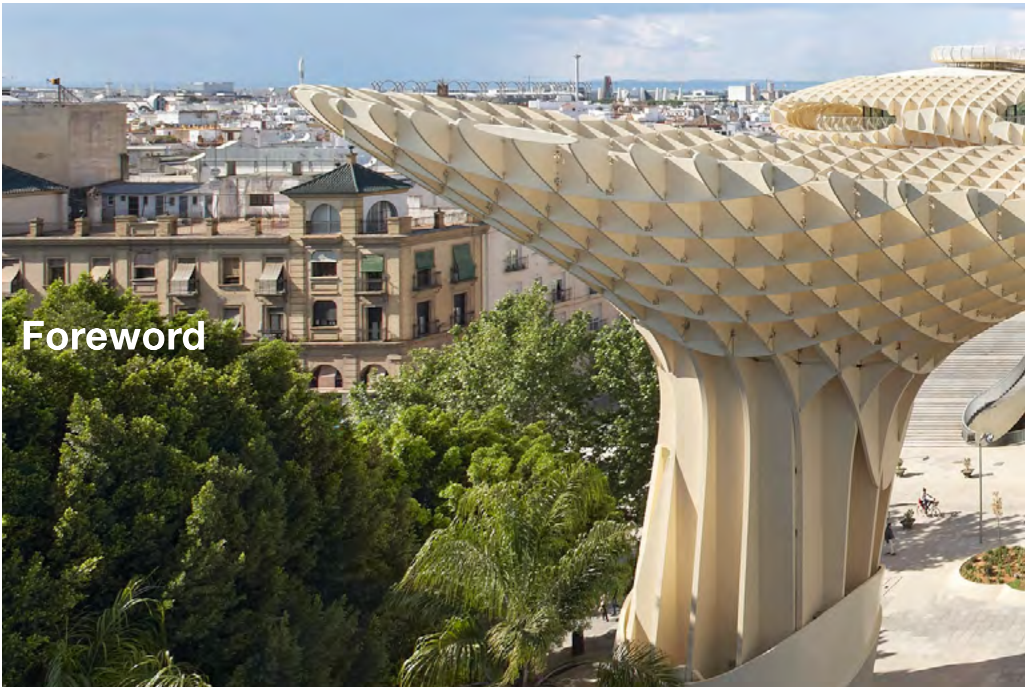

Foreword

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Urbanisation and human population growth are increasing the pressure on our planet's precious resources with visible signs of anthropogenic damage. It is estimated that two billion square metres of new building stock are needed every year between 2019 and 2025, especially for housing. Global carbon dioxide emissions (CO_2) have increased by almost 50% since 1990. The construction industry alone produces around 15% of these global emissions.

There is an urgent need to limit global warming to 1.5°C to prevent the worst impacts of climate change, as stated in the Intergovernmental Panel on Climate Change (IPCC) special report on climate change released in October 2018. This strategy requires greenhouse gas emissions to be cut to net zero by around 2050. Net zero is the point at which greenhouse gas emissions are balanced by the removal of these gases from the atmosphere. An intermediate target of 45% reduction by 2030 is also recommended. We all need to take responsibility to make changes to energy systems, changes to the way we manage land and changes to the way we move around with transportation. We also need a radical rethink in our approach to construction to deliver a net zero built environment.

Above: Metropol Parasol, Seville, Spain.

Timber is one of our most traditional construction materials and has a key role to play on both sides of the net zero balance. Forest enhancement is seen by many governments as a crucial part of their emissions mitigation strategy, as trees absorb carbon from the atmosphere to grow. Timber is also less carbon intensive to manufacture, transport and erect than steel and concrete structures. Therefore, increasing the use of timber in our buildings will reduce the carbon impact of construction. A thriving sustainable forestry sector also contributes to the non-urban economy, reducing urbanisation.

The timber industry has been enjoying significant growth in the last decade, primarily due to the increase in mass timber products such as cross-laminated timber, glulam and laminated veneer lumber, as well as many board products such as OSB, that make use of smaller offcuts. Yet timber as a structural material seems to invoke a more emotive response than its competitors, dividing opinions and stifling the much-needed debate on how and where timber can best be used to safely develop low-carbon buildings; namely by addressing further research needs in relation to fire safety performance, floor dynamics, robustness and durability.

This wide-ranging report explores seven different perspectives on the use of timber in building design and construction. I hope it informs debate and moves the discourse forward on the increasing use of timber as part of the construction industry's concerted endeavour to build a safe, resilient and net zero future.

Preface

This report is intended for anyone wanting a strategic overview of timber construction and its recent upsurge in popularity. It considers seven perspectives on the use of timber in building design, exploring where and when it is used, factors influencing its adoption, and how it might evolve. These seven factors best reflect timber's current social, technological, environmental, economic and political context, and provide a broad and holistic review:

1. Managing our carbon budget
2. Urban densification
3. Wood and well-being
4. The future is prefabricated
5. Sustainable sourcing
6. Knowing the material
7. Innovating with wood

The report is relevant to those who need to take a long view of construction industry trends, and anyone who has a stake in the materials we choose to build with, and the implications these choices have for the environment, for speed of process, for quality of outcome, and for the amenity and safety of occupants.

Terminology

This report describes a new method of designing and constructing multi-storey timber buildings, variously called *massivholz* (German), mass timber, massive timber, heavy timber, solid timber, or engineered timber. The term used in this document is mass timber.[1] The performance characteristics of mass timber are different to those of traditional stud and joist construction in just about every respect such as structural, fire resistance, building acoustics, physics and dynamics.

Glossary

Brettstapel: method of adhesive- and nail-free softwood timber construction using hardwood dowels to join components.

Cassettes: prefabricated timber components for use in wall and roof assembly.

CLT: cross-laminated timber comprises layers of timber boards, also known as dimensional lumber, arranged perpendicular to one another and glued together, forming a single structural member. The perpendicular layers provide additional strength and stability.

Glulam: glued laminated timber comprises layers of timber arranged along the same grain and glued together to produce a single structural member.

LVL: laminated veneer lumber comprises multiple layers of wooden veneer bonded with glues.

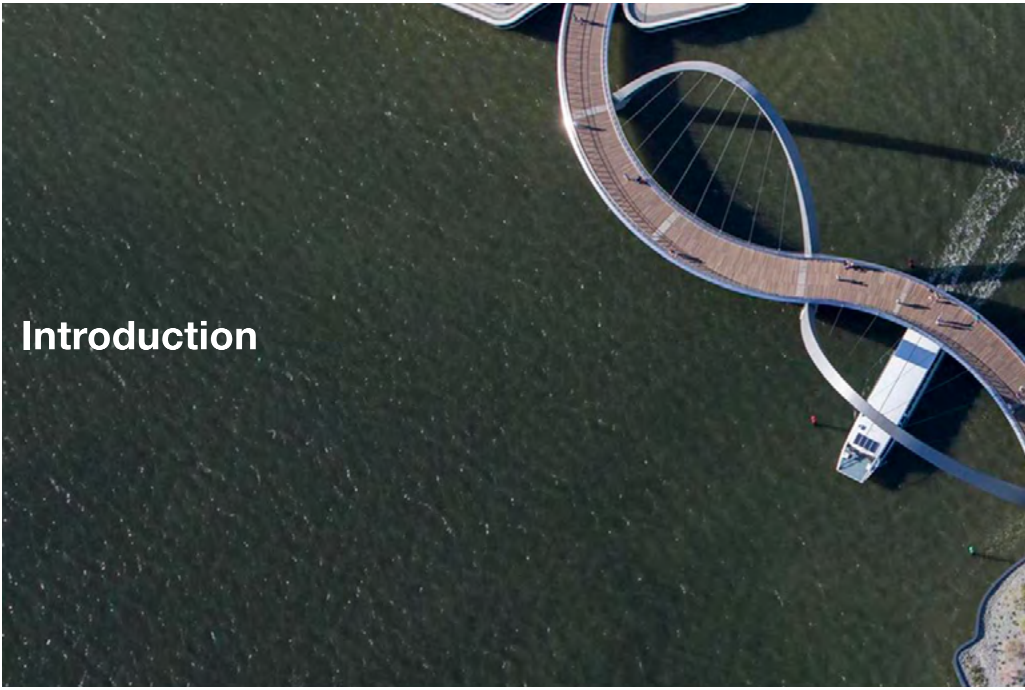
Massivholz: a German term for engineered timber, also referred to as mass timber, massive timber, heavy timber or solid timber.

PSL: parallel strand lumber comprises multiple layers of thin wooden veneer strips, bonded with resin.

Roundwood: felled wood that is largely in its natural state.

Stud and joist: timber pieces arranged into horizontal 'joists' and vertical 'studs'. The horizontal joists can support a floor, for example, and the vertical studs can form walls and/or support structural loads.

TCC: timber concrete composite systems combine concrete and timber components, creating a hybrid that benefits from the material properties of both. Commonly used in floors.



Introduction

Population growth, increased longevity and urban expansion are putting pressure on our planet's resources like never before, and calling into question established approaches to the design and construction of our built environment. To keep pace, it is estimated that two billion square metres of new building stock will be required every year between 2019 and 2025 alone.[2] We need to consider what impact these new structures will have on our planet and on the people that will inhabit them, as well as the consequences of our material, design and fabrication choices.

Space and resource constraints, climate change mitigation and resilience, and a greater focus on human well-being, among other factors, have stimulated new solutions and encouraged innovation. For some this has meant a return to one of our oldest building materials: wood. The potential of this versatile material is immense, with benefits including reduced energy consumption, reduced CO_2 emissions, healthier spaces, and a route to sustainable forest management — all key tenets of the UN Sustainable Development Goals (SDGs). Improved techniques and recent precedents provide the basis for this

timely review, which aims to explore and ultimately re-think the role of timber and its value.

Above: Elizabeth Quay Pedestrian Bridge, Perth, Australia.

This report acknowledges that multiple perspectives are needed to provide a useful overview, given advances in the types and techniques of mass timber fabrication. While many interrelated factors will shape the future role of timber in building design and construction, we have sought to distill these into seven topics.

Firstly, the report considers how timber can play a role in tackling the construction industry's CO_2 problem, with its material properties potentially helping to reduce a building's carbon footprint, if appropriately managed, supporting the reductions in greenhouse gas emissions agreed under the Paris Agreement. The report then considers the city scale, and how new approaches to urban densification appear to be well-suited to timber, with the potential to open-up challenging sites and work with existing structures. We then assess the human aspect, and whether the use of wood can provide the healthy buildings and spaces our growing cities

Timber-framed waterfront warehouse, 1908, Vancouver: the Leckie Building, architect Dalton and Eveleigh.

need. Reflecting on the wider construction industry, we go on to consider the proliferation and effectiveness of pre-fabrication and timber's role, followed by an assessment of forestry practices, supply-chains and the realities of sustainable sourcing. The final two perspectives tackle timber as a material, looking first at its properties and performance, including approaches to fire safe timber; and then at new timber research, processes and innovation, and how they might influence future design choices. The seven perspectives are complementary for a holistic overview.

The use of timber alone will not solve our many challenges, but it could form a vital component of how we choose to design and build, and underpin a more resilient built environment. These seven perspectives combine to help us rethink this most pervasive of construction materials, and explore its new potential.

A short history of timber construction

To fully understand timber's relevance today we must first consider how its use as a building material has changed throughout history. In prehistoric times when humans lived nomadically, simple, light, temporary structures were suitable for shelter. Timber was an ideal construction material, having both tensile and compressive strength, a high strength-to-weight ratio, and easy workability. In Neolithic and early Bronze Age Europe, timber was widely used for the construction of residential longhouses and roundhouses, reinforced with clay walls and thatched roofs. As humans began to settle and take up agriculture, timber gave way to stone and clay bricks to build more lasting settlements. Vast temple complexes, public forums, residential buildings and paved streets were raised in stone and brick.

Although the archaeological record does not always preserve timber, the use of wood as a building material continued well into the Classical period and beyond. The Romans, for example, were notable for their use of wood in the construction of bridges that spanned rivers and in the multi-storey apartment blocks (insula) that housed a million residents in ancient Rome. In the Middle

Case study

The Toronto Tree Tower

Toronto, Canada — Penda architects and timber consultants Tmber have designed a modular 18-storey mass timber building for central Toronto. Their conceptual design embeds construction efficiency, sustainability and natural beauty, with prefabricated CLT units stacked on top of one another and a timber-clad façade that incorporates trees and plants. The tower would provide 4,500m^2 of residential space.

Hundreds of prefabricated solid timber panel buildings have been erected in the UK alone, starting from zero in 2000.

Ages timber construction was again revived for urban building resulting in a dense network of two and three-storey buildings, which can still be seen in many old European city centres today.

Historian Lewis Mumford considered wood and water to dominate the first phase of the European machine age, from the 10th to the 18th centuries.[3] Wood was used for buildings, bridges, windmills, watermills, war machines, ships, carts, furniture and utensils. As Robert Youngs notes "In Europe the water-and-wood phase reached a high plateau around the 16th century with the work of Leonardo da Vinci and his talented contemporaries. At about this time, the availability of timber diminished, particularly in the UK. The scarcity was caused by the expansion of agriculture, the increasing use of wood as a structural material and fuel, and from growing demands of the smelting furnaces. To smelt one cannon took several tons of wood."[4]

In the Far East timber construction developed independently of European influence. 'Bracket set' jointing of columns and beams dates back to 1000 BC, and reached maturity in buildings like the Yingxian Pagoda (1056 AD), one of several extant buildings in China from the period. Meanwhile Japanese carpenters developed mortise and tenon joinery into an art form, still applied today in the construction of Shinto temples.[5]

By the 18th century, coal with its higher calorific value began to replace wood for fuelling industrial processes. More efficient smelting with coal also led to more iron production, and soon iron and steel began to displace timber in structural applications, including shipbuilding, formerly the unchallenged preserve of timber.

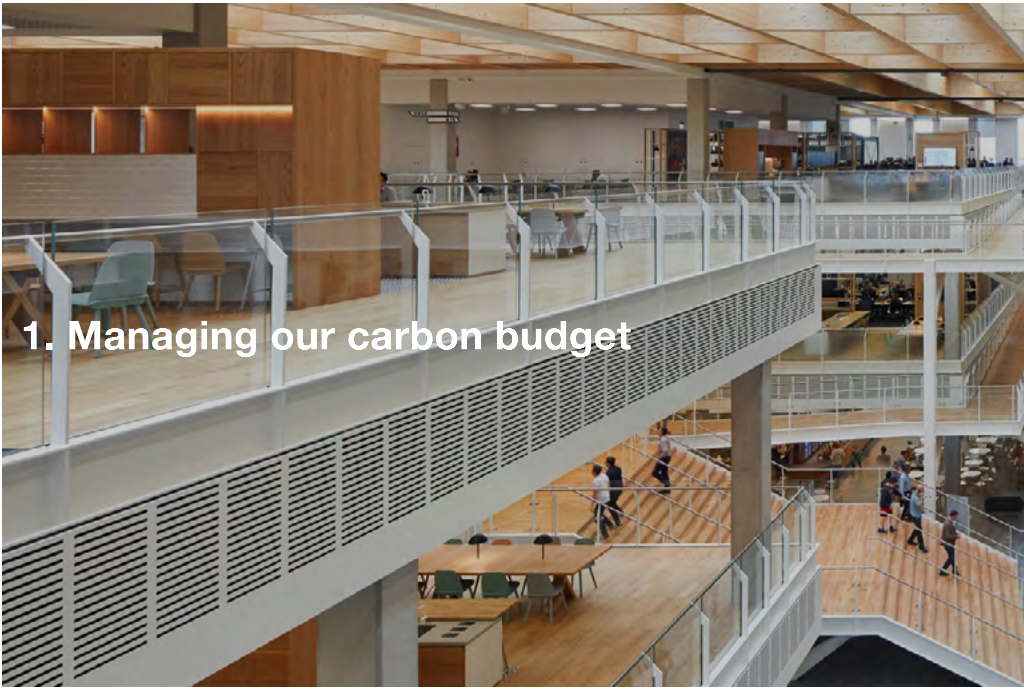
In America, the 19th century saw a massive expansion in the use of wood for buildings, railroad ties, telegraph lines, ships, and charcoal fuelled steel mills. Wood consumption reached a plateau around 1850, about 200 years after the peak in Europe, and began to be replaced with coal.[6] While timber remained in favour for the port structures and warehouses built during North American trade expansion in the late 1800s and early 1900s, by the 1920s, reinforced concrete had entered the market, and apart from domestic applications little has been seen of multi-storey timber construction since.

In addition to these economic shifts, tighter controls on the use of timber for construction were implemented in the wake of major city fires like those of London (1666), San Francisco (1851) and Chicago (1871), and the fire safety of building materials remains a major concern today. Indeed, in November 2018 the UK government restricted the use of combustible materials in the external walls of designated buildings over 18m tall in the wake of the Grenfell Tower fire.[7] The implications for mass timber as a construction material in the UK (and internationally) are still to be understood.

Durability issues have also caused periodic reassessment of timber as a structural material. As Will Pryce notes, “Augustus the Strong (1670–1733)… articulated a common prejudice when he boasted that he had ‘found Dresden small and made of wood and had left it large, splendid and made of stone.’”[8]

Given this varied history, what should we make of the current upsurge in interest and output in timber construction?
In recent years we have seen regulatory authorities in the US, Canada, Germany, Italy, Switzerland, Poland, Finland and Australia all move to allow taller timber buildings.[9] Hundreds of prefabricated solid timber panel buildings have been erected in the UK alone, starting from zero in 2000.[10] And while the global total of timber buildings over six storeys is still very modest as of March 2019, a few 20-storey buildings are now being discussed or are under construction. To understand these trends and their implications we need to assess the full breadth of timber’s potential, a different aspect of which is explored in each of the following seven sections.

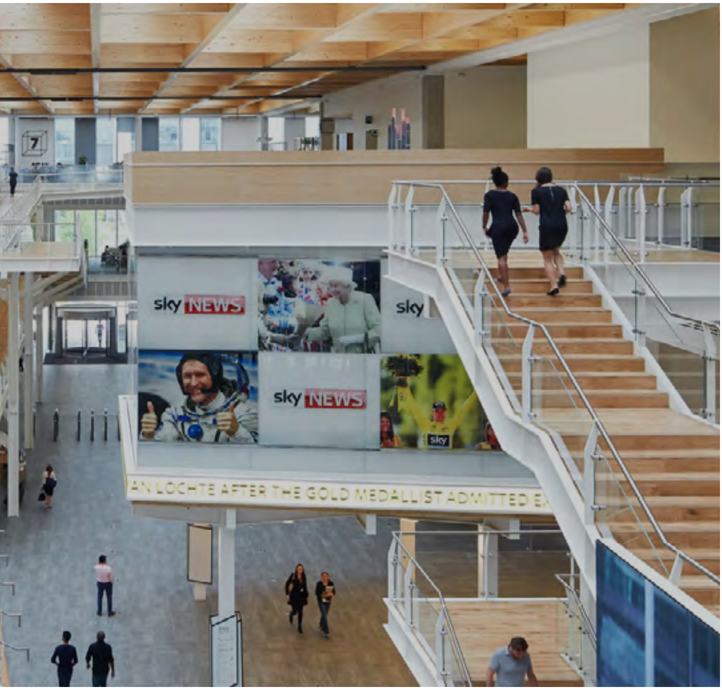
With a global population of 8.6 billion expected by 2030, we must question how we can deliver the scale of construction necessary in the face of growing global commitments to reduce carbon emissions.



1. Managing our carbon budget

At a glance

- The environmental impact of construction is unsustainably high, with choice of building material a significant contributor to greenhouse gas emissions.
- Given the high carbon footprint of cement and steel production, timber is increasingly a compelling third option.
- The CO_2 captured during photosynthesis gives timber a head start over other construction materials, but this captured CO_2 needs managing at end-of-life.
- End-of-life options include reuse, recycling, biomass energy extraction through combustion and anaerobic burial to fix (most of) the carbon. Choice may be limited by chemical adhesives, preservatives and coatings present in the wood.
- Policies that include carbon pricing and trading are growing in number, and all support CO_2 abatement. These include ‘timber first’, CO_2 compensation, forest carbon stock inventory tracking, and industry voluntary schemes incorporating LCA (life cycle assessment).



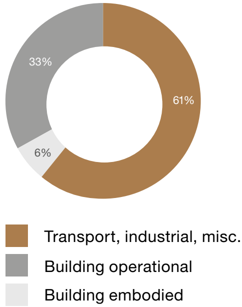


Figure 1 Building-related embodied emissions in 2014 were about 6% of total man-made GHG emissions.[15] (Arup, 2018)

Left: Sky Believe in Better Building, London, UK.

Reducing the carbon footprint of buildings

The resources we extract from the earth and manufacture into materials for buildings and infrastructure contribute substantially to annual global greenhouse gas emissions.[11]

How can we best tackle these emissions? Choice of construction materials is currently dominated by concrete and steel. Both concrete and steel industries have programmes in place to reduce their carbon footprints, and cement substitutes are also gaining ground, with blast furnace slag, fly ash and silica fume among the most used.[12] Depending on the mix of these substitutes, there can be drawbacks such as lower early strength, potentially resulting in delays to de-propping and post-tensioning and a slower construction cycle. Recycling of concrete still offers plenty of scope for uptake[13], however the core issue of carbon emissions from cement production itself still needs to be dramatically reduced. Cement production as a whole currently accounts for around 8% of global CO_2 emissions.[14]

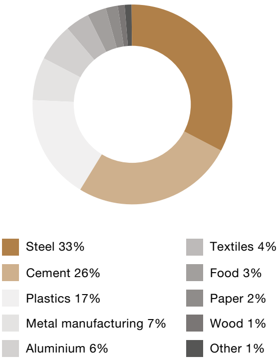
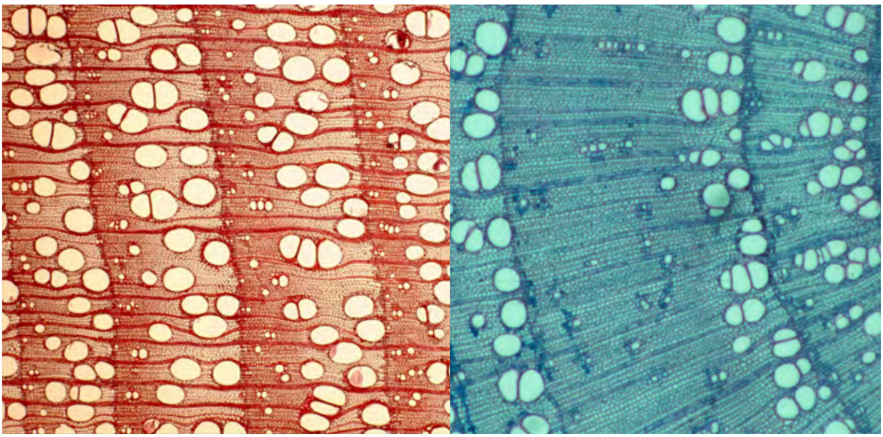


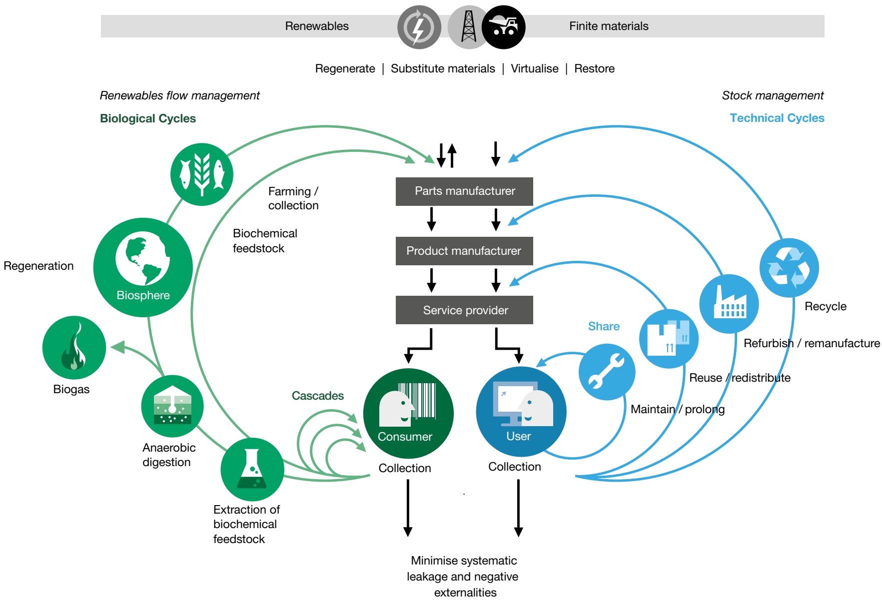
Figure 2 The above chart shows relative percentages of CO_2 emissions by material in China, home to the world's largest construction and manufacturing markets.[18]

The iron and steel industry has made big strides to improve energy efficiency but still accounts for between 6–7% of global CO_2 emissions.[16] Its best promise lies with increasing the extent of recycling, which some studies show as low as 35–40% of steel globally.[17] These figures are likely to increase as we transition into a low carbon 'circular economy,' in which high-embodied energy materials like steel are repurposed indefinitely, and to ensure we meet global emission-reduction targets.

Given the high carbon footprint of cement and steel production and the challenges these industries face transitioning, timber is becoming a compelling third option. Timber is one of the few renewable construction materials and, by its very nature, the production of wood via photosynthesis removes CO_2 from the atmosphere. Depending on the end-of-life disposal scenario for the wood product, most of this captured carbon can also be sequestered or result in net-zero carbon emissions if burned for biomass energy (assuming a fossil fuel offset).



Trees absorb about two tonnes of CO_2 to create one tonne of their own (dry) mass. In the spring, softwoods like spruce (left) add large cells to carry water up the trunk for quick growth. In the summer, the cells become smaller as the emphasis changes to producing wood for strength. Hardwoods like ash (right) start off in spring with a ring of even larger diameter vessels.[19]



Circular economy system diagram: the circular economy approach separates material flows into interacting biological and technical cycles. Within the biological cycle, renewable resources are used, regenerated, and safely returned to the biosphere. Within the technical cycle, human-made products are eventually remanufactured into new products. Timber participates in both cycles, albeit mass timber products ideally stay in the technical cycle. Entering anaerobic digestion at end of life would constitute significant down-cycling and loss of value added.

Figure adapted from Ellen MacArthur Foundation and McKinsey Center for Business and Environment, and Braungart & McDonough, Cradle to Cradle (C2C).

Forests as carbon sinks

The CO_2 storage potential of timber is enormous, assuming we are in a dynamic situation, where either forest area is expanding, or timber is harvested and held in long-term storage in durable products, and replaced with new-growth trees. The IPCC recognises this opportunity: "In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit".[20] Forest carbon stock also depends on the quality of the forest.

Younger, dense populations, for example, are not as high in carbon or as resilient as diverse old growth. Longer rotations can help to increase carbon stores significantly.[21] Land use constraints will limit the expansion of forests, so our best forestry future for maximum CO_2 capture will need to follow IPCC advice and ensure that our forests are 'producing an annual sustained yield of timber…'. Forestry agencies keep carbon stock registers to monitor changes and confirm outcomes for national inventories. The carbon sequestration role of forests is further underscored in the UN SDGs, where sustainable management is a key objective. Designing to species from regions that monitor and incentivise increasing carbon stocks in their forests helps to support these outcomes.

The timber in the Believe in Better Building for Sky UK represents 1242 t embodied CO_2, having deducted emissions for manufacture and transport from Austria (200 t CO_2).[22] The alternative structure with steel frame and concrete slabs would have cost 553 t positive embodied CO_2, i.e. emitted to atmosphere. Given the building's energy saving features including rooftop PV, LED lighting and CCHP, the net contained carbon represents about 13 years of operational emissions.

Case study

Native forests

New South Wales, Australia — Forest typologies in New South Wales include ‘conservation’ forests, with no harvesting, and ‘multiple use’ forests, with sustainable harvesting. The potential CO_2 drawdown of each forest type was modelled over a 200-year period. The conservation forest quickly reaches CO_2 equilibrium (black line), while the multiple use forest (top line, with product substitution benefit and fossil fuel offset benefit from biomass energy conversion of forest residues) continues to extract CO_2 from the atmosphere.[23]

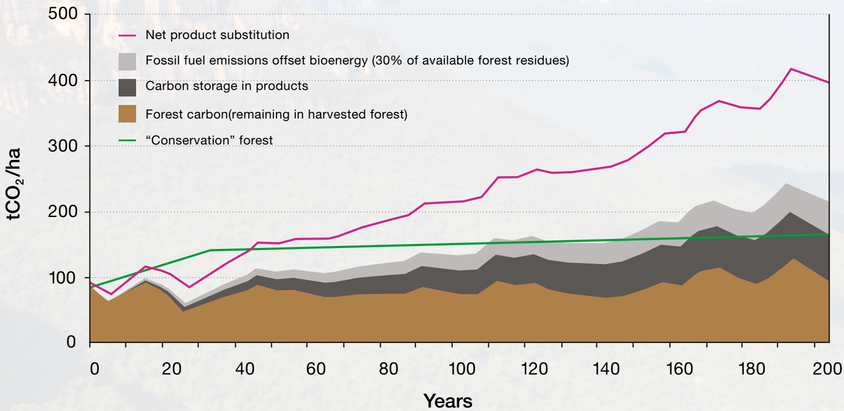


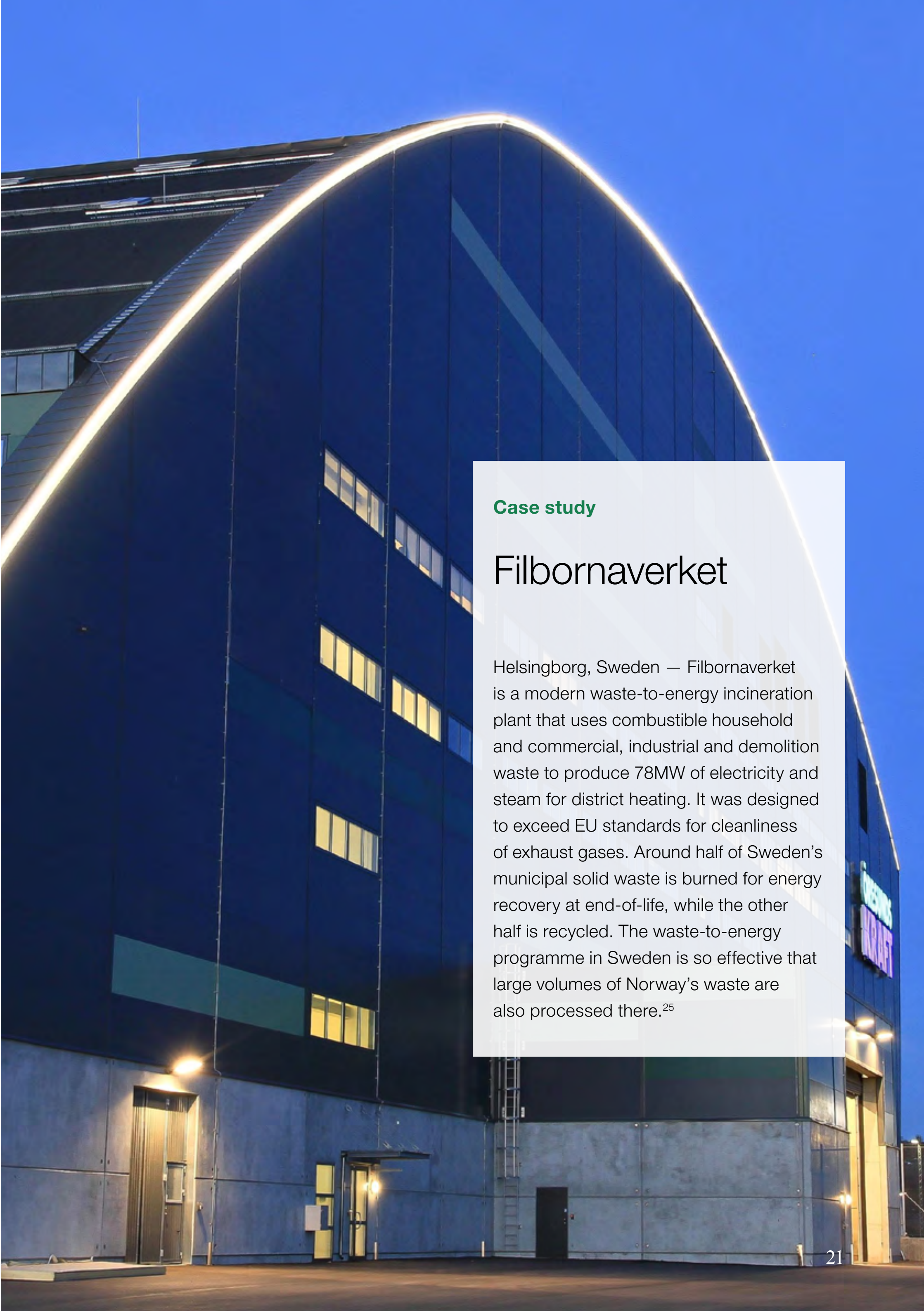
Figure 3 Greenhouse gas implications for forest types over a 200-year period. (Journal of Forestry, 2012)

End-of-life choices

Timber will eventually decay and return its CO_2 to the atmosphere when left unprotected. For timber buildings, disassembly, adaptation and reuse is the ideal disposal option at end-of-life, and will become more attractive with the increasing use of large-section glulam beams and columns and large CLT (cross-laminated timber) floor and wall panels. They have had enough value added during manufacture to warrant reuse and recycling even in the present-day market, albeit the extent to which the process can be closed- or open-loop may depend on the types of chemical adhesives, preservatives and coatings used in the fabrication process.

Biomass energy conversion of the timber at end-of-building-life will be an option for emissions reduction only as long as existing energy generation relies partially on fossil fuels, thereby enabling a fossil fuel offset. Waste to energy at end-of-life returns CO_2 to the atmosphere resulting in a net CO_2 release over the life of the wood product. Direct incineration of solid waste can produce toxic gaseous emissions however, and glues, paints, preservatives, and natural resins that come with wood waste can be contributors to this. A process called gasification, in which high gas combustion temperatures allow improved scrubbing of pollutants in the flue gas cleaning phase, could potentially address these concerns.[24]

The prefabrication of timber buildings typically comes at zero emissions cost. Wiehag's glulam plant at Altheim near Stuttgart generates 38 GWh pa of renewable energy by biomass conversion from 10,000 t pa of sawdust and offcuts. That is enough energy to supply all of the plant's electricity and heating needs, including kiln drying. Excess offcuts are sold as product, and excess power is sold to the grid.



Case study

Filbornaverket

Helsingborg, Sweden — Filbornaverket is a modern waste-to-energy incineration plant that uses combustible household and commercial, industrial and demolition waste to produce 78MW of electricity and steam for district heating. It was designed to exceed EU standards for cleanliness of exhaust gases. Around half of Sweden's municipal solid waste is burned for energy recovery at end-of-life, while the other half is recycled. The waste-to-energy programme in Sweden is so effective that large volumes of Norway's waste are also processed there.[25]

Sections of timber products retrieved from a Sydney landfill site after 46 years of burial. Research in the US and Australia using both landfill mining and laboratory simulation indicates typical long-term retention rates for carbon in buried wood products as high as 90–100%.

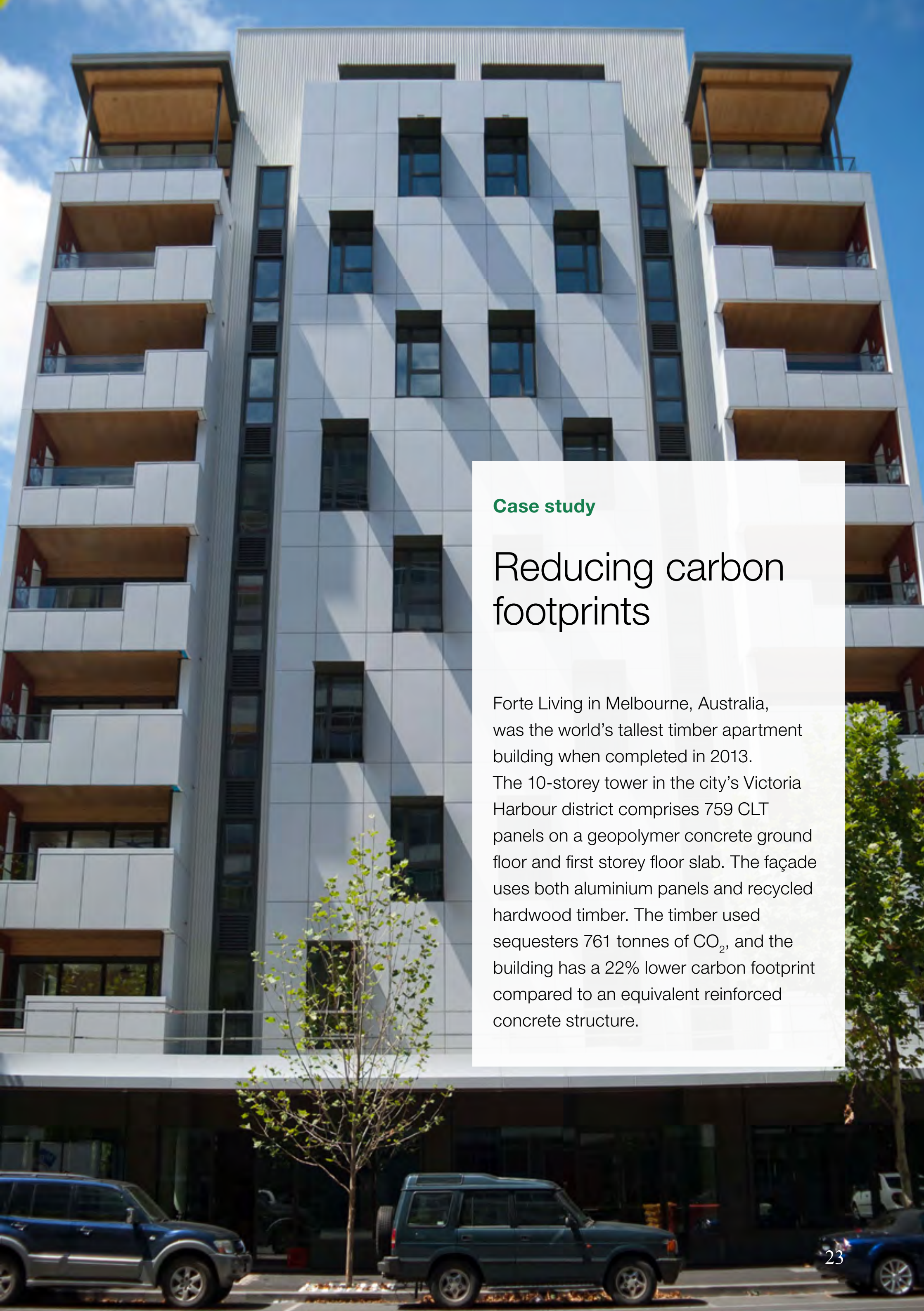
The switch to using renewables for energy will eliminate the fossil fuel offset. As such, extracting energy from demolition timber and the associated return of CO_2 to the atmosphere will no longer be acceptable. The next step should therefore be to sequester as much as possible of the carbon that the trees have drawn down. Potential approaches include conversion to biochar, extracting bio-energy but with carbon capture and storage from exhaust emissions, or by storing the timber long-term in anaerobic environments.

Political drivers for carbon emission reductions using timber

We can expect future government action on climate change to harness the sequestration potential of timber, given that forest carbon stocks are likely to become tradeable on international carbon markets through mechanisms such as ITMOs (Internationally Transferred Mitigation Outcomes) as countries work towards their COP21 Paris Agreement commitments.

Paris also saw gatherings of city and regional leaders, who continue to advance their own abatement plans alongside national ones. In some countries, 'timber first' policies have been introduced at municipal or regional levels of government, including Canada, New Zealand, Germany, Finland, USA and Australia. In most instances there is an active local forestry industry, with notable exceptions including the London Borough of Hackney.[26] Japan introduced its Wood First Law in 2010 and like many of the schemes it has multiple aims — including increased timber self-sufficiency as well as emissions abatement.[27]

While governments grapple with emissions policy, voluntary green building ratings schemes will continue to have a positive effect. These schemes have been evolving too: LEED and BREEAM have moved to recognise life-cycle assessment (LCA) as an important tool, which means that timber's unique embodied energy storage can be more accurately quantified. There are exceptions, however, with LCA methods in the USA not including sequestration in tools used for the new LEED credits.



Case study

Reducing carbon footprints

Forte Living in Melbourne, Australia, was the world's tallest timber apartment building when completed in 2013. The 10-storey tower in the city's Victoria Harbour district comprises 759 CLT panels on a geopolymer concrete ground floor and first storey floor slab. The façade uses both aluminium panels and recycled hardwood timber. The timber used sequesters 761 tonnes of CO_2, and the building has a 22% lower carbon footprint compared to an equivalent reinforced concrete structure.

2. Urban densification

At a glance

- City planning policies are shifting rapidly from uncontrolled spreading of urban areas toward densification, for social, environmental and economic reasons.
- Densification includes building taller, building in air rights spaces, and building on sites previously considered unsuitable.
- Adding storeys to existing buildings becomes more feasible with timber's lighter weight.
- Building in air rights spaces where transfer structures are required, lighter weight means reduced transfer loads and associated structural costs.
- Timber's lighter weight is also an advantage when building on sites underlain by poor foundation material.

Stücheli Architekten added two extra storeys in timber to this existing four storey 1920s concrete-framed building in Zurich, increasing usage by 25%.[28]

Above left: Central Hong Kong and Victoria Harbour.

Timber-based 'drop-top' opportunities

As cities look to increase the number of people living in urban areas, re-purposing old office buildings for residential use and the addition of new floors will see more take-up as a densification strategy. The reduced load from the use of the structure (occupancy by people, equipment and storage) for this change of use relieves design load on existing columns and foundations, and so creates an opportunity for adding extra storeys simultaneously. If the old building is of concrete construction, the opportunity for extra storeys is enhanced further because concrete strengthens with age, allowing the existing columns to carry more design load.

Used structurally, timber's light weight allows the maximum number of extra storeys to be added. The softwoods typically used in modern multi-storey timber construction have around 20% of the density of concrete. Comparing residential construction in precast concrete and CLT, wall and floor panel thicknesses are similar in the two materials, so total timber building structural weight is around 20% of the concrete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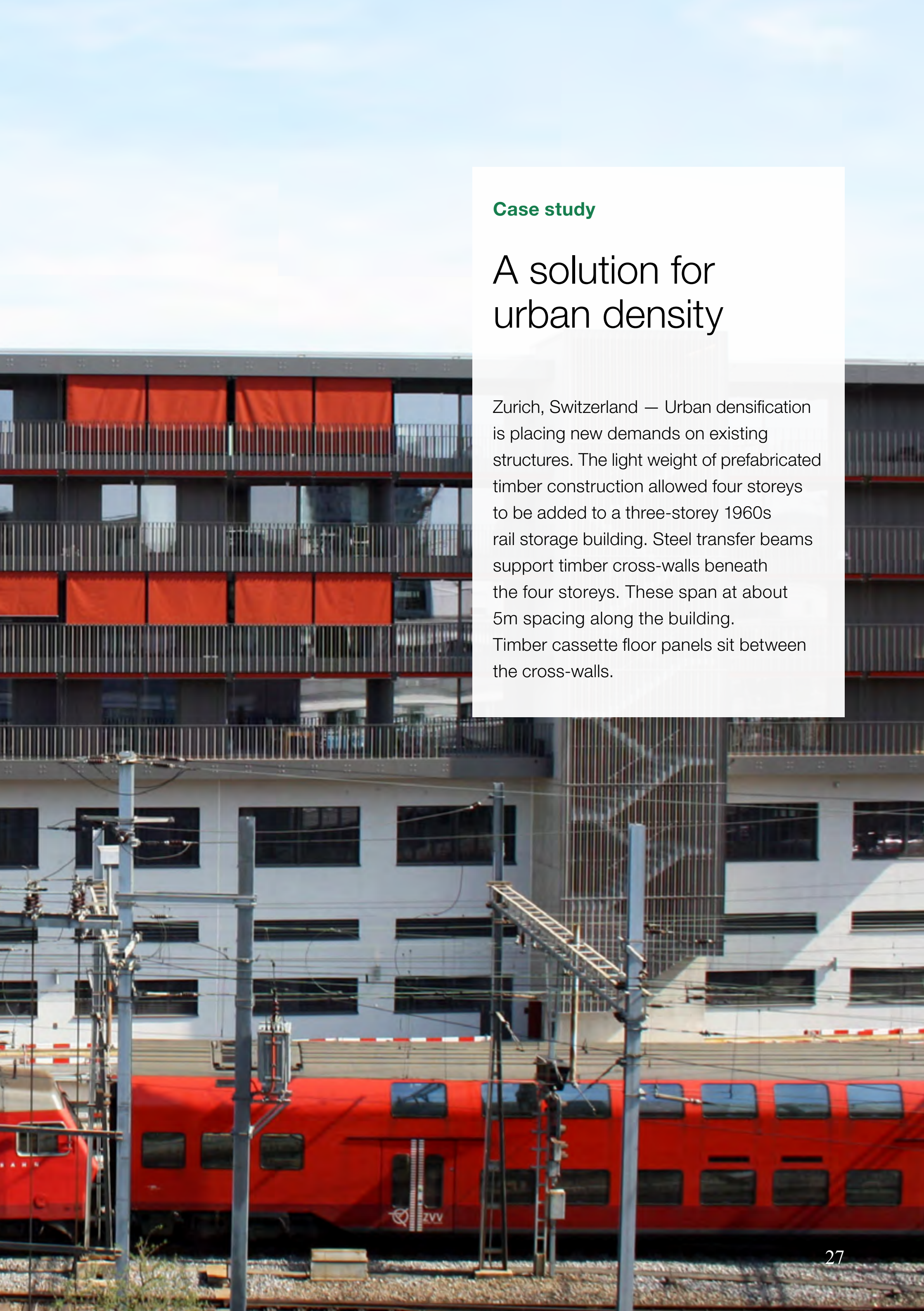
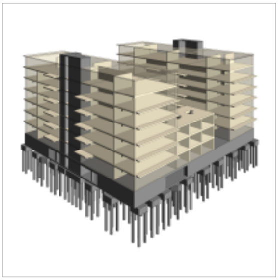


Case study

A solution for urban density

Zurich, Switzerland — Urban densification is placing new demands on existing structures. The light weight of prefabricated timber construction allowed four storeys to be added to a three-storey 1960s rail storage building. Steel transfer beams support timber cross-walls beneath the four storeys. These span at about 5m spacing along the building. Timber cassette floor panels sit between the cross-walls.



For the foundations to a proposed 500 residential unit development west of London, pile length — and thus pile capacity — will be limited to avoid penetrating underlying aquifer beds. If a CLT superstructure is adopted, the saving in foundation load will reduce pile numbers substantially, as well as allowing a shallower and cheaper transfer structure over the basement carpark.

equivalent. However, load bearing precast concrete walls are less common than concrete columns with lightweight infill walls, and the weight of finishes and cladding have to be added to both building types, as do loads from building plant and services, and live loads like occupants and furniture.

Overall, total design load for a typical timber building ends up around two thirds of the concrete building equivalent.[29] The lighter construction might represent the difference between maintaining tenancy of the existing building during extension works, versus vacating to allow access for internal column strengthening works if the added floors were of heavier construction. CLT floors can also be expected to achieve additional weight savings when compared with steel and concrete composite construction rather than all-concrete construction.

One of the main concerns regarding the use of timber in such cases, and more generally, is the need to ensure adequate attenuation of air-borne and impact noise through walls and floors, and to ensure that the lighter floors will have satisfactory vibration performance. While lateral wind load on the vertically extended building will be similar with timber or concrete extensions, lateral design loads for earthquakes are reduced with timber because of its lesser weight. As is required for any construction material, fire safety relies on the suitable provision of compartmentation, protection and escape. For example, increasing the height of an existing mid-rise building could trigger an increase in fire resistance of all elements (existing and new), or lead to fundamental changes in other aspects of the fire strategy, such as evacuation protocols, all of which would need

> *"The biggest issue shaping the future of our cities, and our nation, is the question of how we grow. Do we continue to try to sprawl our way to the American Dream, or do we add the density that powers innovation and economic growth?"*
>
> **—TRADA (2015) Case Study, Believe in Better Building, London**

to be reassessed to ensure the building in its new configuration and occupancy meets all safety requirements.

All the other advantages of prefabricated construction in timber, like speed and reduced disruption from noise, dust and traffic, are especially relevant for 'drop-top' applications on existing buildings.

Transport for London has shortlisted development partners to build 10,000 new living units on 50 sites across its property holdings.[31] Some sites will involve construction over tracks and tunnels, some over existing stations and depots. At Southwark station on the Jubilee Line shown above, 300 units were initially planned in air rights space above the station and on sites adjacent to the station.[32] Minimum disruption to station operations, including minimum strengthening works to the existing structure, will be an important aspect of construction planning.

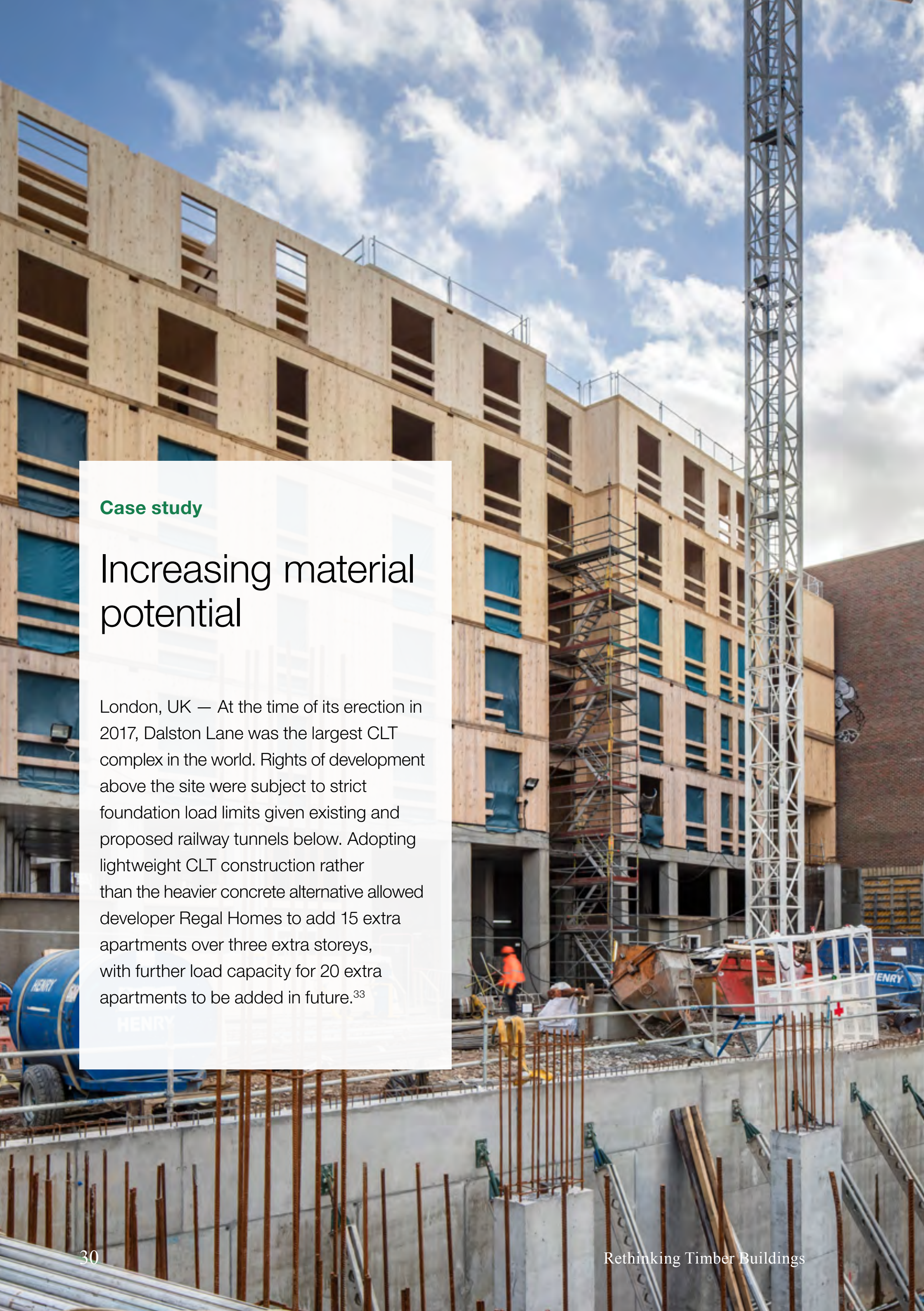
Air rights opportunities

City densification also includes construction in air rights space, particularly along rail and road corridors. The Hong Kong Mass Transit Railway Corporation is famous for its 'rail-property' development model for property value capture along transit corridors as a means of funding rail infrastructure. Such pre-planned overhead development ensures the process is integrated and non-disruptive, regardless of the construction material adopted.

For most cities however, the opportunity for air rights development on transport corridors is retrospective, so all the benefits of rapid lightweight prefabricated timber construction cited for 'drop-tops' are equally applicable. Also, timber's light weight can allow construction of transfer decks over stations, depots or tracks that are shallower, cheaper and constructed more quickly, with corresponding reductions in the size of vertical support structures and foundations that need fitting between tracks or on platforms. These are factors that can affect the feasibility of retro-fit air rights developments.

Opportunities on challenging sites

Pressure will grow to develop sites that have so far remained undeveloped because of the high cost of site preparation, related to issues such as poor ground bearing conditions, in-ground obstructions, or site contamination. Low-lying and swampy areas adjacent to coastal cities are good examples where deep piled foundations are often required, with a high unit cost.



Case study

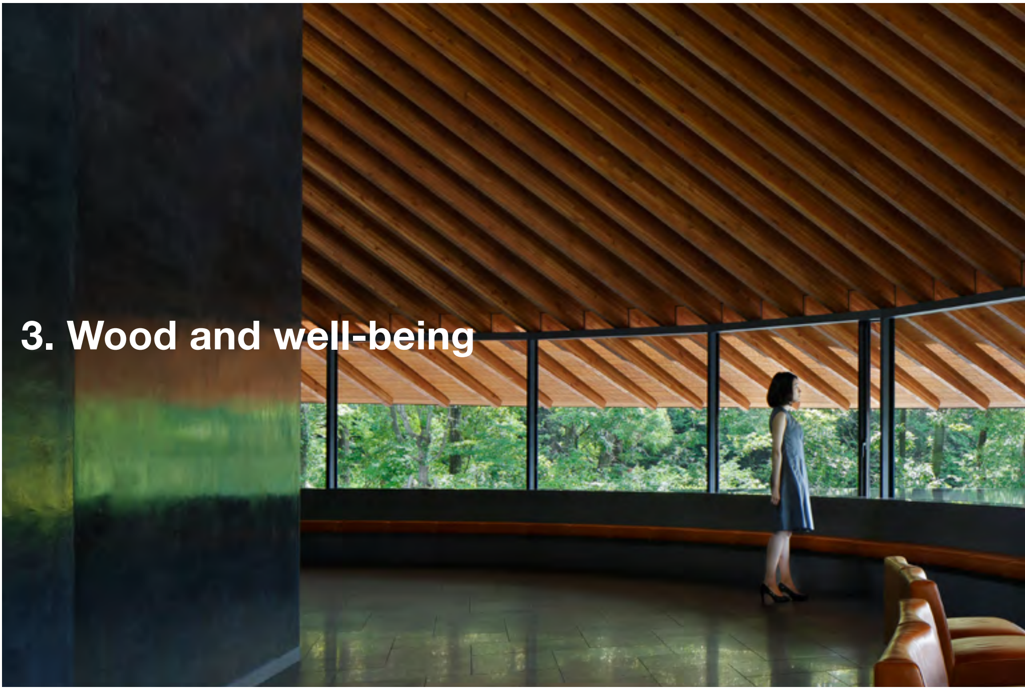
Increasing material potential

London, UK — At the time of its erection in 2017, Dalston Lane was the largest CLT complex in the world. Rights of development above the site were subject to strict foundation load limits given existing and proposed railway tunnels below. Adopting lightweight CLT construction rather than the heavier concrete alternative allowed developer Regal Homes to add 15 extra apartments over three extra storeys, with further load capacity for 20 extra apartments to be added in future.[33]

With potential savings in foundation design loads up to a third of the loads from equivalent heavyweight construction[30], timber can make development on these sites more commercially attractive. This is particularly true if the reduced loads allow use of a shallow raft foundation rather than deep piles that might otherwise be required. The case for a raft is strengthened when the site is first elevated with engineered fill, allowing further spreading of the load seen by the soft strata below. This opportunity often occurs with low-lying sites, where fill is used to address risk of flooding and sea-level rise.

Regarding highly seismic sites, the challenge is to build safely but economically. This is made easier with timber because of its light weight. The ‘seismic base shear’ to be resisted by a building is generally proportional to the building’s weight, so the lateral stability system can be designed for lower loads.

Carbon12 is an eight-storey residential tower with ground floor retail. Its height (26m) established new benchmarks for tall wood buildings in the US when completed in 2018. The building comprises a timber and CLT structure around a steel frame brace core. This approach has resulted in an extremely robust earthquake-resistant structure that meets the highest seismic design requirements.



3. Wood and well-being

At a glance

- The pressure to make our cities denser will be balanced by another pressure — to incorporate more urban woodland and green infrastructure.
- In internal spaces, access to natural materials like wood is related to decreased occupant stress and increased positive responses.
- Regarding VOCs (volatile organic compounds), more stringent criteria are leading to new formulations for wood glues, while research continues into biomass-based glues.
- Wood preservative processes that avoid toxic compounds now include acetylation, furfurylation and thermal treatments.
- Timber construction can provide insulation and air tightness benefits.

Neighbourhoods connected by the 7km Greenlink cycleway and parkland in Motherwell are among the most deprived in Scotland. Removed from the site during landscaping were 27 burnt-out cars, 91 tonnes of rubbish and 87 shopping trolleys. One study showed that the benefits of increased exercise, improved safety and upskilling in Greenlink-related projects, is delivering a social return of £7 for every £1 invested.[36]

Above left: Sayama Lakeside Cemetery Community Hall, Saitama, Japan. Architecture by Hiroshi Nakamura & NAP.

The need for more liveable cities

Trees in urban settings are well-known for their role in promoting biodiversity, cleaning air and water, and for reducing flooding, heat island effect, salinity, erosion and noise.[34] Less well-known is how access to nature, planting and trees contributes measurable benefits to social integration, local investment, economic activity, property appreciation, reduced crime, and improved physical and mental health, with attendant savings in social services. With New York's High Line, London's Olympic Park, Chattanooga's Urban Forestry Program or Stockholm's Hammarby Model, there are now countless examples of these less tangible benefits.[35]

At a time of substantial social inequality, these examples offer useful lessons in promoting social cohesion. One of the most striking examples concerns Chicago's Robert Taylor housing project, the largest public housing development in the world when completed in 1962. Of the 28 tower blocks, studies showed that those surrounded by trees and greenery were linked to 48% fewer property crimes and 56% fewer violent crimes

Research has shown that spending time in nature can help reduce stress and focus attention. Kaplan's attention restoration theory holds that viewing natural patterns, such as clouds moving across the sky or leaves rustling in a breeze, can induce a state of "involuntary attention" allowing our minds to relax.[41]

compared to identical blocks surrounded by barren land. The green spaces were found to bring people together outdoors thereby increasing surveillance and discouraging crime, while also reducing aggression and helping people relax. The city planted 20,000 more trees as a result of the study.

Much like indoor plants and green façades, timber itself represents a close link to trees and nature, whether used as cladding on the outside of a building, exposed as structure or finishes inside a building, or used for fittings, furniture or equipment. The well-being benefits of wood in our living and working environments have been demonstrated in numerous research studies.[37]

Buildings for better health

Building ratings schemes such as WELL and the Living Building Challenge reward building designs that promote occupants' physical, mental and emotional health, and realise the benefits of 'biophilic' environments (those connected with nature).[38] Not surprisingly, access to nature and natural materials like wood is found to be a key benefit. Research points to increased positive feelings and decreased stress, implying reduced risks from depression and impaired immune system functioning, and improved long-term health.[39] Just being able to see a tree through a window can be enough to improve hospital post-operative outcomes.

Theories vary on the source of our enjoyment of natural materials, whether from cultural conditioning, pre-historic evolutionary responses or biophilic preferences. Whatever the source, there is no doubt that we have a strong affinity for natural environments, and there has been much research aimed at quantifying the benefits of access.[40] Regarding reduction in stress levels, measurements have involved blood pressure, pulse rate, skin conductance, muscle tension, and electrical activity of the brain. Studies have considered visual, tactile, and olfactory responses to demonstrate the beneficial effects of wood.

Perhaps these tests just tell us what our intuition already knows to be true. Architects and interior designers are therefore encouraged to make holistic choices regarding indoor environmental quality, including choice of materials. Research that helps quantify our responses can provide useful insights however, just as research into our psychophysiological responses to natural ventilation and lighting have been useful in design for physical comfort.

A Canadian study measured responses of 119 subjects carrying out stress-inducing tasks in an office devoid of wood surfaces, and one featuring wood. Observations were based on measurement of pulse rate and skin conductance. The study concluded that wood provides stress-reducing effects similar to the effect of exposure to nature, well-studied in the field of environmental psychology.[43]

De-toxing timber components

Concern is sometimes raised about chemicals used in glueing of laminated or fibrous wood components, and in preservative treatments to improve the durability of timber.

Humans have historically relied on natural adhesives from plant, milk and animal sources. Modern chemistry gave us the formaldehyde family of glues, with some forms providing excellent strength, moisture resistance, durability properties and performance under higher temperatures. Over recent decades however, health concerns have progressively reduced acceptable levels of formaldehyde vapour in inhabited spaces from products such as glued wood panels.[42] These concerns are multiplied if the timber is involved in a fire, exposing occupants and fire fighters to toxic gases. Further fire-retardant treatments for woods, designed to slow the rate of fire spread across timber, also present a toxicity hazard. The impact of increased toxicity may exceed the benefits of reduced surface spread of flame, especially as the retardant is typically only of real benefit under small fire exposure.

Some fabricators have responded by switching to polyurethane glue, another petrochemical product. Others have chosen to adjust the formaldehyde chemistry and institute testing against a new stringent vapour criteria. This approach is consistent with the low glue-to-wood ratio typical of the glulam beams and columns, and CLT slabs used in modern timber buildings, compared with the higher glue volume ratios in wood products like particleboard and fibreboard.


WOOD
CUBE

Case study

Woodcube, all wood construction

Hamburg, Germany — The ‘Woodcube’ apartment building in Hamburg showcases the idea of ‘all wood’ construction, including both structure and external cladding. Timber layers in the laminated floor and wall panels are connected by beech dowels rather than more conventional glueing, using the Thoma Holz100 panel system. Insulation is wood fibre-based, the use of glues, foils, and plasterboard encapsulation has been avoided, and wood surface coatings have been minimised. The cladding is untreated larch.

Timber board products using soya-based glue by Columbia Forest Products, top, and applied as ceiling panels at Sacramento Airport, bottom. Modifications to the soy protein glue base were modelled on marine proteins found in blue mussels, to improve adhesion strength and durability.

Looking to the future, there is much new research ongoing into traditional glues based on biomass products such as tannin, lignin, cellulose, starch, plant proteins, and extraction, liquefaction and thermolysis products of forest and agriculture wastes. Soya bean protein is proving popular, especially for non-structural uses of particleboard, fibreboard and plywood.[44] For structural products such as glulam and CLT, more work will be needed on these naturally sourced glues to determine moisture response, durability, strength, creep and performance in fire before we can expect greater availability.[45]

Meanwhile there is another movement, toward laminated timber products that use wood or steel connectors rather than glue. Connectors include hardwood screws and dowels, interlocking edge joints, and nails.[46] These cannot match the strength of glues but can produce products which are useful for less demanding applications.

Developers, insurers and funding agents — among others — have a close interest in the durability of construction materials. In the case of modern multi-storey timber buildings, they have been happy to accept that preservative treatment is typically not needed where the timber is fully interior. Protected from water it is immune to fungal attack, and in most temperate geographies it is not at significant risk of insect attack.

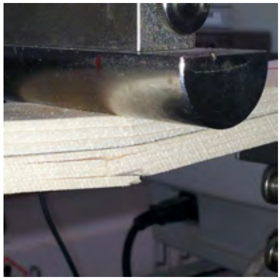
Wood used externally is more vulnerable. Preservative treatments to prevent fungal or insect attack vary depending on environment, species choice, maintenance regime, and lifetime expectation. Impregnation with man-made biocides is common, often involving heavy metals like copper, chromium, tin, zinc or metalloids like boron or arsenic. Concern about health effects has led to research into alternatives that do not rely on these chemicals, and some methods have now been commercialised.

Frontrunners among the more benign preservative methods involve 'wood modification', where the chemistry of the wood cell wall components (cellulose, hemicellulose, lignin) is changed to make the wood less susceptible to fungal and insect attack. Popular methods include acetylation (which uses an acetic acid derivative to modify hydroxyl groups so making the wood indigestible to predators), impregnation then polymerisation using furfuryl alcohol, and thermal treatment at 180–230 °C.[47]

Trees have their own defences against biological attack, including production of biocides like tannin. Tests have shown that natural tannin extract also provides ongoing protection when introduced into wood specimens, especially when fixed against leaching loss with small amounts of inorganic additives.[48]

Regarding paints and clear coatings, R&D continues into formulations that generate low or zero volatile organic compounds, with many products now commercialised.

With regard to fire safety, both internal and external timber components may need treatment to achieve "reaction to fire" requirements (these control flame spread behaviour and contribution to fire growth). Where restrictions exist, timber typically requires impregnation or coatings to achieve the necessary standard.



The glue in this laminated beam is natural lignin, combined with a synthetic resin and hardener. Strength test results were promising, matching those of the control sample which used phenol formaldehyde glue. This EC-supported R&D project was carried out by Chimar Hellas SA, a resin technology company based in Thessaloniki, Greece.[49]

Case study

Cross-laminated timber in Europe

Trondheim, Norway — this softwood façade was pre-treated with a non-toxic process, where furfuryl alcohol, a by-product of corn and sugarcane, acts to polymerise the wood cell walls and provide greatly enhanced durability. The building is part of the Moholt student housing village in Trondheim, Norway, one of Europe's largest CLT projects.[50]

The connection between timber and comfort

Construction materials can affect the thermal comfort of building occupants through their thermal mass, and their hygroscopic (moisture absorbing) properties. They also contribute to insulation and air tightness.

Heavier materials such as concrete and masonry have more thermal mass than timber. This means they are better able to attenuate high or low peaks in external temperature, thereby helping to keep internal conditions more constant. However, in order to maximise this benefit the masonry or concrete must remain exposed to the occupied space and the daily external temperature range must be sufficiently extreme. Likewise, realising the benefits relies on discontinuous occupancy (day or night), security and ambient noise environments that allow the building to be opened up for night-time air flushing, and occupants willing to operate such a programme.

Timber exposed internally still offers a degree of mass that is useful in many situations, and it can be supplemented if required. Conversely, there are cases where low thermal mass is an advantage, such as for the rapid heating or cooling of spaces that are not in continuous occupation.

An 80-year design life was specified for this timber roadbridge designed by OAK Architects in Sneek, Netherlands. Prior to glue-laminating the radiata pine boards into curved truss elements, they were treated with a non-toxic acetylation process to provide high resistance to fungal and insect attack.[51]

> *"Individuals living in 'greener' buildings reported more social activities, more visitors, knew more of their neighbours and had stronger feelings of belonging."*
>
> **—TRADA (2015) Case Study, Believe in Better Building, London**

4. The future is prefabricated

At a glance

- Despite its slow adoption, prefabrication continues to promise transformative benefits for the construction industry.
- Easily machinable, timber has an excellent fit with the CNC-based factory processes underlying prefabrication.
- Timber's ease of splicing and lamination have given rise to a vast array of prefabricated timber products.
- Timber's light weight and ease of assembly also invite modular volumetric prefabrication.
- Speed of construction in timber can translate into cost benefits to offset its typically higher capital cost.
- Other benefits that follow from all-dry prefabricated timber construction include quieter, safer and less disruptive sites with fewer trucked deliveries.

Singapore's Building Control Authority (BCA) is seeking to improve productivity and build capability in the construction industry, including supporting the adoption of prefabrication. CLT and glulam, used for JTC launchpad, an industrial facility in Queenstown, Singapore, are singled out by BCA as exemplars of prefabrication technologies to be encouraged. Companies can receive funding up to 70% of the cost of adopting mass timber under the Productivity Innovation Project (PIP) scheme.

Above left: MultiPly, Sackler Courtyard, V&A, London, UK.

Uptake of prefabricated buildings

Prefabricated buildings are made up of component parts manufactured in remote factories, transported to site, and assembled into whole buildings. Studies into ways of improving productivity and quality in the building industry typically recommend increasing the portion that is prefabricated.[52] The benefits are clear: faster construction times, better quality products, less waste and lower unit cost. Other benefits include less noise, dust and site disruption, improved health and safety, continuity of employment, workforce upskilling, predictable product performance, and lower product operational costs.[53]

Yet progress toward this appealing future has been frustratingly slow, a fact underlined by the UK Construction Leadership Council report Modernise or Die.[54] It speculates that the biggest barrier to more off-site working is linking new factory investment to continuity of demand in an industry now serving a largely 'for sale' housing model based on individual home ownership, and therefore vulnerable to

Case study

Automation in timber construction

Zurich, Switzerland — University-based research institutes worldwide are collaborating with robotics manufacturers, construction companies and timber suppliers to develop next-generation prefabrication and assembly technologies. This track-mounted industrial robot by ABB uses spatially-aware software to re-position itself while fabricating a modular timber wall for researchers at ETH Zurich. The robot responds to a mixture of construction tolerances arising from both human and robot-made components.[55]

boom and bust cycles. A social housing programme that compensates with demand in lean times could break the status quo, but not all governments are keen to provide this facility. Countries making the transition to off-site include Sweden (84% prefabricated), Netherlands (20%), Japan (15%)[56], with Singapore eager to catch up.[57] Each of these countries currently has or formerly had supportive government policy.

The role of timber in prefabrication

Visionary pathways to a prefabricated future include flying factories, on-site factories, and factories-in-a-box.[58]
In the short-term we are more likely to see an evolution of existing methods, like flat pack, transportable volumetric or a combination of the two. These methods have been applied successfully in precast concrete, steel framing and lightweight timber framing.

The benefits of prefabrication in mass timber are many. These include greater accuracy of machined components, (i.e. compared to pre-cast concrete panels, no requirement for extra structural framing of solid panel options, and higher dimensional stability than traditional timber frame systems from products with crossed-grain lamination). Further, the use of timber offers easier factory handling, transportation and on-site erection due to its light weight, and wood machining processes that are ideally suited to BIM and CNC (with potential technology transfer to industry from timber-based robotics research centres). It also supports easier jointing and fixing, both for the sub-assembly itself and for services, fitout and finishes applied to the sub-assembly.

Several of these factors have also supported the growth in passive house design. Prefabricated timber frame closed panel systems are particularly effective here, as it is easier to achieve the required airtightness and low U-values (heat loss) building off site and with timber.[59]

The 'Lignatur' laminated cassette floor component system offers choice of perforated soffits to moderate room acoustics, choice of flange thickness for fire resistance level, and choice of additional in-cell mass for inter-floor noise transmission level, as well as footfall vibration performance.

Towards a shared component warehouse

Inventive designers have created a wide range of patented timber components for prefabricated buildings.[60] With the growth of BIM, robotics, CNC and mass customisation, this range will expand further. Some components can also be combined to make larger sub-assemblies, such as I-beam joists making up cassette floor panels. Some combine directly on-site, for example CLT panels for walls, floors and roofs.

For developers, selecting timber components to use at scale is a challenge in a market where international standards are not yet established. National and international industry associations and code committees have a role to play in establishing standards, as was the case for the steel and concrete industries. As the market matures, the most widely used, effective and versatile timber components will gain market share and economies of scale will lead to standardisation and lower unit prices. What looks promising for timber is that rewards from optimisation and standardisation are still largely to come, given multi-storey mass timber is still relatively new.

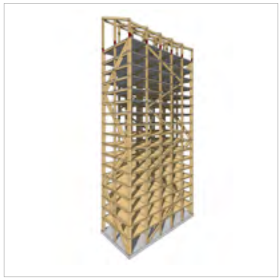
Suppliers may initially resist standardisation so they can exploit any marginal advantage attached to local forest products. Their real opportunity however lies in devising unique lamination layups and material combinations that exploit any such local material advantage, while embracing standard product performance criteria shared by other manufacturers making similar products.[61] Once suppliers accept this strategy, everyone wins with economy of scale and greater simplicity for specifiers, just as happened with structural steel.

Whole-building systems

To provide the required volume of construction at the right quality and price point, prefabrication will need to go beyond components and deliver whole-building systems. This is starting to happen, with panelised timber systems already found in single houses, apartment buildings, hotels, student accommodation and offices. The North American preference for drywall partitions leads to residential solutions based on open structures with glulam beam and column frames and CLT floors and shear walls.[62] Conversely, Europe, Australia and New Zealand tend to favour load-bearing CLT walls throughout for residential construction.

Glulam beam and column frames supporting CLT floors are proving popular as a solution for commercial and campus buildings in many countries. Beam-less floors with solid panels bearing directly on columns are also beginning to appear, analogous to flat plate floors in reinforced concrete. Stability structures for these open-plan building types rarely conform to a repeatable system however. Concrete walls for escape and firefighting stair shafts are still the rule in some countries, while CLT cores predominate in others. Stability using cross-braced perimeter bays will be an increasingly attractive option for taller open plan buildings, as it maximises lateral stiffness while allowing panelised core walls to use simpler joinery for faster erection.[63] Some systems claim enough versatility to address both cellular residential construction and open-plan office construction.[64]

The economics of whole-building systems turns on output volume, just as it does for components. One future scenario described in a recent construction industry report envisages an industry-wide DfMA (design for manufacture and assembly) protocol that enables a common platform to be created that supports the interchangeability of components.[65]



Cross-braced perimeter bays provide stability and lateral stiffness for this 18-storey mixed-use timber-framed building in Brumunddal, Norway, allowing simpler assembly of the prefabricated CLT core.[66]

Competitive tendering for government start-up funding could help establish the favoured platform or system, or a small number of them. A supply chain would then emerge making components to service the selected systems. Developers with a large turnover and short timescales would be reassured about capacity. The supply chain would feed a volume market, inviting investment in enhanced performance and further cost reduction. Barriers to entry would be lowered because of reduced investment risk.

The impact of timber on construction time and costs

In a direct cost comparison, concrete still has the advantage over timber in most construction markets. There can be many reasons for choosing timber however, and speed of construction is one that can shift the cost balance. It is not hard to show how reduced site costs due to shorter construction programmes can demonstrate timber's value, assuming there has been sufficient upskilling in the local mass timber construction market to deliver the shorter programmes.[67]

How can we be sure that dry construction in prefabricated timber will be faster than in-situ concrete or steel-concrete composite construction when we never witness the same building built in both materials? The available evidence of short floor cycles from real timber projects is persuasive and time and motion studies are now emerging from real sites that will add more rigour to theoretical programme comparisons.[68]

Timber's construction speed follows mostly from its light weight which allows larger and fewer lifts (assuming minimal crane down-time due to high winds), dry jointing of components on site (if wet grouting and curing procedures are avoided), fewer and stronger joints (if time-consuming screw installation is kept off the critical path) and precise sequential packing and delivery of components to meet the optimal erection programme (if adequate lead time is allowed for their prefabrication).

> “*There is now a shift towards prefabrication through political pressure to construct affordable quality homes and by major problems inherent within the construction industry.*”
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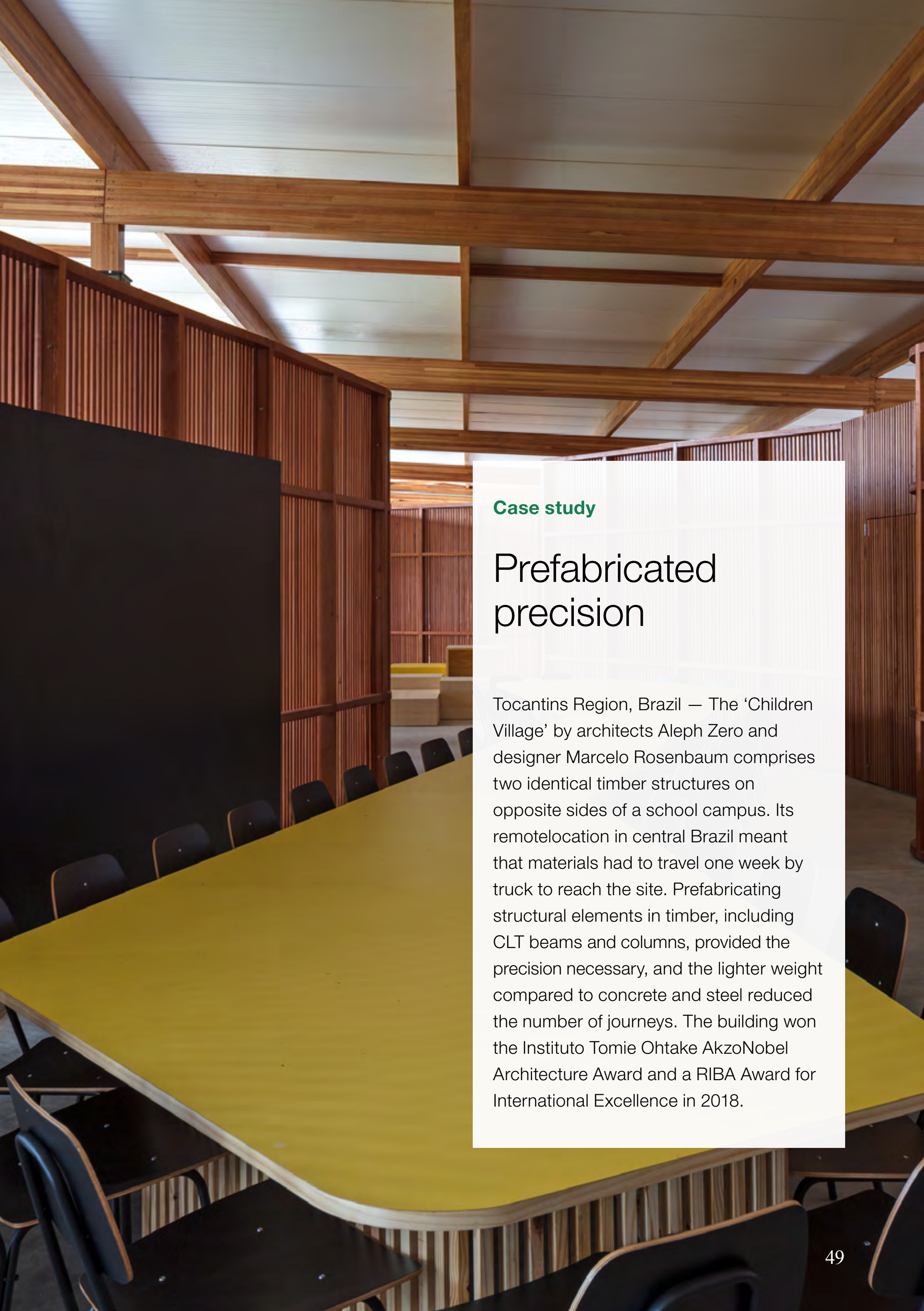
> **—HSE (2015) Offsite Production in the UK Construction Industry**



Case study

Prefabricated precision

Tocantins Region, Brazil — The 'Children Village' by architects Aleph Zero and designer Marcelo Rosenbaum comprises two identical timber structures on opposite sides of a school campus. Its remotelocation in central Brazil meant that materials had to travel one week by truck to reach the site. Prefabricating structural elements in timber, including CLT beams and columns, provided the precision necessary, and the lighter weight compared to concrete and steel reduced the number of journeys. The building won the Instituto Tomie Ohtake AkzoNobel Architecture Award and a RIBA Award for International Excellence in 2018.

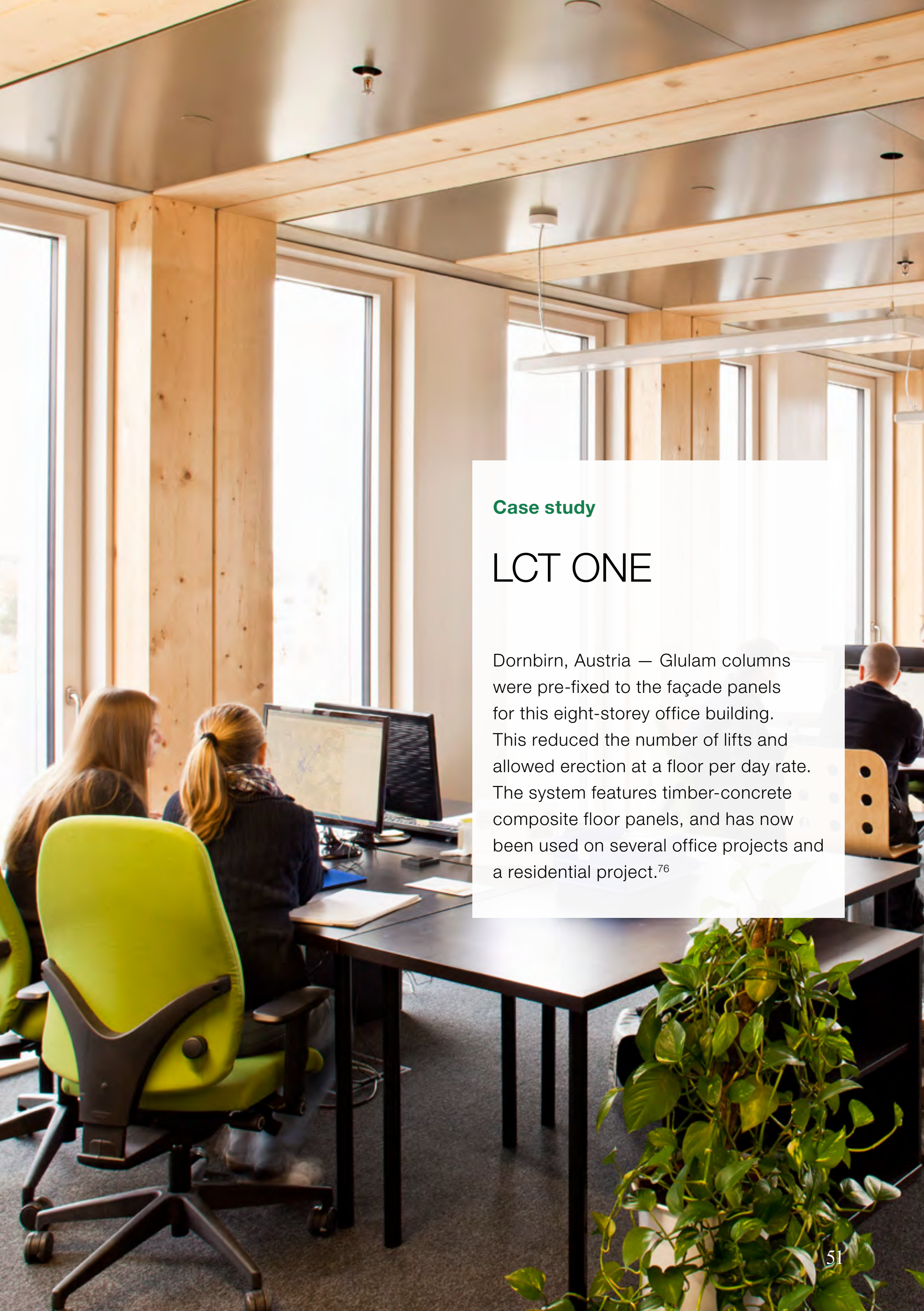
The commercial value of faster construction will vary considerably between projects. It will at least include savings from reduced cost of preliminaries[69] and reduced costs of project financing. Where an earlier income stream from earlier building occupancy is also available, the benefit of faster construction can be considerable. In higher-end rental property markets, it can easily eclipse any capital cost premium attaching to timber. We can expect this premium to reduce as more contractors gear up, as more prefabrication factories come on line, and as confidence grows in delivering the shorter programme times.

Stacked volumetric timber modules fit inside a mega-frame of prefabricated glulam trusses for this 14-storey apartment block in Bergen, Norway. The team cited a two-month shorter construction programme compared to conventional on-site methods.[75]

Implications for noise, speed and safety

As residential densities in downtown areas increase, statutory constraints on traffic disruption and construction noise and dust will become more stringent.[70] This trend will accelerate the move from on-site to off-site working. Studies have shown emissions from vehicle movements servicing prefabricated building sites reduced by up to 60%[71], and significant reductions in noise and dust pollution. These benefits apply particularly to prefabricated timber construction because of the few simple, quiet, dust-free processes needed for assembly[72], and the ease and speed of handling a smaller number of large lightweight panels.

Most governments maintain pressure on their construction industries to improve site safety, which still lags well behind the safety of factory working.[73] The UK HSE (Health and Safety Executive) cites many opportunities for off-site working to reduce risk. They include potential reduced risks from proximity to heavy plant, also from noise exposure, dust inhalation, cuts and abrasions from manual handling, working at height, trips and falls and UV exposure.[74] Potential benefits accrue with the reduced time and reduced number of personnel needed on prefabricated building sites. Also, lighter erection loads lead to reduced craneage, often allowing un-manned cranes or truck-mounted mobiles.



Case study

LCT ONE

Dornbirn, Austria — Glulam columns were pre-fixed to the façade panels for this eight-storey office building. This reduced the number of lifts and allowed erection at a floor per day rate. The system features timber-concrete composite floor panels, and has now been used on several office projects and a residential project.[76]

The construction phase of timber buildings poses an increased fire hazard. This needs to be addressed for the duration of the construction phase considering that the risk posed will change as construction progresses. Guidance exists relating to fire safety of timber during construction, such as the Structural Timber Association guide to Fire Safety During Construction. During this phase, timber will be stored before installation and is likely to be exposed (not yet encapsulated by fire resisting construction) and therefore at risk of ignition in spaces where fire detection and fire-fighting systems are not yet operational. As an example, the Brock Commons project in Canada agreed a limit of three storeys of unprotected timber, proceeding ahead of encapsulation. Owners, developers and contractors need to be proactive in managing this specific risk for the health and safety of all involved and engage early with their insurers.

Safe site: truck-based craneage, pre-fitted edge barriers, a small site crew of eight installers, and a short on-site construction programme all contributed to site safety for the 9,000m^2 Norwich Open Academy.

Right: Two floors per week was the average erection rate for this 18-storey student housing block in Vancouver. Installing the light glulam columns by hand freed the crane for lifting the cross-laminated timber floor panels. There are no beams — floor panels rest directly on the columns 'flat slab' style, also saving time and money.[77]

5. Sustainable sourcing

At a glance

- Depending on the approach, logging of forests, whether native or plantation, can have major detrimental eco-system impacts.

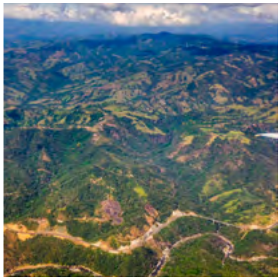
- On the other hand, given the right level of harvesting and agreement on substitution assumptions, managed forests could deliver a higher long-term CO_2 mitigation benefit than equivalent conservation forests.

- Agreeing a definition for sustainable harvesting practice, and implementing it, are therefore important for maximising CO_2 mitigation, as well as for eco-system protection.

- Deforestation in tropical regions remains significant and problematic, despite improvements in some countries.

- Forest-based communities in both developed and less-developed countries stand to benefit from the creation of traceable timber supply chains based on sustainable practices.

- Forestry investment is long-wave. Current stock under sustainable management is sufficient to support a build-up in timber construction.



Deforestation reached its peak in Costa Rica in the 1980s and has since reversed thanks to legal controls on land-use change and stable funding through a PES (payment for ecosystem services) scheme. Priorities for PES funding include forest and watershed protection, conservation, agroforestry and reforestation with native species.[83]

Above left: Nishi Hotel, Canberra, Australia. Architecture by March Studio.

Reliability of supply

The ECE countries (which include those in Europe, North America and Central and Western Asia) produce most of the world's sustainably sourced roundwood, and have seen demand drop 16% since 2000 thanks to a slow recovery in housing construction after the financial crisis, the more recent economic slowdown in China (the world's biggest importer of roundwood), and the ongoing downturn in pulp production for paper products.[78] In the same period, ECE harvesting has been below the net annual increase of forest stock, and forest area has increased.[79] For now, this all points to spare capacity and a downward pressure on prices, favourable conditions for reliable supply and a resurgence in timber construction. Beyond that, there are still temperate regions where yield from native forests could safely be increased, subject to sustainable harvesting practices.[80, 81, 82]

What is sustainable forest harvesting?

Forestry can be controversial, with conservation policies and production policies often presented in stark contrast by opposing supporters. Foresters refer to the 'abattoir syndrome': enjoying wood products but preferring not to see a tree cut down. Humans have affected the natural environment since Neolithic times when our move from hunting to farming resulted in a loss of about a third of global forest cover.[84] More recently we have had a measurable impact on the atmosphere and the oceans. Now well into the 'Anthropocene age'[85], we have become de facto caretakers of our environment, including our forests. UN SDG 15 (concerned with the sustainable use of the planet's ecosystems) recognises this impact and — as well as afforestation and reforestation — it calls for the sustainable management of all types of forests.

If we are to be guided by the views of the Intergovernmental Panel on Climate Change (IPCC) on the value of managing forests for sustainable yield[86], we need a way of setting that yield. Sustainable forestry certification schemes like the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) set out to do just that. Their express aim is to balance environmental, social and economic benefits in forest management, and they provide a framework for stakeholders to agree what the 'sustainable' balance should be.

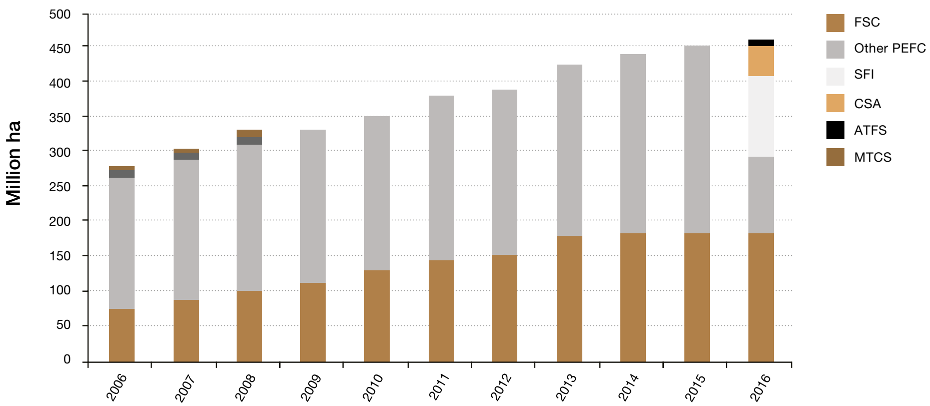
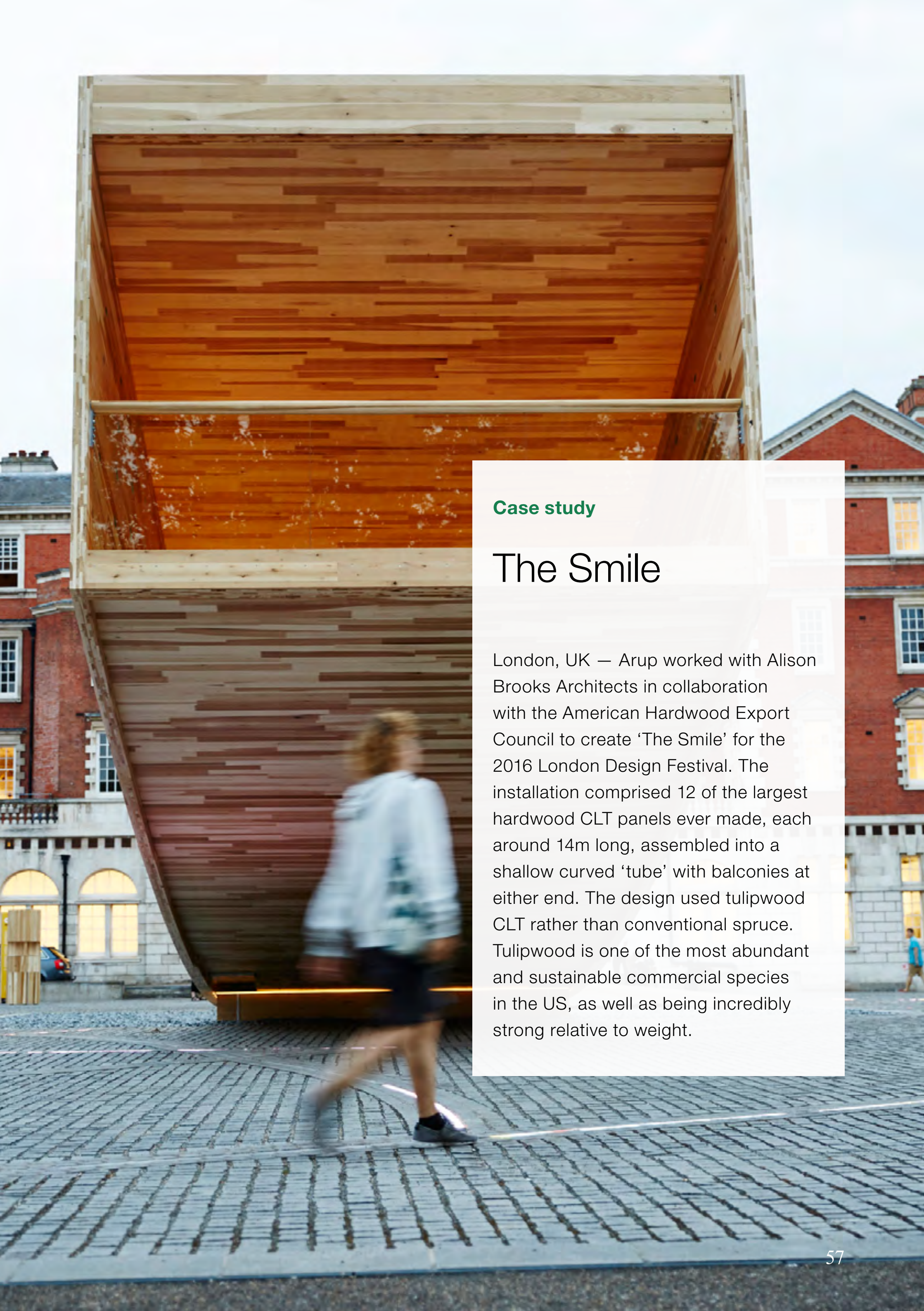


Figure 4 Cumulative forest area managed under the major sustainability certification schemes.[87] In 2016 the proportion of worldwide roundwood production from certified forests was estimated at 29%.[88] Forest area covered by these schemes has increased over 30-fold since 2000.[89] (UNECE / FAO, 2016)



Case study

The Smile

London, UK — Arup worked with Alison Brooks Architects in collaboration with the American Hardwood Export Council to create 'The Smile' for the 2016 London Design Festival. The installation comprised 12 of the largest hardwood CLT panels ever made, each around 14m long, assembled into a shallow curved 'tube' with balconies at either end. The design used tulipwood CLT rather than conventional spruce. Tulipwood is one of the most abundant and sustainable commercial species in the US, as well as being incredibly strong relative to weight.

These programmes also address the many ecosystem services forests give us beyond carbon benefits, for example healthy soil and water, biodiversity habitat protection, and limits on chemical fertilizers. In addition, some seek to address indigenous people's rights, fair labour and traceability, to differing degrees.

Plantations currently supply about a third of total global industrial roundwood demand.[90] There is a growing body of research into the dangers of mono-cultures and the benefits of species diversity and longer rotations including the potential for increased growth rates and fire resilience, which should also encourage more sustainable management practices.[91]

In terms of forest management, there is more carbon benefit from harvesting to maximise yield instead of harvesting to maximise profit. Policies should reflect this. In the meantime, sourcing from forests that are managed for multiple objectives (watershed protection, non-timber products, recreation etc) rewards landowners that tend to retain higher carbon stores in their forests. In most regions, FSC is the best indicator of management that maximises carbon stores. While we still need to improve how the FSC premium makes its way back to the land owner, greater demand for FSC in general shows carbon-optimised forest management has value.

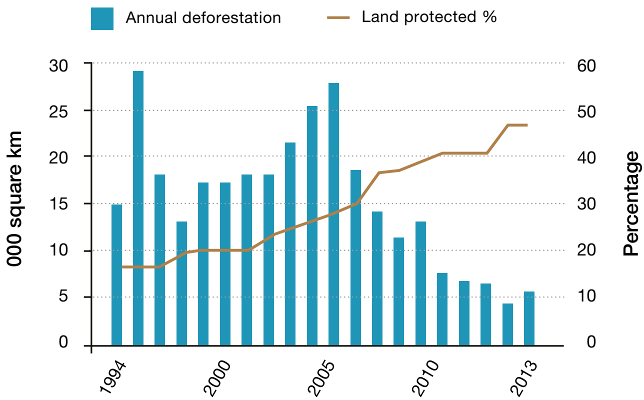


Figure 5 Since its peak in 2004, the annual rate of deforestation in Brazil's Amazon basin has dropped by 70%. Contributing factors include government policy and enforcement, rewards as well as punishment, external subsidy incentives, pressure from NGO's, and favourable responses from the soya and beef industries.[92] (INPE / PRODES, 2014)

Deforestation

If sustainable forest management fails, deforestation can follow. Can deforestation be managed and how might the rise of timber construction impact these efforts? Deforestation remains a significant issue at 7 million ha pa. This occurs almost entirely in the tropics, and is mostly related to agricultural expansion, with large-scale commercial agriculture most prevalent.[93]

Funding programmes such as UN REDD, the Norwegian Climate and Forest Initiative, the Amazon Fund and the Billion Tree Campaign have had some effect, and the 2016 UN Food and Agriculture Organisation (FAO) report highlights a reversal of the trends in Chile, Costa Rica, the Gambia, Georgia, Ghana, Tunisia, Vietnam and Brazil. To leverage Brazil's success, in 2011 the World Bank's Forest Carbon Partnership Facility developed a knowledge sharing initiative between Brazil and six African countries.[94]

Will the timber building industry have a favourable or unfavourable impact on deforestation? Ensuring timber production is sourced from sustainably managed forests is critical, however these practices are usually only found in wealthier countries. Legislation to control

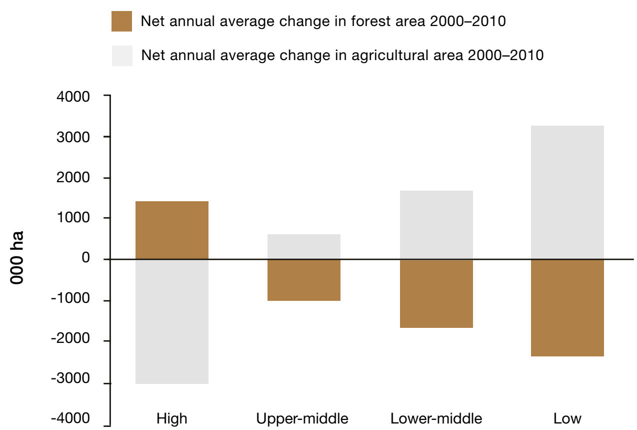


Figure 6 Net annual average change in agricultural and forest area in countries grouped by income category, 2000–2010. (FAO, 2016)

In Than Hoa province Payment for Forest Ecosystem Service (PFES) help fund projects such as fences that prevent cattle from damaging forest areas. The programme is co-funded by the US Government, and other schemes include ecoystems services and upstream forest catchment enhancement paid for by hydropower users.[98]

importation of timber has been introduced in the US, Australia and the EU, and criminal convictions apply.[95] If the price is right, another incentive for controlling deforestation will come from the trading of forest carbon stock initiatives, which FAO expects to be available under the COP21 Paris Agreement to help countries meet their declared emissions targets.[96]

In poorer countries the UNEP Sustainable Buildings and Climate Initiative (SBCI) reports that "the demand for shelter is so pressing that it can only be met by 'informal' housing — often self-built, usually illegal."[97] A lot of informal housing is constructed from timber, often from sources that contribute to deforestation. SBCI aims to assist but relies on broader poverty alleviation programmes. There is no shortage of international programmes which wealthier countries can support to help turn deforestation around. Trade agreements also need to encourage rather than inhibit poorer countries as they improve their own forestry practices.

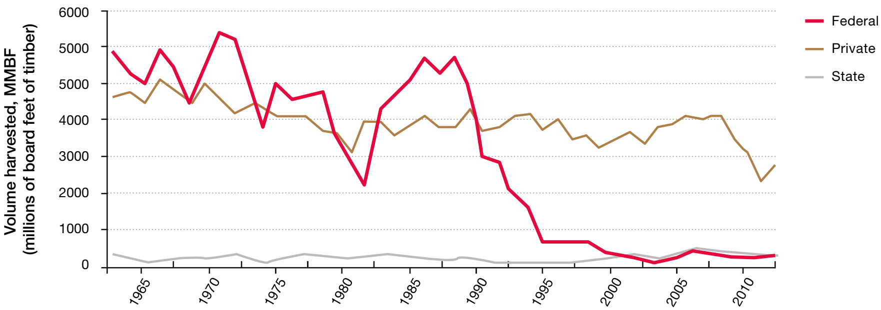
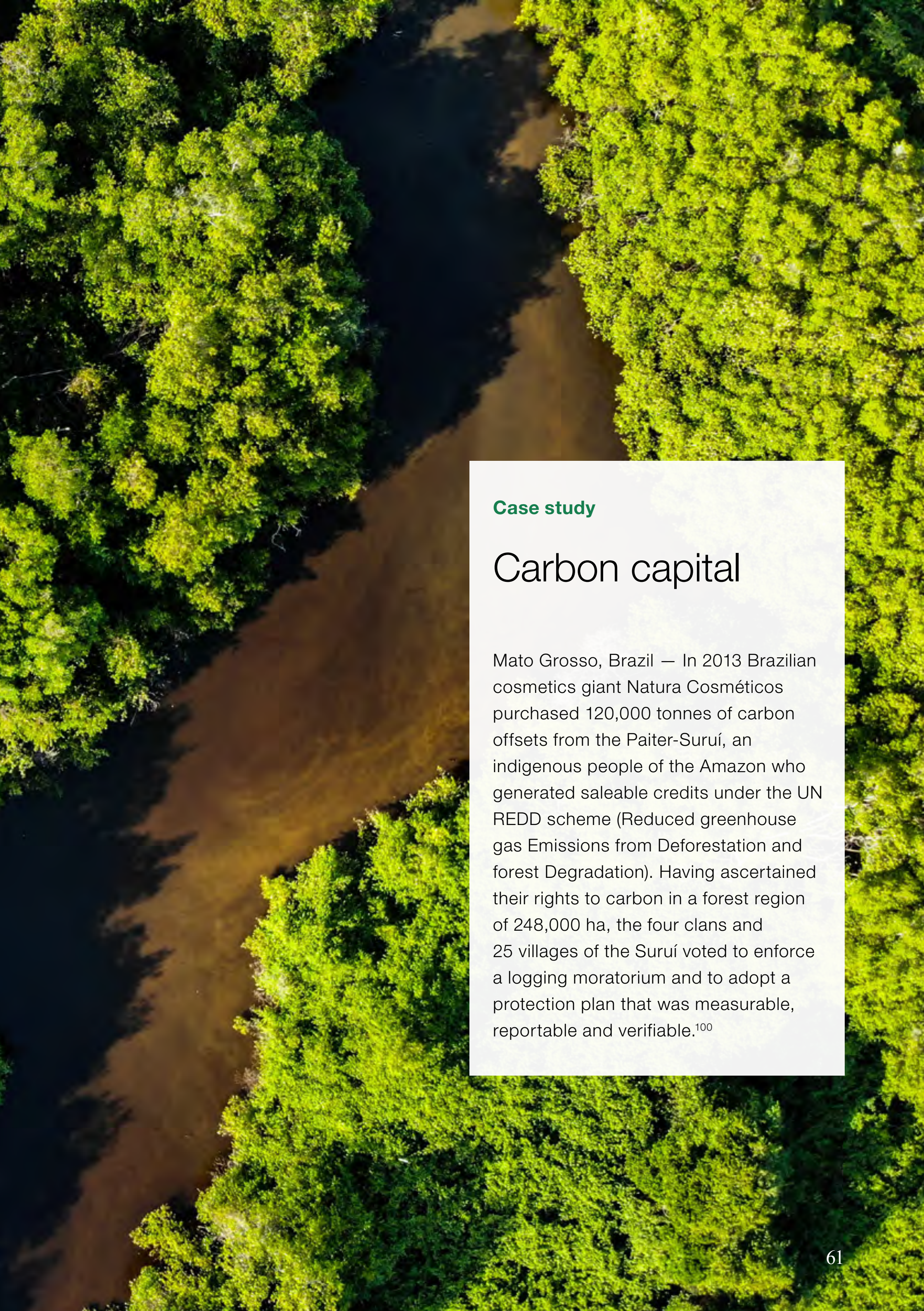


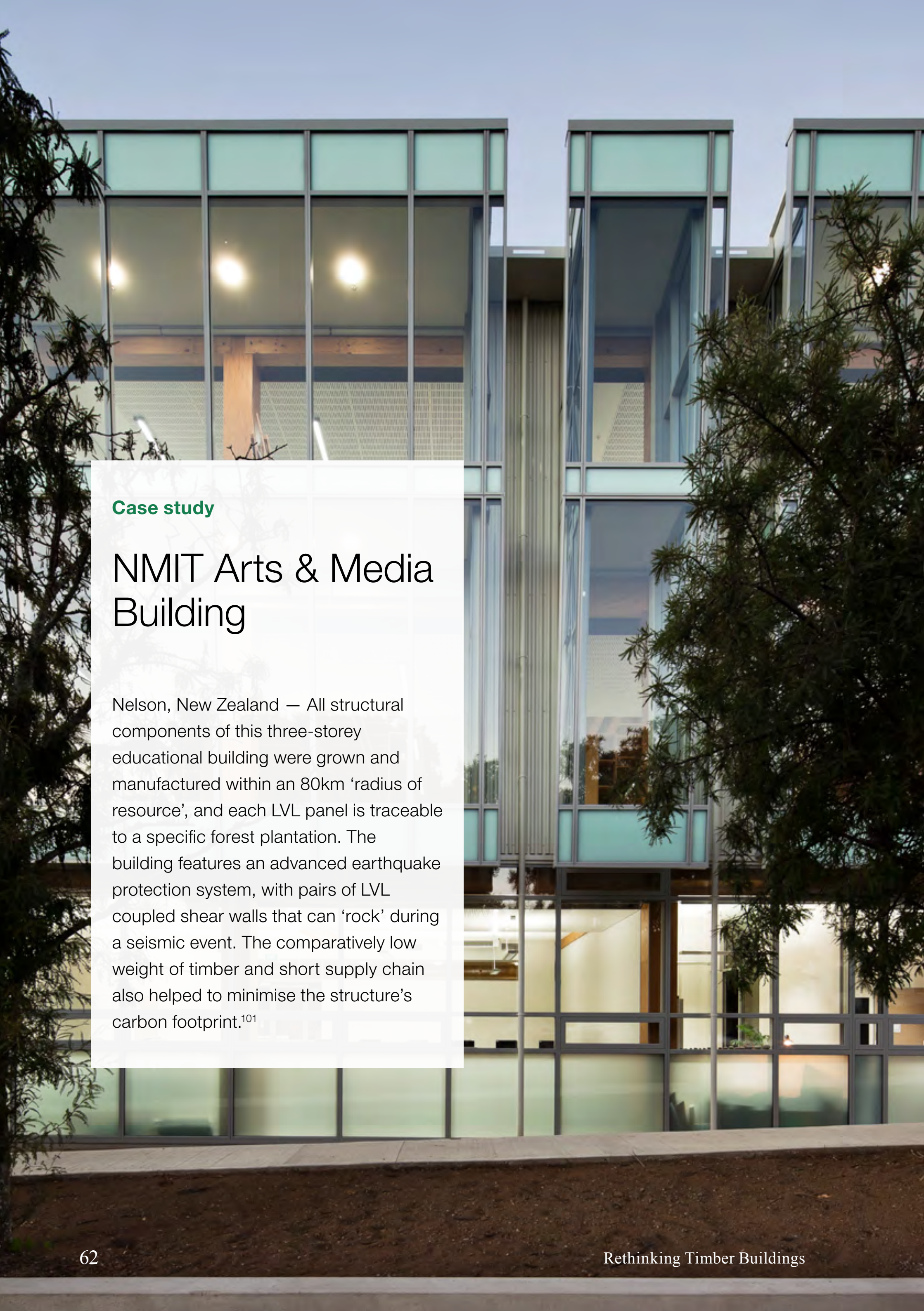
Figure 7 Pacific North West moved to emphasise habitat protection through the US Federal forest mangement policy in the 1990s. As a result, harvesting fell by 90% in Oregon's Federal forests.[99] (Oregon Department of Forestry retrieved 2017)



Case study

Carbon capital

Mato Grosso, Brazil — In 2013 Brazilian cosmetics giant Natura Cosméticos purchased 120,000 tonnes of carbon offsets from the Paiter-Suruí, an indigenous people of the Amazon who generated saleable credits under the UN REDD scheme (Reduced greenhouse gas Emissions from Deforestation and forest Degradation). Having ascertained their rights to carbon in a forest region of 248,000 ha, the four clans and 25 villages of the Suruí voted to enforce a logging moratorium and to adopt a protection plan that was measurable, reportable and verifiable.[100]



Case study

NMIT Arts & Media Building

Nelson, New Zealand — All structural components of this three-storey educational building were grown and manufactured within an 80km 'radius of resource', and each LVL panel is traceable to a specific forest plantation. The building features an advanced earthquake protection system, with pairs of LVL coupled shear walls that can 'rock' during a seismic event. The comparatively low weight of timber and short supply chain also helped to minimise the structure's carbon footprint.[101]

Forest-based communities

Around 1.6 billion people rely heavily on forest resources for their livelihood, including 60 million indigenous people living in tropical rainforests.[102] In less wealthy countries, community forestry is characterised by limited capital access and low labour costs, which are consistent with harvesting by single tree selection. Start-up sawmills can add value to sustainably harvested product for local or export timber markets.

It is not just in less developed countries that rural communities need help securing their futures if they are to carry out a forest stewardship role. In the US, the shift of manufacturing to Asia, the global financial crisis, and forestry conservation movements have taken a toll on rural communities that have traditionally relied on their forests.

A number of public sector initiatives, such as the EU Timber Regulation, promote the consumption of sustainably-produced forest products.[103] Conservation policies like these lead to increased carbon stores and help to protect endangered species in forest regions, alongside economic benefits.

6. Knowing the material

At a glance

- Timber is a complex and variable material. Theory and observation have given us practical design rules, which are continually refined through further research.

- Fire safety design in mass timber buildings requires assessment of life safety hazards posed by timber for the building occupants and fire fighters. Key considerations include building height, occupancy, and the reaction of mass timber when used in compartments, when used as structure, and when used in internal walls.

- Design for durability involves consideration of environment, species choice, weather protection, preservation treatments, insect barriers and inspection regimes.

- Design for satisfactory acoustics requires consideration of factors including noise sources, flanking path effects, absorbing underlays and resilient supports and bearings.

- Dynamic modelling and site measurement of timber buildings enable us to predict vibration outcomes relative to preferred comfort criteria for new designs.

- Modelling and measurement of environmental conditions inside timber buildings provide the basis of predictions for thermal comfort and energy performance.

The material properties of timber vary hugely, depending on species, building context and fabrication process, for example the structural use of mass timber (i.e. CLT, glulam, LVL etc) compared to its use externally (i.e. acetylated, charred or treated boards).

Above left: Mactan Cebu Internation Airport Terminal 2, Cebu City, Philippines.

Variability and predictability

Some material scientists shy away from timber, calling it a 'pre-purposed' material. They prefer the control over properties that comes with 'man-made' materials. Solid wood can vary in strength over a hundred-fold depending on species, stress direction, moisture content and load duration, all explicable in terms of its original purpose within the tree. Structural design and specification in timber therefore needs to accommodate these complexities.

Alongside solid wood, there is a rapidly growing inventory of reconstituted wood-based materials made from fibres, chips, plies and laminates. These materials are effectively man-made, and conform to pre-specified behaviours, which simplifies the designer's task. The carbon cost of breaking down and recombining the constituents can be significant, but even at the scale of small fibres it is typically much less than the carbon already captured in the fibres themselves, so still offers a positive outcome in terms of carbon balance.

Wood products for buildings also need to meet requirements for durability, acoustics, vibration, building physics, and both fire resistance and reaction to fire. (Fire resistance being the capacity to perform a function during a fire, e.g. load carrying or insulation, and reaction to fire concerns how the material reacts and its contribution to fire growth.)

These aspects are the subject of ongoing research, which has escalated in recent years in parallel with the renewed interest in timber itself. We know enough to provide safe answers for designers and specifiers, but the industry's focus must be to maintain safety while also researching further to refine the answers.

A joint research project by the University of Edinburgh, Arup and KLH has explored combustion and safety issues in mass timber buildings. Variables explored included rate of fire growth and time to flashover, total heat release rate, duration of combustion, and potential for secondary flashover.[104]

Otto Hetzer's patent on glulam dates back to 1906, but many modern timber products like CLT, LVL, PSL and LSL were only invented in recent decades and R&D programmes to explore and exploit their potential are correspondingly short. That is in contrast to steel and reinforced and prestressed concrete that have been the subject of intensive research for over a century. The timber industry can anticipate decades of catch-up in that regard, benefiting at the same time from further refinement and optimisation of its products.

Fire safety

Fire safety is a fundamental objective of any project. Building from a combustible material can seem counter intuitive and must be done knowingly and with caution. International codes and standards do not fully address timber for high-rise buildings yet and performance-based solutions are restricted by available research. In order to move forward there is an urgent need for more research and understanding. In the meantime, responsible designers and engineers need to advise clients of the opportunities but also the limitations.

Building and fire codes normally assume that the load-bearing structure does not form part of the building fuel load. They have generally dealt with combustible timber structures by limiting the height of the building or by requiring the timber to be ‘encapsulated’, typically by protecting exposed timber surfaces with appropriately tested fire resisting construction. These solutions will often still be acceptable for low rise buildings where occupants are awake and able to evacuate, provided the materials of construction are considered by the design team when developing the fire strategy for a building.

If a timber structure is left unprotected, it will form part of the fuel load present within a given compartment in a fully developed fire.[105] The combustible structure will then contribute to the rate of burning and the duration of the fire. The risk posed by this behaviour requires specific assessment in buildings whose failure would have significant consequences for human life, for example tall buildings or healthcare facilities with high-risk occupancies and complex evacuation procedures. The timber design and its protection are required to mitigate that risk to the extent that it becomes tolerable.

Charring tests on CLT elements. CLT char fall-off (also known as delamination) is the subject of ongoing research.

The fire may be brought under control by an effective sprinkler system or by fire-fighting services. Automatic sprinkler systems are designed to control or suppress a fire in its growth stages and before it reaches a size which is a threat to the structure. They can therefore contribute to reducing the risk of structural failure, as is the case for all types of construction. However, where they are not able to do so the structure must achieve the required fire resistance performance for occupant and fire fighter life safety.

These considerations have led to a renewed impetus in timber fire engineering research. They require moving beyond fire testing of individual elements like beams, columns and panels, and addressing questions about whole-compartment and whole-building behaviour. Tests at that scale require significant resources and as such the number completed so far has been limited.

Of particular interest is how a single compartment or room fire will be impacted when there are significant areas of exposed timber, such as CLT. They have typically included tests with all room surfaces of CLT exposed, a single surface exposed, multiple surfaces exposed, and all surfaces protected, and they have consistently demonstrated that the exposed timber affects the fire dynamics, with an increase in the fire heat release rate, a lengthening of fire duration and where there are low ventilation conditions, potential impact on exterior flame propagation.

The tests have also shown that limited areas of exposed timber can be acceptable, with relevant factors including the type of laminated timber product and the locations of the exposed areas. These affect the risk of re-radiation between burning surfaces, and the ability of the fire rated plasterboard linings of unexposed surfaces to remain in place and prevent charring of the underlying timber. Further testing and a greater understanding will inform the safe extent and configuration of exposed mass timber surfaces within compartments, a key concern for engineers, architects, developers and owners.

A full-scale fire test for glulam beam to column connectors, testing the connector to meet a minimum of 1hr fire resistance rating.

Other fire engineering issues under research include CLT char fall-off (also called delamination), integrity of fire protection to timber surfaces, and protection of structural connections. Char is the layer that forms on the timber surface during combustion; char fall-off occurs when the layer breaks away, typically at lamination gluelines.[106] The char layer provides a degree of temporary protection to the unburnt timber. Its loss causes an increased rate of burning at the freshly exposed timber face, which can lengthen fire duration, consume more timber, and lead to fire re-growth or 'secondary flashover'. Research into the fire performance of CLT, including char fall-off is ongoing. Patterns of behaviour are appearing but there are currently a limited number of fire tests on which to base definitive conclusions.

As a result of large-scale fire testing within the US, the North American CLT manufacturing standard has recently been updated to exclude CLT adhesives that will lead to char fall-off in fire. The adoption by industry of adhesives which are proven to not delaminate in fire will remove a major safety concern for CLT. [107]

Structural connection research addresses the risk of premature loss of strength at the connection, due to such effects as combustion of exposed timber that may be protecting steel embedments, penetration of the fire into cavities at the joint, and temperature increase in steel components themselves.

Building envelopes or façades made from timber also need careful consideration. A fundamental objective of high-rise fire safety design is to contain a fire to one or two storeys. That is, a fire should not spread beyond the compartment of fire origin, internally to the building or externally via the façade. Façade systems involving timber as a material are combustible and should be detailed and designed for fire safety to remove the risk of fire spread over multiple storeys. Tested and certified products for the protection of the structure, and the passive protection products required to seal compartments (such as firestopping, fire doors, cavity barriers), are critical to the delivery of fire-safe buildings. For timber, a bespoke suite of such products that are tailored to the real fire performance of mass timber is required. This presents a significant opportunity for stakeholders in the use of mass timber, in a context where wholesale change in product fire performance has emerged as an urgent focus.

Nanchan Temple was built in 782 CE during China's Tang Dynasty, and its Great Buddha Hall is currently China's oldest preserved timber building.

Best practice for fire safe design, regardless of material used, is to design knowingly using evidence from research, testing and validated methods of calculation. This allows specific risks to be defined and quantified and appropriate fire safety provisions made as part of a holistic design strategy. Cleary in some cases it may not be possible to build safely using current knowledge and understanding; in which case further research or alternative approaches should be determined in order to achieve the project's overall objectives.

The floor system at Limnologen, Vaxjo, Sweden, features double construction for acoustic insulation. The upper spanning structure uses a three-layer CLT top flange stiffened by downstand glulam webs; the separately spanning ceiling structure below uses solid timber beams.[109]
The yellow blocks are inorganic mineral wool batts for extra acoustic insulation.

Durability

We know that Japanese and Chinese temples constructed from timber in the 7th and 8th centuries, such as the Nanchan Temple, are still in use today, though few modern building owners are concerned with such longevity. More relevant to current interests is a 2005 study of reasons for demolition of buildings in Minneapolis. Researchers deduced there was no relation between useful building lifespan and material of construction, whether concrete, steel or timber.[108]

The best way to avoid fungal damage to timber buildings is to keep them dry. An indefinite lifespan is therefore not difficult to ensure for the vast majority of timber buildings where the structural timber is internal. Internal timber can be protected from rain and from risk of leaks and excessive condensation by adequate design and construction.

Risk of insect attack varies with geography, needing more consideration in hot or moist climates, and is addressed by local national advisories. Responses include choice of timber species, in-ground barriers, concrete plinths, access for inspection, or in high risk locations treatment of the timber by toxic or non-toxic means, as discussed in the previous section.

Wood used externally is more at risk and is given a life expectancy consistent with location, species, treatment, detailing and maintenance. Wood cladding and external shading systems are in this category and may need replacing within the lifetime of a building's structure.

Acoustics

Timber's comparatively light weight, usually one of its key advantages, can also prove a disadvantage for sound insulation, particularly in apartment buildings and especially with impact noise transmission and airborne sound in the low-frequency range, 20-200 Hz. Sixteen research partners from eight EU countries are collaborating as part of the *Silent Timber Build* project to produce better modelling and predictive tools to give designers and owners confidence in likely acoustic outcomes from different floor and wall constructions.

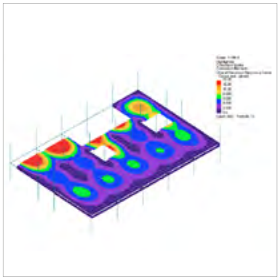
Meanwhile experience with multi-storey multi-occupancy mass timber apartment projects using typical cellular CLT wall and floor construction has demonstrated that code-based noise insulation levels can be achieved with confidence provided consideration is given to arrangement of cavities, impact absorbing underlays, and added mass either as dry sheeting or as concrete screed.

There is often an intention to deliver outcomes better than statutory minimum. One design response is to incorporate elastomeric bearings in wall-to-wall joints to help address flanking path transmission through wall and floor junctions, a growing area of acoustics research.[110] In taller buildings, soft bearings can raise questions about overall building movement however, particularly lateral deflection under wind, and this has become another area for research.[111]

A more elaborate design response for improved acoustic performance is full-cavity double-structure construction for walls and floors. This approach can suit full-volumetric prefabrication where wall and floor structures may be duplicated at module interfaces.

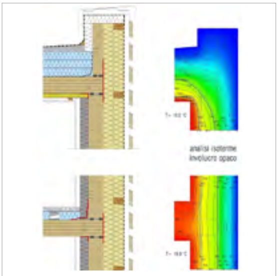
Dynamics

With the arrival of mass timber construction, timber building designers are finally able to address traditional concerns of flexibility and vibration. The issue of discomforting floor vibration in thin concrete and steel-concrete composite floors was studied in the early 2000s, when floor depths were being minimised to reduce storey height in city office buildings. Research at the time produced predictive tools for checking likely floor dynamics against acceptable levels of vibration based on comfort tests on large populations.[112] The tools have now been adapted to timber floor design, and verified against field tests on real timber buildings.[113]



Dynamic response factor contours for the timber floor of an open-plan building, using modal analysis of a finite element model. Inputs included assumptions about floor stiffness, joint stiffness, mass, damping and walking speeds. Field measurements of the real vibration environment after building completion then provided feedback, so modelling assumptions could be checked.

Tall timber buildings also need checking for risk of excessive vibration under the action of lateral wind load. While mass timber has nearly half the strength of concrete, it has rather less stiffness especially when the joints are taken into account. A floor plan for a 15–20 storey concrete building usually includes a concrete core with lifts and stairs that will automatically provide enough lateral stiffness to avoid vibration discomfort. Translating the same plan into mass timber with a similar 200–300mm core wall thickness in CLT or glulam will not necessarily provide the required stiffness, and resort may be needed to engage the internal walls if the building is residential, or else a bracing system on the building's perimeter, or the use of concrete or steel to assist. Issues like these are now key considerations for tall timber building research.



Solid wood structural panels contribute to the thermal insulation performance of walls and roofs. This thermal analysis is part of the extensive building physics modelling and site testing carried out on Energy Box, an environmentally efficient house in L'Aquila, Italy, by engineer Pierluigi Bonomo.[115]

Building physics

We have seen how the choice of mass timber construction can affect a building's insulation, air tightness, thermal mass, and hygrothermal performance. The follow-on effect on building energy consumption may lead to capital or operational cost savings, or both. Indeed, the use of mass timber is a common feature of passive house design, taking advantage of its thermal mass and precision finish to achieve air-tight and highly-insulated building envelopes.[114]

Insulating layers can add 200mm or more to wall thicknesses in cold climates. This can be an issue on constrained city sites. Timber is well known for its insulating properties, and allows either a reduction in the thickness of added insulation, or enhanced insulating performance. In very mild climates, there are examples of added insulation being avoided altogether.

Care is needed with all-wood façade systems however, including wood cassette cladding panels, which typically have wood facings and wood webs connecting the facings with insulation sharing the same zone as the wood webs.
Expert building physics analysis becomes important in these cases, to ensure that moisture migration will be in the

desired direction, and there will not be excessive condensation that could compromise the system.

Regarding air tightness, the greater accuracy achieved by machining of wood panels compared to pre-casting of concrete panels, for example, reduces the reliance of mass timber on post-applied sealants to achieve low specified levels of permeability.

Thermal mass can be useful in helping maintain steadier internal temperatures against external highs and lows and so potentially reduce energy costs. Whether this represents a disadvantage for lighter timber construction with its relatively lower thermal mass is discussed in the 'Wood and well-being' section of this report.

The four-storey-tall timber cassette cladding panels on this timber office building for Sky UK comprise internal and external wood facing panels separated by timber webs. Insulation occupies the spaces between the webs, and internal and external membranes control the passage of any moisture that may appear in the insulated cavity. With integrated assemblies like this, rigorous building physics analysis is important to give confidence in the thermal and moisture performance of the system.

7. Innovating with wood

At a glance

- Throughout history, wood has been the catalyst for many innovations, and the resurgence of interest in timber technology promises more.
- Research into bio-material fibres has accelerated recently, and given rise to new wood polymer composite products and nanocellulose applications.
- Clear coatings are under test that aim to preserve the original surface appearance of new wood cladding despite being exposed to weather.
- New prestressed timber structures offer benefits of jointing simplicity, deflection control, enhanced tensile strength, and self-centring after seismic events.
- Timber is being used in new combinations with concrete, steel, and even glass, to maximise structural efficiency.

This all-wood bicycle helmet has an impact-absorbing liner made from wood-based nanocellulose. It also has a wood veneer shell and straps of a modified paper product. Stockholm startup Cellutech and researchers at KTH Royal Institute of Technology developed the nanocellulose biopolymer and foresee applications in packaging, flame retardant laminates, water filtration, and antibacterial barriers.

Above left: The Smile, Rootstein Hopkins Parade Ground, Chelsea College of Art, London, UK.

Building on the past

As interest grows in new uses for wood, sometimes it is old techniques that are being revisited and extended. Wood and plant fibre composites go back to ancient builders adding straw to reinforce mud bricks. Current research in composites draws on more recent work in aerospace regarding fibre-matrix bonding and its effects on strength and stiffness. The late 19th century precedents of cellophane, celluloid and viscose are well-known to modern researchers in wood fibre technology. Coatings to protect externally exposed timber surfaces also have a very long lineage, though the search for clear coatings that preserve the original appearance of the wood is quite recent.

Modern material science is working on wood modifications to address durability, UV sensitivity, dimensional stability, and fire resistance.[116] Fracture mechanics is opening up new ways of viewing wood's structural performance and safe usage.[117] Wood chemistry and micro-imaging continue to give new insights into wood's macroscopic behaviour and so contribute

The front mask, side skirts, dashboard, door panels and interior panels of the Biofore Concept Car are made from a wood fibre plastic composite suitable for injection moulding, extrusion and thermoforming applications. The vehicle runs on a wood-based renewable diesel. The car was developed at Helsinki's Metropolia University of Applied Sciences and displayed at the Geneva International Motor Show 2014.[118]

to innovations in structural engineering, acoustics, building physics and fire engineering.

International forums including the World Conference on Timber Engineering and Garmisch Holzbauforum continue to showcase new research, inventions, patents and products. The topics mentioned under 'Knowing the material' have all seen new research programmes launched, some at newly formed institutes, others at universities not previously active in timber technology.

Fibres and microfibres

Bio-material R&D using forest products has seen major investment in recent years, pushed by an interest in finding new uses for pulp in a declining paper market, and pulled by an increasing demand for less environmentally-damaging materials.

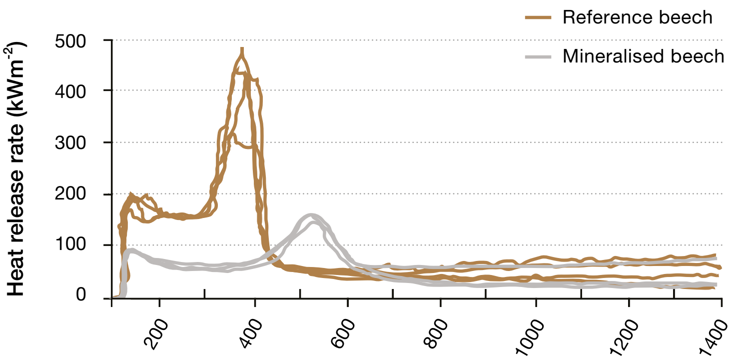


Figure 8 Towards fire resistant wood. Impregnation of beech with a calcium carbonate solution results in calcium salts forming in the wood cell lumens, or cavities. This creates a mineralised hybrid material with a much reduced, and delayed, heat release rate.[119]

Wood polymer composites are a subset of natural fibre polymer composites (NFPC), which are seeing a big uptake in product design, being lightweight, cost-effective, and potentially bio-degradable depending on choice of polymer. Many automotive manufacturers are increasing their use of NFPC's for body, door and lining panels, floor trays and other fittings.

Building applications of wood polymer composites so far include outdoor decking, cladding, fencing and furniture. Used externally, they are more resistant to decay than wood itself, but have lower strength and stiffness — potential targets for further innovation. Wood cement composites use cement paste as the matrix and wood fibre as the reinforcing component, and have also been developed for external cladding and decking uses.

The manufacture and application of nanocellulose from wood is the subject of major R&D programmes worldwide. Nanocellulose refers to the tiny cellulose microfibres that coil around to create the walls of the much larger hollow fibres of the wood. These microfibres can be extracted by high pressure, impact or temperature or by chemical means, to form nanocrystalline cellulose. Reducing the embodied energy of the extraction process is a topic also under research. Potential applications are extraordinarily diverse, ranging from low calorie replacements for carbohydrate thickeners in food, to computer components, medical, cosmetic and pharmaceutical applications, antimicrobial films, and improving the mechanical properties of paper products and plastics.

The Finnish Bioeconomy Cluster FIBIC has produced a birch fibre cloth using a new extrusion process involving an ionic liquid that can be regenerated, allowing the chemicals to be recycled. The birch fibres are stronger than cotton or viscose and the textile resists abrasion, feels comfortable, and shimmers. Since the expansion of cotton production is constrained by limits on water and farmland, sustainably harvested birch could provide an alternative source of fibre.[120]

Clear coatings

A long-anticipated innovation yet to be realised is a clear coating process that will protect externally exposed timber cladding against the effects of weathering, while allowing it to maintain its fresh cut wood colour and texture. Weathering is the slow breaking down and dislodgement of wood surface fibres, leading to erosion and roughness, accompanied by loss of colour. It is different to decay, which comes with extended

A two-storey vertically prestressed CLT shear wall undergoing testing at Washington State University, one of eight universities and industry bodies collaborating in a programme funded by the US National Science Foundation to develop CLT shear wall systems suitable for regions of high seismicity.

exposure to moisture, a significant rise in wood moisture content and large-scale fungal attack.

Weathering is initiated by the UV photo-oxidation of lignin, the ‘glue’ that holds adjacent wood fibres together. The degraded lignin is washed away in rain, leaving microcracks between the wood fibres. Moisture, wind, temperature change and fungi can all then work away at eroding the fibres. The extractives that provide wood with its colour also break down with UV exposure. With loss of surface lignin and extractives, the remaining cellulose-based surface fibres then give the wood its grey weathered patina.

This dynamic surface environment has proved a major challenge in the development of durable clear protective coatings. Opaque coatings have been much more successful given their positive UV blocking function, but the market continues to seek clear coatings that preserve the original wood colour and texture.

Favourable research directions appear to be pre-treating of the wood prior to application of the coating, to address dimensional stability of the surface, photostability of the lignin, and fungal risk. The coating itself also needs additives to increase its UV blocking function.[121]

Prestressed wood

The idea of vertical prestressing of buildings to tie them down against the overturning effects of earthquake or wind is not new. Vertical prestressing of LVL or CLT shear walls for the same reason is new, and has been the subject of research at the University of Canterbury, Christchurch, and at Washington State University. Systems under development are intended to self-centre after an earthquake to minimise post-earthquake repair, and to minimise structural damage by use of energy absorbing devices.

Case study

Netball central headquarters

Sydney, Australia — In 2015, Arup collaborated on the design of Netball Central, the new headquarters for Netball NSW in Sydney. The building is home to nine international standard netball courts that sit beneath a large timber roof structure. The roof is made from 38m span LVL timber portal frames that use an innovative connection detail to fit together, saving time during construction. The building has also been designed to maximise natural ventilation of the courts, reducing the need for high levels of air conditioning.

Research indicates that the response of timber to prestressing is not dissimilar to that of concrete, and design principles can generally be carried across from concrete to timber.[122] As with prestressed precast concrete, prestressing of glulam or LVL stability frames offers jointing benefits, and self-centring benefits in seismic regions.

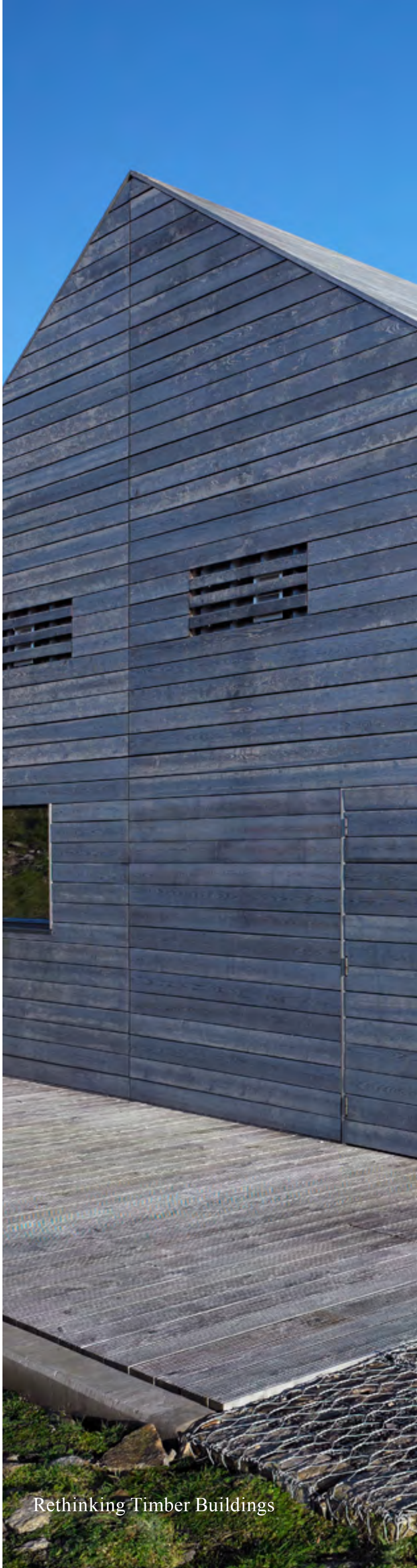
Several prestressed buildings have been designed and constructed on the basis of early research.[123] Another intended application of vertically prestressed LVL shear walls is for the 14-storey Cathedral Hill project in Ottawa.[124] For the design of this light all-timber building, wind loads are more important than seismic loads. Vertical prestressing of the wall segments will provide a much stiffer jointing method than conventional non-stressed steel fixing details.

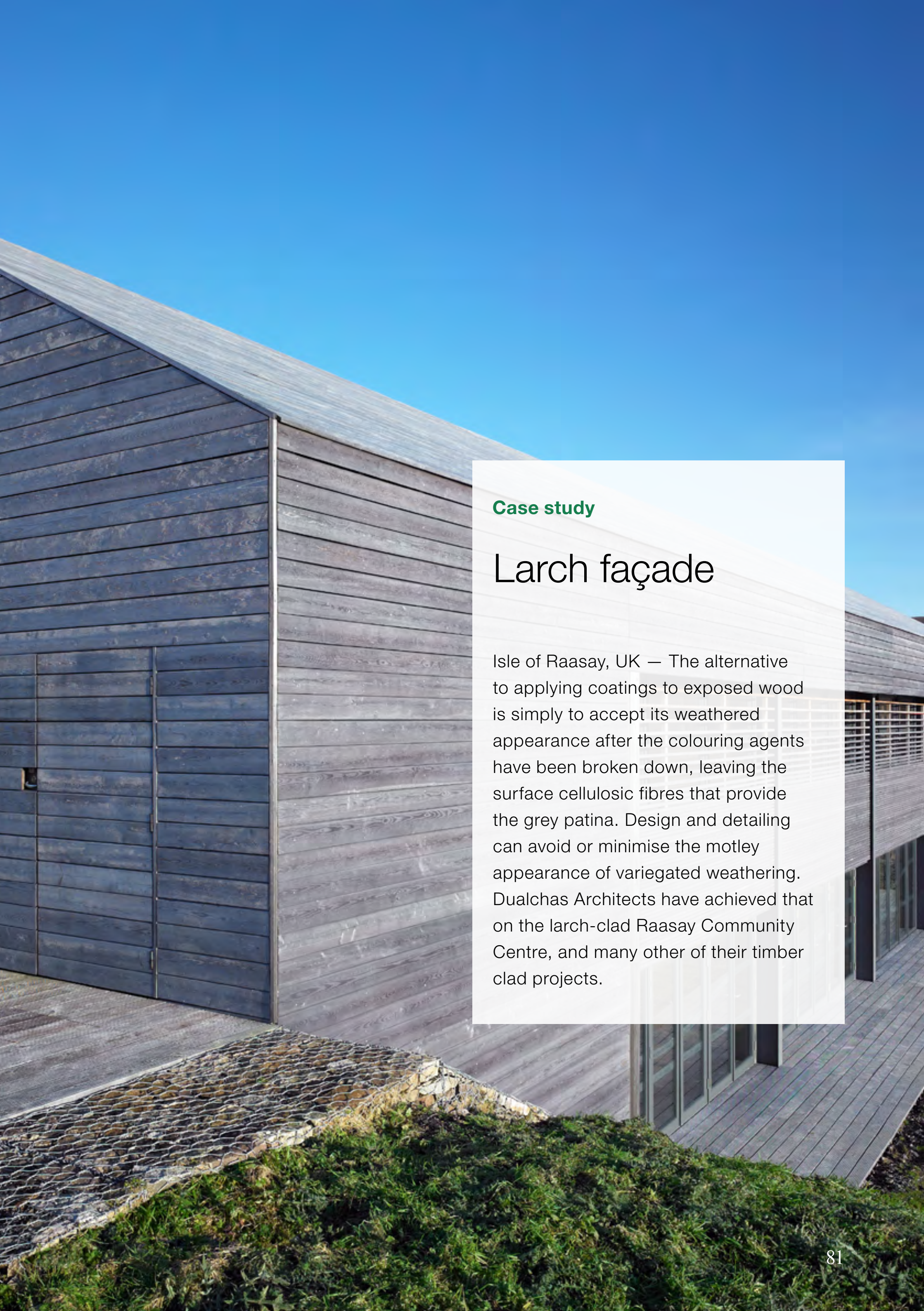
Aside from shear walls and stability frames, prestressed timber beams can also offer benefits in cases of long spans or heavy loads, by providing extra beam strength through 'load-balancing' with draped tendons, and by decreasing deflections, usually the critical design criterion for long-spans.

Hybrids and composites

Concrete and timber work well together, typically with the concrete as a thin floor slab supported by shear-linked LVL or glulam beams beneath. Several prefabricated floor panel versions of this timber-concrete combination have been used in recent multi-storey buildings. Looking ahead, innovation opportunities concern control of concrete shrinkage and creep effects, refinement of the shear connectors, and optimisation of the composite's performance regarding fire and acoustics.[125]

Steel has been combined with timber throughout history to increase timber's strength and stiffness. There are many innovative combinations of these two materials currently under research, including the use of glulam encasement to stabilise thin-walled steel beam sections[126], braces for seismic design[127], upstand trussed steel joists shear connected to a CLT bottom flange, and the opposite arrangement where a steel beam





Case study

Larch façade

Isle of Raasay, UK — The alternative to applying coatings to exposed wood is simply to accept its weathered appearance after the colouring agents have been broken down, leaving the surface cellulosic fibres that provide the grey patina. Design and detailing can avoid or minimise the motley appearance of variegated weathering. Dualchas Architects have achieved that on the larch-clad Raasay Community Centre, and many other of their timber clad projects.

is shear-connected to a CLT top flange which serves as the floor surface.[128] Innovation opportunities include ways of improving damping, maximising stiffness of the steel-timber shear connection, optimising performance of the composite regarding fire and acoustics, and balancing the amount of steel and timber for maximum economy.

Glass may seem like an unlikely match for timber, but researchers at several European universities have been exploring its performance in the web of timber beams, in timber footbridges, and even in providing strength and stiffness for whole buildings against lateral loads like wind and earthquake when used as window glass in timber framed façades.

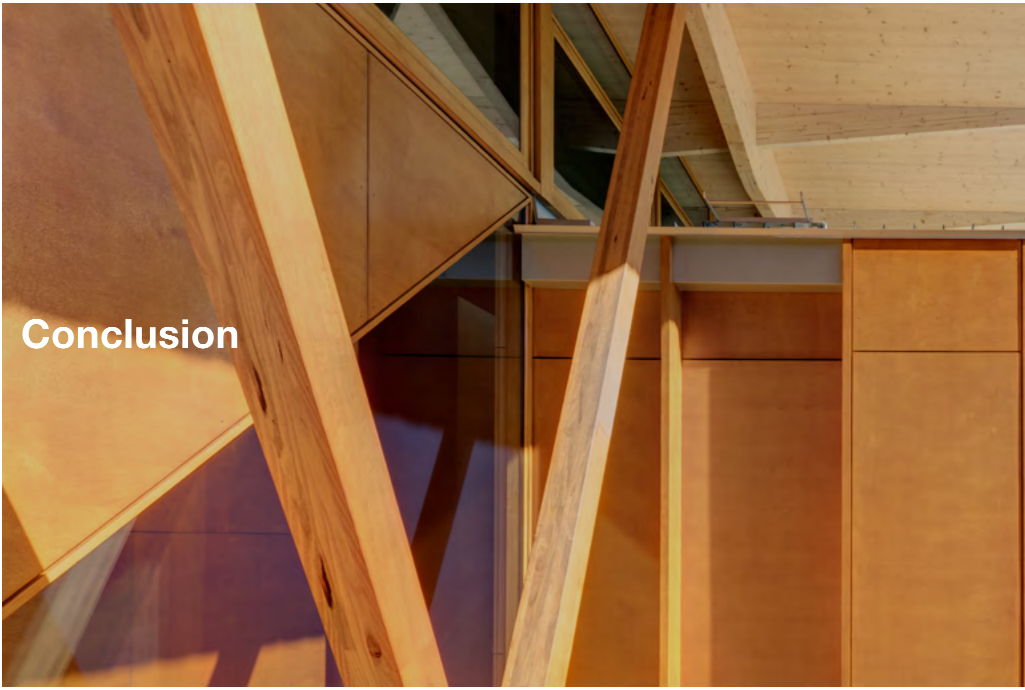
These glass-wood composite research projects on windows are addressing issues including the short and long-term behaviour of structural sealants between glass and timber frames, and the stiffness and strength of composite assemblies under racking loads.

This steel beam section comprises thin-wall cold-formed twin channel sections stabilised against lateral buckling by encasement in a split glulam beam. Optimum sizing is when both materials reach their limiting bending stresses simultaneously under load. The hybrid allows a shallower depth than an all-glulam beam, and simple steel-to-steel beam-column connections if the column is also a steel-glulam hybrid.[129]

Case study

Glass wood composite

An annealed laminated double glass panel in a CLT surround, under test at the University of Zagreb for strength and energy-absorbing potential during simulated seismic loading. While most glass-timber composite research uses a structural adhesive between the materials, this project is exploring friction from direct glass-timber contact.[130]



Conclusion

Above: Macquarie University Innovation Hub, Sydney, Australia.

Material choices have consequences. Compared to cement and steel, we have seen that the negative environmental impacts of timber are less severe. Whether optimal end-of-life scenarios are employed or not, timber still claims a smaller carbon footprint than other major construction materials, as well as being sustainable and reusable. And if techniques such as anaerobic burial can be harnessed, timber could help to actively reduce the environmental impact of construction. This is something the architecture, engineering and construction industry urgently needs to address if we are to play our part in achieving the UN SDGs and help to build a sustainable future. Supportive policies are helping to create a positive environment for timber's greater adoption, including carbon pricing, life-cycle assessment and CO_2 compensation. These position timber as a key component in energy efficient and sustainable approaches to building design and construction.

By rethinking the uses of timber, we can find new opportunities to increase the density of our cities and help to meet global construction demand. This includes re-vitalising otherwise

impractical sites, such as 'air-rights' over stations; by adding multiple additional storeys to existing structures rather than sending them to landfill; and by development on soft sites unsuitable for heavier buildings. This is enabled by the light weight of mass timber compared to concrete or steel, and its suitability for prefabrication.

As well as enabling the upwards growth of cities, and helping to balance our carbon budget, timber construction can provide healthier indoor environments. The use of natural materials, such as wood in internal spaces, helps decrease occupant stress, contributes to a comfortable internal climate, and can reduce exposure to VOCs. While research into 'de-toxed' timber components is ongoing (and in some instances, already commercialised), its marked ability to improve human well-being again appears to offer benefits over conventional choices — but only if its ability to do so is recognised and adopted. Prefabrication is beginning to disrupt established approaches to building design and construction. Timber frame construction can accelerate its uptake, using new laminated and fibre products combined in new ways. This will lead to better-made buildings that are built faster and at potentially lower cost. The rapid development of CNC processes and advanced digital design techniques are, perhaps surprisingly, also well-suited to this ancient material. In either case, off-site pre-fabrication with timber will only play an increasing role if we are to build at the scale we need, and with the most beneficial material choices. Again, this will only be realised if designers, developers and others understand and capitalise on its potential.

Construction in timber will not solve climate change single-handedly, but it can make a useful contribution. Along with its ability to balance or reduce atmospheric CO_2, timber also supports better forest management and a curb on deforestation, both major climate change issues. If brought to bear on underutilised forests, sustainable harvesting could also help provide employment to rural communities.[131]

Right: 'HAUT' timber residential tower Team V Architecture. The design for the 21-storey building in Amsterdam's Amstel Quarter features CLT and concrete shear walls and CLT floors. It will be the tallest timber hybrid tower in the Netherlands.

To fully realise the potential benefits of timber buildings relies on entrepreneurial contractors, developers and clients; it will also depend on dialogue and collaboration with regulatory authorities and more R&D. Both of these are underway and starting to provide solutions to the complex and critical issues that hinder the uptake of timber construction, in particular with regard to fire safety and durability.

The greater use of timber in building design and construction should not be seen as a threat to concrete or steel. Rather, timber should be seen as an adaptable component of the global construction mix, one that is well-suited for use in composite components and hybrid structures, in combination with concrete, steel, polymers and even glass.

While the seven perspectives considered here combine to provide a compelling case for a marked increase in the use of timber, the more pragmatic proposal is a balanced role for wood, in support of diversity and resilience for our cities and economies. In the construction industry wood offers the 'third way' that works alongside and in combination with steel and concrete, but one which is a functioning component of a circular economy. In this scenario, choice of material is based

Above: The Ogden Centre for Fundamental Physics, University of Durham, UK.

not on force of habit but on fitness for purpose, reliability of supply, and market forces. The latter will likely change as carbon mitigation policies including carbon pricing start to take effect, and the longer-term environmental consequences of material choices are better factored into our built environment. The resurgence of timber and its increasing popularity will provide more choice for the construction industry and for consumers, supporting resilience through diversity.

Welcome to Wood City

It is tempting to paint a picture of 'Wood City' where not just the buildings and infrastructure are made of timber, but also the furniture, the crockery and cutlery, not to mention the cars, the bicycles, the ships, and the trains with their rolling stock and track. Certainly, all these products were popular in wood at various stages of history, and are now, like buildings, mostly made from high emission materials that we trade at a low price.

Using modern methods of wood modification for durability, stability and fire protection, we could imagine any or all of them reappearing in Wood City. The tree would be our 3D printer of renewable porous cellulose microstructure, which we would modify chemically to be fit for purpose, whatever the purpose might be.[132] As the most abundant organic compound on earth, cellulose is a ubiquitous renewable resource, and trees are responsible for a large share of global production.

Wood City also provides connections — economic, technological and cultural — between urban dwellers in their new high-rise timber buildings, and rural communities where the forest resource grows and where rural dwellers manage the environmental services on which the survival of the city ultimately depends.

Above: Kroon Hall,
Yale University, New Haven, USA.

It is clear that the vision of Wood City needs tempering, but if it helps us imagine what it might be like to shift urban growth toward renewable (and recycled) materials, and simultaneously to lessen the cultural and economic gap between country a nd city, then it will serve as a useful pointer on the road to the circular economy.

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This report considers the trends, technologies and new uses that are supporting a resurgence in this most ancient of building materials. Supported by historic precedents and recent global exemplars, *Rethinking Timber Buildings* examines seven different perspectives on the use of timber in building design and construction. It aims to consider a range of implications — including speed, quality, safety and human experience — relevant to anyone who has a stake in the materials we choose to build with.

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