Joseph William Gottstein Memorial Trust Fund

European Case-studies for Multi-storey Mass Timber for Moisture-safety and Energy Efficiency

Marcus Strang

2023 GOTTSTEIN FELLOWSHIP REPORT

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The Trust is a living legacy which honours Bill (Joseph William) Gottstein who died in a tragic accident in 1971, at a forest harvest site in PNG. Bill was a scientist and a leader in the CSIRO forest products division. He was an exceptional, innovative man and was liked and respected in Australia and in international circles.

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I would like to thank the Gottstein Trust for their award that allowed this study tour to take place throughout Europe. A big thanks to Andrew Dunn, who led a 7-day WoodSolutions tour though landmark timber projects, fabrication, and manufacturing facilities through Sweden & Norway with a group of leading Australian architects, engineers, developers and building professionals. A big thank you to our guides, who demonstrated their significant expertise touring us through their precedent projects. These included Kenneth Widehall from Binderholz, Frida Sethsson from BoKlok, Joacim Hansson from Randek Prefab, Shaban Shipoli, Sixten Westlund from Karlstad Kommun, Åge Holmestad from Moelven Limtre, Christian Olofsson from Derome, Anders Carlsson, Morten Johansen from Splitkon, Ola Landqvist from Södra, and Rune Abrahamse from Moelven Limtre. The WoodSolutions tour finished in Oslo, Norway, the location of the World Conference on Timber Engineering (WCTE 2023), where I presented my PhD research. I would like to thank Stefan Winter from Technical University of Munich, Mariapaola Riggio from Oregon State University, Shinya Okuda from the National University of Singapore, and Carmen Amaddeo and Carl Larsson from Linnaeus University for speaking to me about the developments in their respective research fields. Thanks also to Anne Cecilie Haug from Snøhetta for taking me through the innovative Norwegian architectural firm and giving me an insight into the mass timber design work that that their team is working on.

After the conference, I then travelled to Germany to visit the Passivhaus Institute in Darmstadt. Where I had the pleasure to speaking to Jessica Grove-Smith, Jürgen Schneider, Elena Reyes, Susanne Theumer, and Carl Halbeck. Moving on to Technical University of Munich, I spoke to Roland Göttig and Nadine Engel from the Chair of Building Physics about their work how to build across different economic, cultural, and climatic conditions, as well as Sandra Schuster about her team's circularity work at the TUM.wood Group. Lastly, I visited Hartwig Künzel and Simon Schmidt from the Hygrothermics department at Fraunhofer Institute for Building Physics in Holzkirchen accompanied by Nina Flexeder from Technical University of Munich and Sol Villanustre Coppola from the Chilean Centre of Excellence for the Wood Industry (CENEMAD).

I'm immensely grateful to the Gottstein Trust and to all those that I met with during the study tour. Let us continue to progress two-way knowledge exchange, collaborate, and inspire each other towards building more efficient bio-based buildings.

Figure 1. *Group photos of the study tour group in Växjö's train station (left) and Mjørstarnet Wood Hotel (middle), as well as the Australian delegation at the WCTE2023 Conference in Oslo (right).*

About the Author

Marcus is the Technical Lead (Passivhaus) at HIP V. HYPE, working within their Better Buildings team as a specialist in highly energy-efficient building design. As a former board member of the Australian Passivhaus Association, Marcus also led their technical working group and currently teaches the Passivhaus Designer course. Marcus recently completed his PhD researching pathways to net-zero energy for multistorey mass timber buildings in hot and humid climates, presenting his findings around Australia, as well as in Chile, China, Germany, and Norway. He retains a research role at the University of Queensland to advance offsite manufacture of adaptable lightweight high-performance panelised timber assemblies with component reuse. Through his consulting role as a Passivhaus Institute Accredited Certifier and Certified Passive House Designer, Marcus has worked on a number of industry-leading sustainability projects across the public and private sectors. Marcus specialises in the Passivhaus standard and mass timber design, which he sees as fundamental steps towards a net-zero carbon-emission society.

Abstract

The aim of this study tour was to visit key projects, manufacturers, and meet thought-leaders and organisations in the area of mass timber construction and high-performance buildings. This is done by highlighting best-practice precedent case-studies, exploring the topics of on-site stormwater management, energy and material efficiency, and the diversity of mass timber projects within Europe. With the main objective to provide value to the local Australian construction industry by building confidence for building designer, engineers, and developers to utilise mass timber construction in the Australian context.

Key findings are that wetting can be minimised or even eliminated by implementing stormwater strategies, such as prefabrication to moisture content monitoring. While low space conditioning energy consumption can be achieved through careful planning and includes design elements, such as good levels of insulation, appropriate window sizing, quality and shading, excellent airtightness, low solar absorptivity of cladding, along with dedicated dehumidification and mechanical ventilation with enthalpy recovery. Certain assessment frameworks such as the ByggaF method and certification against the Passivhaus standard were identified and highly recommended to provide a rigorous process to ensure that the building owner will achieving the expected level of moisture safety and energy efficiency.

Keywords: mass timber, hygrothermal performance, net-zero energy, moisture management, material efficiency.

Contents

Introduction

The Gottstein Memorial Trust Fund was used to enable an international study tour to expand professional networks, visit key mass timber case-studies and manufacturers, and to meet leading academics and building designers in the field of timber design and durability, who have made strides in innovation in the area of high-performance multi-storey mass timber buildings. The location of this study tour took place in Europe, while the case-study learnings have been organised into the themes of protection from stormwater, and energy and material efficiency. Originally, the aim of this study tour was to produce novel climate-specific envelope construction and connection details. However, the aim shifted to identifying best-practice solutions for avoiding construction wetting and maintaining the ability for the assembly to dry out—which plays an increasingly greater issue with modern impermeable building materials and increasing airtightness requirements. This goal stemmed from the need to implement strategies that have been well-established in overseas markets for mass timber buildings, however, have not yet been incorporated into the Australian construction industry processes due to inadequate education. This research will have significant benefits for the timber construction industry by promoting two-way knowledge transfer between academia and industry, thereby encouraging the construction of timber buildings in Australia.

There is a strong need to implement these strategies in Australia promptly, as Mills, Love, & Williams (2009) found that defects are common phenomena in the Australian construction industry with one house in eight reporting defects and that the cost of rectification was 4% of the construction contract value. While, an examination report by Deakin and Griffith University (Johnston and Reid, 2019) highlighted that fabric and cladding systems formed 40% of all building defects in Australian residential multi-storey. Furthermore, Lane (2018) found that poor indoor environment quality, including an epidemic of mould and dampness in Australia, may be the cause of seven million Australians suffering from respiratory conditions. These issues come at a time when there is a significant driver to construct increasingly energy efficient buildings. As mass timber buildings are now facing increasing interest from developers and multi-story apartment buildings are the fastest growing property type (Easthope, Buckle, & Mann, 2018). Therefore, these factors point to a growing urgency in the construction industry to advise building designers on the appropriate building methods to avoid defects in the form of moisture risks and structural deterioration, while any key learnings can be developed and applied across different Australian climatic conditions, ensuring highly energy-efficient operation.

Methodology

This report is based on a combination of site visits and interviews. The study tours and interviews were undertaken in Norway, Sweden, and Germany. Key projects and organisations visited are shown in Table 1.

Table 1. *Key projects and organisations visited during study.*

Country	Project/Organisation	Contact
Sweden	Limnologen, Välle Broar	Ola Malm (Bolaget Architects)
	P-huset, Sege Park	Kenneth Widehall (Binderholz)
	Fyrtornet, Hyllie	Kenneth Widehall (Binderholz)
	Pilgläntan, Varberg	Anders Carlsson (Derome)
	Train Station, Växjö	Ola Malm (Bolaget Architects)
	Södra CLT Plant, Värö	Ola Landqvist (Södra)
	BoKlok Factory, Gullringen	Frida Sethsson (BoKlok)
	Randek Robotics, Arvika	Christian Olofsson (Derome)
	Södra Climate Arena, Växjö	Sixten Westlung (Karlstad Community)
	Eva-Lisa Holt Arena, Karlstad	Sixten Westlung (Karlstad Community)
	BoKlok Housing Village, Växjö	-
	World Conference on Timber Engineering, Oslo	-
Norway	Mjørstarnet Hotel, Brumundal	Rune Abrahamsen (Moelven Limtre)
	The Viking Ship, Hamar	Åge Holmestad (Moelven Limtre)
	Moelven Limtre, Lillehammer	Rune Abrahamsen (Moelven Limtre)
	Spor X, Drammen	-
	HasleTre Office Building, Oslo	-
	Norsenga Bridge, Kongsvinger	-
	Håkons Hall, Lillehammer	Rune Abrahamsen (Moelven Limtre)
	Splitkon, Åmot	Morten Johansen (Splitkon)
	Norwegian Stave Churches, Oslo	-

Germany	Fraunhofer Institute for Building Physics, Holzkirchen	Simon Schmidt & Hartwig Künzel (Fraunhofer Institute)
	TUM.wood Group, Technical University of Munich	Sandra Schuster (TUM)
	Passivhaus Institute, Darmstadt	Jessica Grove-Smith, Jürgen Schneider, Elena Reyes, Susanne Theumer & Carl Halbeck (PHI)
	Snøhetta Studio, Oslo	Anne Cecilie Haug
	Timber Pioneer, Frankfurt	-
	Holzhybridhaus, Frankfurt	-

Projects Demonstrating Strategies for Stormwater Management

This section summarises key information about 10 precedent case-study projects and organisations that were visited during this study tour. Followed by a discussion how they incorporated specific strategies to minimising moisture risks during the construction stage.

Limnologen, Välle Broar

Växjö, situated in Southern Sweden, is pursuing its eco-ambition to become 'fossil-fuel free' by 2050. A component of this mission involves transforming the town into a focal point for timber construction, positioning itself as a knowledge centre for the development of multi-storey timber buildings. During a visit to Välle Broar, attention to sustainability was evident as bricks were carefully reclaimed at a demolition site. Guided by Ola Malm from Bolaget Architects, known for their innovative designs, we were toured through the Limnologen site comprising of four 8-storey residential apartment buildings. These were the first 8-floor timber buildings in Sweden. Noteworthy elements of these buildings included a CLT floors and walls structure, supported CLT balconies that were untreated, and a diverse range of cladding materials such as 6 m long 30 mm thick glulam boards as a rainscreen cladding, and a rendered externally insulated cladding system (ETICS) from mineral wool. After the wall and floor assemblies were pre-fabricated in a factory, they were wrapped in plastic film, covered by a tarpaulin and transported to Växjö (Serrano, 2009). The assembly of elements were constructed under a tent, which was raised floor-by-floor to protect the exposed floor plate from stormwater during construction.

While these buildings represent significant milestones in the construction of timber buildings, challenges existed in meeting stringent energy standards such as Passivhaus (PH) certification. Despite being hailed as the first passive house high-rise building primarily constructed from wood (Lowenstein, 2009), unfortunately, the project fell short of achieving the PH standard (Žegarac Leskovar and Premrov, 2021).

Table 2. *Limnologen site in Välle Broar, Växjö.*

Typology	*4x7-storey residential apartment buildings*
City	*Växjö*
Country	*Sweden*
Floors	*8*
Structure	*CLT*
Floor area	*10,700 m²*
Collaborators	*Architect - Bolaget Architects*
Constructed	*2009*
Highlights	*Project constructed under a tent that was raised as construction progressed.*

Limnologen site with supported timber balconies and rendered ETICS façade.

Tenting strategy for stormwater protection (Serrano, 2009).

Complete building (Žegarac Leskovar and Premrov, 2021).

Evidence of workers meticulously recovering bricks at a nearby construction site.

Untreated timber balconies.

Adjacent mass timber buildings with cedar timber shingle cladding.

P-huset, Sege Park

P-huset Sege Park provides district carparking for the surrounding neighbourhood district. It stands as a significant architectural achievement in Southern Sweden, representing the region's first wooden parking garage with 6-storeys. Constructed from 1,000 m³ of glulam and 3,850 m³ of CLT, assembled in 6 months, this structure offers 600 parking spaces, along with accommodation for bicycles and electric vehicles (EVs). It is the first parking garage made entirely from solid wood. The collaboration with Austrian Binderholz was instrumental in the assembly of the wooden frame, supplying the glulam columns and beams (PMalmö, n.d.). Notably, the facade incorporates high-performance features such as triple glazing and hydronic radiant heating, while integration of photovoltaic cells on the roof for its 120 EV charging points, reflects a commitment to sustainability.

An absence of specific specifications or guidelines for mass timber carparks resulted in a close partnership with timber specialists, as addressing potential moisture and weathering issues was paramount throughout the construction process to ensure the project's success. Surface treatments such as Intergrain were applied to combat surface mould discoloration, while the use of Siga weather resistant barrier (WRB) membranes were adhered to the 5-ply CLT behind the cladding to ensure protection from wind-driven rain. Despite the weathered appearance at the CLT panels at the entrance of the carpark, our guide explained that adequate ventilation ensures rapid drying in case of wetting, maintaining safety standards, which was validated during the design-stage by hygrothermal modelling. Furthermore, the concrete foundation was limited to a height of 300 mm, to mitigate contact with snow, pooling of water, and to protect the glulam columns from risks of car collisions.

Table 3. *P-huset Sege Park district carparking, Sege Park.*

Typology	*Car park*
Location	*Sege Park*
Country	*Sweden*
Floors	*6*
Structure	*CLT, glulam*
Constructed	*2022*
Collaborators	*Architect - Lloyd's Arkitektbyrå* *Timber - Binderholz*
Highlights	*Surface treatments and WRB applied.*

The external view of P-huset Sege Park

CLT wall panels

300mm concrete foundation footing

Evidence of weathering at the CLT edge-grain

Cast asphalt applied to carpark flooring

Intumescent coating applied at perimeter

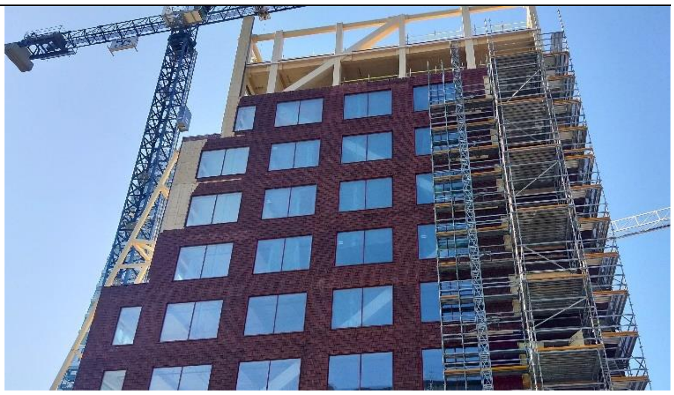
Fyrtornet, Hyllie

Fyrtornet (Lighthouse), located in the Swedish district of Hyllie is part of a 10-year project called 'Embassy of Sharing neighbourhood', which involves the construction of seven buildings containing 300 apartments as well as offices, hotels, shops, restaurants, and meeting places. Fyrtornet is the first building to be constructed in the district and will be Malmö first multi-storey office building built in wood and the tallest wooden office building in Sweden, reaching 11 floors (Kozak, 2023). Interestingly, each floor of the Fyrtornet glulam and CLT structure was completed every 10 days (Granitor, 2022), with 1,030 m^3 of glulam and 1,640 m^3 of CLT being installed in the project. Fyrtornet contains office spaces, a municipal library, and a community meeting place (Rogers, 2022). Other environmental accreditation of Fyrtornet is self-sufficiency in energy, as the district also includes Sweden's largest geothermal energy sharing system, reusing residual energy, as well as sharing renewable energy and heating and cooling resources (Malmberg, 2024). In addition, the Malmö city council enforces that new residential and commercial buildings with rooftops larger than 100 m^2 must construct at least 30% of the roof area as a green roof.

Moisture protection measures for the project include applying a hydrophobic wax treatment (from Koch and Schulte) to the glulam column surfaces to provide temporary moisture protection during construction, with final buffing and varnishing after fully enclosed. Similarly, temporary membranes were installed to protect the glulam end-grains to prevent moisture ingress while exposed. Before installation, all CLT panels were stored in a warehouse, individually wrapped for protection during transportation and handling on-site. Interestingly, the CLT supplier, Binderholz, is among few companies offering CLT panels with adhered edge grains, which enhances airtightness and weather protection. Stringent quality checks were conducted weekly to ensure moisture content did not exceed 18% on CLT panel surfaces and at a depth of 20 mm. The build-up of the external walls from the inside outwards includes internal gypsum plasterboard, battens, airtightness membrane, 190 mm insulation with timber studs, fire-resistant plasterboard, water-resistant barrier, 30 mm semi-rigid continuous insulation, plywood, and shingles providing thermal, vapour, and air control functions. There were unfortunately airtightness membranes that were not fully sealed and subsequently exposed to rainwater ingress at the open top floor level, this required remediation and highlights the importance of continuous interior airtightness membrane for weather resistance even during construction. Additional moisture protection measures were also taken during the construction stage include placing a standalone dehumidifier on each floor to manage humidity levels, while a drain piped externally at each CLT bay was installed to minimize water intrusion risks. These construction practices reflect a commitment to deliver moisture-safe timber buildings.

Table 4. *Fyrtornet, Hyllie.*

Typology	*Multi-family residential apartments*
Location	*Hyllie*
Country	*Sweden*
Floors	*11*
Structure	*CLT, glulam*
Constructed	*Under construction*
Collaborators	*Developer - Granitor* *Builder - Otto Magnusson* *Architect - Wingardhs* *Engineer - Knippershelbig* *Timber - Binderholz*
Highlights	*Moisture-safety strategies included MC monitoring, dehumidifiers, temporary wraps, and coatings,*



Glulam beans showing membrane applied to horizontal end grains and surface wax treatments

Airtightness membrane

Onsite measuring monitoring of CLT moisture content

Drain piped externally for each CLT bay

Build-up of wall assembly layers clearly visible

Surrounding buildings all constructed with green roofs.

Pilgläntan, Varberg

The developer Derome, a vertically integrated family company renowned for manufacturing prefabricated buildings, produces 2,000 modular apartments annually, underscoring their scale in the industry. They predominantly utilize flat pack construction methods and operate five sawmills powered by timber off-cuts (Derome, 2019). Anders Carlsson, the head of research and development at Derome, took us on a tour of a building site in its final stage in Pilgläntan, Varberg. The building was located in a district known as the "Garden city", which would include 32 houses, 14 villas, 24 apartments, and 88 rental properties in time.

Despite the absence of weather protection measures such as tenting strategies during the construction stage, Derome strategically schedules construction activities during dry weather conditions. Their construction approach involves the sequential installation of scaffolding, with three floors erected initially, followed by the addition of new scaffolding for subsequent floors, a process only possible using off-site timber prefabrication. Key aspects of Derome's construction methods include the incorporation of Thermowood facade treatments to enhance timber durability (Sidorova, 2016). The layers of the wall assembly comprise inside to outside of plasterboard, airtight membrane, 170 mm timber studs with insulation, OSB, 50 mm semi-rigid wool insulation, 70mm ventilated cavity, and shiplap cladding. Additionally, 300 mm of EPS insulation was installed under the slab, contributing to thermal performance. Each apartment was equipped with an individual mechanical ventilation with heat recovery (MVHR) system, with ducts integrated into bulkheads for efficient ventilation. Notably, Derome's adoption of a composite balcony system, features a solid wood core with a fiberglass shell.

Despite the longevity of CLT balconies in European construction practices, their susceptibility to moisture poses a risk that requires planning and oversight. Collaboration with moisture experts is crucial to developing moisture plans and implementing protective measures. The balcony design with lowest risks are typically disconnected from the wall assembly and self-supported by frames and foundations as constructed in this project (refer to research by Passian and Toresten (2023) for further CLT balcony considerations). This type of design also assists with energy efficiency by reducing thermal bridging. Moreover, waterproofing membranes necessitate a positive slope of at least 2% to mitigate water ingress risks (Glass et al., 2013). These insights underscore the importance of informed decision-making and rigorous implementation of moisture-safe detailing practices.

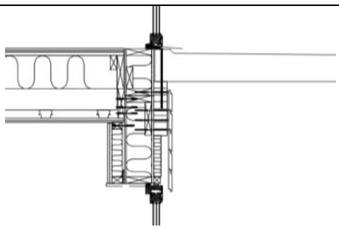
Table 5. *Pilgläntan by Derome, off-site manufactured apartment buildings, Varberg.*

Typology	*Off-site manufactured apartment buildings*
Location	*Varberg*
Country	*Sweden*
Floors	*6*
Structure	*CLT*
Constructed	*Under construction*
Collaborator	*Developer - Derome*
Highlights	*Construction timed only during dry weather.*

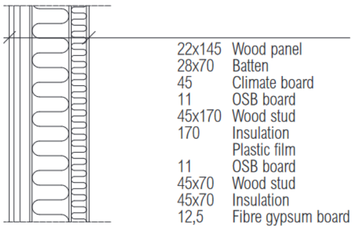
Interior view showing depth of window reveal.

Meticulous installation of semi-rigid insulation panels mechanically fixed to external wall.

Prefabricated perimeter insulation element.



Section detail drawings of balcony (Derome, 2020).



Make-up of wall assembly (Danauskis, 2020).

Adjacent completed building showing self-supported CLT balconies.

Train Station and Townhall, Växjö

Växjö, renowned as "the Greenest City in Europe" earned the prestigious European Green Leaf Award in 2017, highlighting its commitment to environmental sustainability (European Commission, 2018). Embracing this ethos, the municipality mandates that 50% of all new municipal buildings must be constructed from wood and established a Sustainability Agenda for 2030 (Växjö Kommun, 2019). Notable among these initiatives is a 7-storey mass timber train station and townhall project utilizing glulam pillars and beams. The project encompasses 16,400 m^2 of floor space, accommodating 600 workplaces, and features 354 solar panels installed on the roof.

Innovative design elements include a double glass facade incorporating five different types of glass cladding angled at varying directions, along with triple glazed curtainwall windows and automated fabric shading systems. Moreover, proactive measures for stormwater protection, such as the installation of a large tent covering the entire site, shields construction materials from adverse weather conditions and wind (Skanska, 2024). This minimises risks associated with moisture and weather exposure. After just over a year, the weather protection was removed after the facade was completed. Continued collaboration with academic experts from Växjö Linnæus University provides ongoing moisture monitoring initiatives advancing expertise in long-term timber moisture management.

Table 6. *Train station and townhall, Växjö.*

Typology	*Train station and townhall*
City	*Växjö*
Country	*Sweden*
Floors	*6*
Structure	*Glulam*
Floor area	*13,700 m²*
Constructed	*2020*
Collaborators	*Developer - GBJ Bygg* *Architect - White Arktekter* *Timber - Binderholz*
Highlights	*Built under a single large tent for weather protection.*

Triple glazing curtainwall windows with automated operable fabric shading elements.

Radiant hydronic systems located under most windows.

Large glulam pillars are visible and make a design statement.

Site built under a full tent for the duration of construction (Skanska, 2024)

Mjørstarnet Wood Hotel, Brumundal

During our tour of Mjørstarnet Wood Hotel, led by Rune Abrahamsen, CEO of Moelven Limtre, we explored the impressive 18-story mixed-use building, encompassing hotel apartments, offices, and a restaurant. Completed within two years in 2019, the building soared to a height of 85.4 m, securing its status as the world's tallest all-timber structure. The construction methodology involved assembling 4-stories simultaneously, facilitated by internal scaffolding, lifts, and a large crane, eliminating the need for external scaffolding (Liven and Abrahamsen, 2023). 4,000 m³ of timber was utilized in the project, emphasizing the extensive use of this renewable material in contemporary construction practices.

CLT elevator shafts and glulam timber beams serving as columns were integral to the construction, highlighting the structural capabilities of engineered timber components.

Notably, CLT panels were employed as floor elements for balconies, suspended from columns with steel bars on the upper six floors. These elements were prefabricated in a factory and hoisted into place using specialized lifting equipment to preserve the integrity of the polyurea membrane coating, sealing, and protecting them from adverse weather conditions (Liven and Abrahamsen, 2023). The external wall assembly, from inside to outside, comprised of plasterboard, air and vapor control membrane, mineral wool insulation, gypsum as a fire and water-resistant layer, ventilated cavity, and fire-retardant-treated softwood cladding.

Strategic considerations were made for elements exposed to specific environmental conditions, such as structural timber elements located in the indoor pool, which were left untreated due to the protective effects of chlorine vapour against mould growth and good ventilation practices which maintained relative humidity (Peper and Grove-Smith, 2013). Thermal bridging was carefully addressed to prevent interstitial condensation within the structure. Though metallic fixings for timber were considered and treated appropriately for the chlorine. Additionally, on the rooftop, large glulam pergola elements with hollow cross-sections were installed, featuring rounded corners to minimize potential shrinkage cracks and improve aerodynamics against wind loads (Liven and Abrahamsen, 2023).

Table 7. *Mjøstårnet Wood Hotel.*

Typology	*Hotel*
Location	*Brumunddal*
Country	*Norwary*
Floor area	*10,500 m*^{2}
Constructed	*2019*
Collaborators	*Developer - AB Invest AS* *Builder - Moelven* *Architect - Voll Arkitekter* *Engineer - Sweco* *Timber - Moelven Limtre*
Highlights	*Timber elements prefabricated with polyurea membrane coating.*

18-story Mjørstarnet Wood Hotel.

Timber staircase and CLT core.

Heat-treated timber cladding.

Glulam columns as large as 0.6 m by 1.5 m were used in the structure.

Ratified as the world's tallest all-timber building in 2019.

View from the hotel rooms.

Hamar Olympic Hall, Hamar

The Hamar Olympic Hall, colloquially known as the Viking Ship (Vikingskipet) due to its distinctive upside-down Viking ship shape, was constructed between 1991 – 1993 for the 1994 Winter Olympics, primarily for speed skating events. Since then, it has served as a versatile venue hosting trade fairs, corporate events, exhibitions, banquets, and concerts, accommodating up to 20,000 people. Contributing to its iconic appearance, laminated wood lattice girders spanned up to 96 m (Visit Hedmark AS, 2023). While a new steel connection system had to be developed to transfer the forced existing in the triangulated truss.

Constructed using approximately 2,000 m^3 of glulam and 40,000 dowels, the arena incorporates steel cables beneath the stadium to provide lateral tension support. The cooling system features pipes situated 100 mm beneath the slab, maintaining a 15 mm thick ice surface prepared to a 10 mm thickness for skating events. This system is complemented by refrigerant pipes for ice rink chilling, designed for the internal heat loads from occupants and floodlights. Adaptive ventilation strategies, including recirculation during low occupancy and active ventilation during high occupancy, ensure optimal environmental conditions within the facility, with cooled fresh air supplied to the rink area while omitting direct supply to the seated audience sections.

The large triangular trusses were assembled in a factory and delivered to the construction site in four parts. During construction, particular attention was given to protecting the timber components from moisture exposure, with the roof installed immediately after the glulam beams were lifted into place, to mitigate potential wetting. Despite being over 30 years old, the structure remains remarkably stable, requiring minimal maintenance for its internal timber elements. However, recent maintenance efforts focused on resealing the asphalt cladding on the rooftop to uphold the integrity of the building envelope and ensure continued protection against moisture ingress.

Table 8. Hamar Olympic Hall (The Viking Ship).

Typology	*Speed skating stadium*
Location	*Hamar*
Country	*Norway*
Floor area	*22,000 m²*
Constructed	*1993*
Collaborators	*Norway Olympic Committee* *Architect - Niels Torp* *+ Biong & Biong* *Timber - Moelven*
Highlights	*Roof installed immediately after glulam beam installation to mitigate potential wetting.*

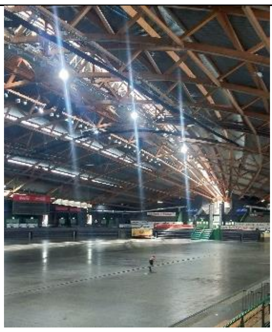
Outdoor concrete supports.

Large supply air ducts.

Maximum 250m width of the arena.

The view of the iconic upside-down Viking Ship.

The large laminated wood lattice girders.



Maximum floor-to-ceiling height of 36m.

Moelven Limtre, Lillehammer

Rune Abrahamse, the CEO of Moelven Limtre, provided us with an insightful tour of their glulam manufacturing and fabrication facility, which has been in operation since 1959. Moelven Limtre is a leading advocate for glulam as a sustainable building material, serving as a primary supplier to Norway's construction industry for notable projects like Mjøstårnet and the Viking Ship (Gray, 2019). According to Abrahamse, glulam offers exceptional strength, precision, and versatility, capable of serving as a standalone structural element and adaptable to various shapes and forms as per customer requirements.

The facility capabilities include the ability to produce glulam beams reaching lengths of up to 31 meters. Equipped with a curved press, the factory can create curves ranging from arches to parabolas and boomerangs. Additionally, the factory integrates state-of-the-art CNC machines for efficient processing and finishing of elements. Glulam is favoured over CLT by Moelven Limtre for its superior material efficiency, where the primary materials are sourced from PEFC and FSC-certified spruce and pine forests located within 150 km of the production facility. Embracing eco-friendly transportation, all vehicles at the factory are electrically powered, contributing to reduced carbon emissions. With a focus on environmental stewardship, Moelven Limtre seeks innovative solutions such as replacing polyurethane adhesives with Melomine alternatives and exploring the potential of using lignum extractives as an adhesive, which is a by-product of the paper industry. All mass timber products are wrapped before leaving the factory for moisture safety during transportation and onsite delivery.

Table 9. *Moelven Limtre glulam factory.*

Typology	*Glulam manufacturing facility*	
Location	*Lillehammer*	
Country	*Norway*	
Collaborators	*Moelven*	
Highlights	*All mass timber products wrapped for weather sealing before leaving factory.*	

		
31 m glulam beams maximum length	Mass timber products wrapped for delivery.	Double curvature bridge with creosote and CCA treatment, 10mm bitumen & 50mm of asphalt for 100+ year life.

Fraunhofer Institute for Building Physics, Holzkirchen

Hartwig Künzel and Simon Schmidt from the Hygrothermics department at the Fraunhofer Institute for Building Physics provided us with a comprehensive tour of their research facilities in Holzkirchen. Established in 1929, the Fraunhofer Institute engages in extensive research across six main categories, including acoustics, energy efficiency and indoor climate, life cycle engineering, inorganic material and recycling, environment, and sensor technology, with a particular focus on hygrothermics (heat and moisture transfer). The institute receives funding from various sources, with contributions from industry contracts, the federal government, the European Union, and universities. Künzel played a pivotal role in the development of the WUFI software (Wärme und Feuchte instationär) during his PhD research, and he has since been advocating for the integration of hygrothermal simulations in the building industry. This software enables realistic calculations of the transient hygrothermal behaviour of multi-layer building components under natural climate conditions. WUFI finds its primary market in hygiene and health applications, with its adoption also driven by litigation cases related to poor design and construction.

Recent updates to the NCC (National Construction Code) 2022 now allows hygrothermal dynamic simulations of construction assemblies to be used as a performance pathway under the condensation management section, aimed at mitigating condensation risks. Fraunhofer's collaboration with Australian industry bodies and research institutions is instrumental in providing appropriate weather datasets and material characterizations for proprietary products. Additionally, Fraunhofer has initiated knowledge exchange initiatives with Australia, focusing on areas such as characterisation of mass timber properties, energy retrofits, and measurement standards through accreditation and standardization efforts. A notable aspect of our visit was the tour of Fraunhofer's extensive field-testing site, where various building assemblies were undergoing assessments for weathering resistance and functional reliability.

Table 10. *Fraunhofer Institute for Building Physics.*

Typology	*Research institution*
Location	*Holzkirchen*
Country	*Germany*
Collaborators	*International and national organisation*
Highlights	*Extensive long-term field-testing for weathering resistance and functional reliability assessment.*

Testing of compressed straw in a Tutor style (expressed timber frame).

Weathering of hundreds of types of cladding materials.

Research facility constructed of arched glulam beams.

World Conference on Timber Engineering 2023, Oslo

World Conference on Timber Engineering (WCTE) 2023 is the world most prestigious biannual scientific forum for the presentation of the latest technical and architectural innovations in timber constructions. Over the 4-day conference a number of presenters spoke about advancements in monitoring of moisture content. Monitoring of moisture is important, as mass timber should not exceed 20% (Kukk, 2022; Kukk et al., 2023). Monitoring can be used to validate the moisture content of mass timber on-site. Presentations by Franke et al. (2023), Kellgren et al. (2023), and Kraler et al. (2023) all described projects where an increase in wood moisture content were identified through constant monitoring at critical locations with pin-type resistance sensors. Thus, monitoring acts as an early warning system through the construction phases avoiding serious structural damage in the future.

Interestingly, a novel moisture sensor printed directly onto a wood surface was presented by Forsthuber et al. (2023). These sensors would allow in-situ monitoring of construction elements such as CLT, across an extensive surface area, rather than at only discrete points, which would be highly suitable for the monitoring of moisture content of timber constructions. Carbon-based inks were used to avoid issues for the recycling process after use of the construction elements. Monitoring systems can also be used for measuring air quality, to increase or decrease mechanical ventilation air exchange rates so that good indoor air quality is maintained both for the health of occupants and the health of the mass timber structure. Riggio et al. (2023) explored developing a federated use of monitoring methods for mass timber buildings to effectively oversee the complexities of merging data from various monitoring projects, while also guaranteeing a smooth and precise integration process. This included strategies to improve the quality of the data and promotes comprehension of relevant phenomena to facilitate informed decision-making.

Projects Demonstrating Strategies for Energy and Material Efficiency

This section summarises key information about 9 precedent case-study projects and organisations that were visited during this study tour. Followed by a discussion for how they deal with maximising energy efficiency, through standards such as the PH standard as well as material efficiency through designing for circularity and re-use of timber products.

Spor X, Drammen

Spor X, situated in Drammen, stands as a pioneering 10-storey all-timber office building featuring a ground-floor restaurant and bar. Conceived by DARK Arkitekter, the project aims to set new sustainability benchmarks in the Nordic region, attaining certification with the PH standard, Energy class A, and BREEAM-NOR Outstanding (Troldtekt, 2021). Timber was deliberately chosen to reduce structural loads, particularly significant given the challenging ground conditions along the riverside location (Overton et al., 2023). The project employed building information modelling (BIM) across all disciplines to facilitate design coordination and ensure construction adherence, resulting in efficient execution within a short timeframe of 15 weeks (PEFC, 2021). The BIM model also had the benefit of checking the build for non-conformances by a weekly scan of the building (Overton et al., 2023).

The Norwegian solid wood producer, Splitkon, delivered and assembled the building components using solid wood and glulam materials. The construction features timber-to-timber beam-to-column connections, emphasizing structural integrity and sustainability. Notably, stabilizing cores comprised of 260 mm CLT panels and two-storey-high glulam beams enhance the building's resilience. External walls utilize prefabricated 'Climatewall' panels, installed via crane, with a mineral service cavity for added thermal resistance, in addition to durable Thermowood cladding (Troldtekt, 2021). To mitigate moisture-related risks, the project incorporates sensor hive monitoring systems installed by a Danish provider, ensuring continuous monitoring of moisture levels in critical areas such as decks, external walls, and bathroom floors. These systems trigger a water guard to shut off water to rooms upon detecting moisture. This system led to reduced insurance costs and enhanced risk management against potential moisture-related issues.

Table 11. *Spor X, Drammen.*

Typology	*Office building*
Location	*Drammen*
Country	*Norway*
Floors	*10*
Structure	*CLT & glulam*
Floor area	*6,800 m²*
Constructed	*2022*
Collaborators	*Architect - DARK Arkitekter* *Developer - Vestaksen Eiendom* *Timber - Splitkon*
Highlights	*Continuous monitoring of moisture levels at critical junctions and areas. Certification with the Passivhaus standard achieved.*

Completion of the timber erection (Overton et al., 2023).

Triple glazed window with operable external fabric elements.

Ventilation ducts visible in the ceiling.

Södra CLT Plant, Värö

Södra, Sweden's largest forest owners' association and an international forest industry group, expanded its operations with the establishment of a new plant at Värö, now one of Sweden's largest CLT production facilities. This plant boasts a capacity to supply framing materials for over 4,000 homes annually, marking a significant tenfold increase in Södra's production capacity (Södra, 2023). Constructed primarily from timber, the building itself serves as a testament to the organization's commitment to sustainable manufacturing and construction practices. With a workforce of 3,300 employees, including 90 at the new CLT facility, Södra aims to process 100,000 m^3 of timber sourced from its forest collaborative organization, comprising 52,000 members across Sweden. Where these members have an average of 50 hectares, with 2 hectares allowable for felling. Interestingly despite increased use of timber in Sweden's construction industry, in less than 100 years, Sweden's forest resources have doubled, at least in part due to the financial incentivisation that members are given for growing timber on their properties that is later to be harvested. The production process at the Värö plant involves a number of steps to transform round timber logs into CLT panels. Boards are finger jointed and glued with a PUR adhesive to form lamellae, which can reach lengths of up to 16 meters. These lamellae are then planed, glued together with PUR adhesive, and pressed to form large plates, incorporating cross-layering for enhanced strength and stability. The resulting mother panel undergoes sanding, CNC milling, and cutting into child panels before being manually adhered with a WRB prior to shipping for protection against wetting.

Södra prides itself on operating one of the world's "greenest" production facilities, with offcuts utilized for combustion to generate electricity and heating for both manufacturing processes and 50,000 nearby homes, contributing to a sustainable energy cycle. While glue constitutes only 1% of the final product, it accounts for 50% of emissions, prompting Södra to allocate half of its profits towards research and development, particularly focusing on the development of bio-based adhesives. The facility's extremely low total global warming potential (GWP_{tot}) of 140 kg CO_2-eq (Norwegian EPD Foundation, 2020) per 1 m^3 of CLT, are attributed to its 'fossil-free' timber production, energy recovery capabilities, sourcing of timber from local forests, and timber offcuts from the factory providing 1% of Sweden's total energy needs for district heating in Sweden. This is in stark contrast with comparatively high GWP_{tot} emissions of Australia's CLT manufacturer of 2,457 kg CO_2-eq (ThinkStep, 2021) because the Australian CLT manufacturers currently lack these sustainability credentials.

Table 12. *Södra CLT plant.*

Typology	*CLT manufacturing plant*
Locations	*Värö*
Country	*Sweden*
Structure	*CLT*
Constructed	*2023*
Highlights	*Extremely low global warming potential per 1 m³ of CLT production.*

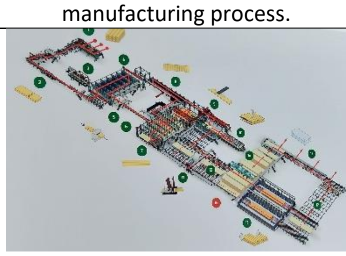
Lamellae are glued together with PUR adhesive.

Lamellae are pressed to form large plates.

Steam from chimney stack belies the low GHG emissions from the efficient manufacturing process.

Structure of factory comprises of glulam columns .

Membrane is manually adhered before shipping.



Schematic of the factory line.

BoKlok Factory, Gullringen

Our visit to BoKlok, a modular apartment building fabrication facility jointly owned by Skanska and IKEA, provided insights into a pioneering residential housing concept. BoKlok homes, primarily constructed from wood, employ a smart, industrialized, and efficient process, ensuring assembly in a controlled, off-site environment using modern construction methods. This approach not only guarantees predictability, high quality, and cost-effectiveness but also fosters sustainability by minimizing waste and environmental impact. Where according to Jenny Adholm, the head of sustainability, the facility recycles most of the leftover materials and disposes of less than 1% of the waste. Responsible for the entire construction supply chain, BoKlok produces approximately 1,200 homes annually, totalling a sum of 15,000 homes across Sweden, Norway, Finland, and the UK. These homes encompass various modules assembled into two, three, or four-bedroom detached, semi-detached, or terraced houses, as well as one or two-bedroom apartments, featuring a standardized yet adaptable design.

With 90% of the homes fabricated in the factory and only 10% assembled on-site, this process streamlines construction processes, reducing labour requirements, site durations, waste generation, and transportation needs (BoKlok, 2024). This means fewer people working on sites and deliveries to site reduced by 75%. While the total number of overall transport movements reduced by 50% when compared to traditional construction (BoKlok, 2024). Interestingly, two full-time staff are employed simply to unwrap IKEA furniture and fixings. BoKlok's innovative assembly line, comprises of five stations and combines automation with manual processes where necessary. For instance, installation of plasterboard with a manual gib is often still more efficient than automated robots. This integrated approach enables BoKlok to offer prefabricated homes at $2/3^{rd}$ the price of the market value. Constructing under the factory roof minimizes moisture risks while contributing to consistent quality through the precise installation of the bulk insulation batts (2x90 mm in walls), WRB sealing across assemblies, and installation of a MVHR systems in all homes.

Table 13. *BoKlok factory, Gullringen.*

Typology	*Modular apartment factory*
Location	*Gullringen*
Country	*Sweden*
Floor area	*65,000 m^2*
Collaborators	*Developer - IKEA & Skanska*
Highlights	*Precise installation of insulation is visible on the right.*

Five stations combines automation and manual processes.

Weather resistant membrane sealing across assemblies.

Boklok village in Telestadshöjden (Växjö) completed 2024.

Randek Robotics, Arvika

Randek's zero-labour robotic system represents a significant advancement in prefabricated construction technology. These robots are designed to automate various processes involved in producing building elements such as walls, floors, or roof components. The system is highly customizable and can seamlessly integrate into existing production lines, offering versatility and adaptability to meet specific manufacturing needs. The system has the capability to construct building elements with multiple layers, including sheathing, framing, gluing, or insulating (Randek, 2024). These processes are key to producing affordable, reliable high-performance buildings. The installation of Randek's robotic systems involves significant investment, with set-up costs ranging from $30 – 40 million and a lead time of approximately two years. The dimensions of the robotic stations typically measure 20 m by 170 m. By strategically placing robots where they are most needed, Randek aims to eliminate physical strain and reduce labour costs significantly, streamlining production while enhancing product quality and output. Moreover, the introduction of robots in manufacturing facilities often leads to a reduction in insurance premiums, reflecting the improved safety and efficiency associated with automated processes. Drivers for the demand in prefabrication include rapid urbanisation, stringent government regulation for safety, lack of skilled labour, and demand of affordable housing, and offsite construction benefits.

The innovative features of Randek's robotic systems extend beyond basic automation, incorporating sophisticated equipment such as calibration stations equipped with air cushions to float panels into position and suction cups that bend panels as they are lifted to prevent interference with underlying structures. Future developments may include the utilization of off-cuts for assembly, recycling materials, or optimizing maintenance schedules to ensure continuous operation with minimal downtime. These prefabrication manufacturing robotic systems have found a growing demand in in regions like British Columbia, that have seem a strong focus on delivering the PH standard and net-zero energy developments (Paradigm Building Solutions, 2024).

Table 14. *Randek, zero labour robots, Arvika.*

Typology	*Zero labour robots*
Location	*Arvika*
Country	*Sweden*
Highlights	*Robotic production process ensures unmatched precision towards low energy solutions.*

Robotic arms ready for delivery.

Calibration table.

Suction cup station to pick up material layers.

Södra Climate Arena, Växjö

The Södra Climate Arena, a collaborative project between Södra and Ready Play Tennis, stands as a pioneering example of energy-efficient design in sports facilities, aiming to embody the concept of the "tennis centre of tomorrow." This PH-certified arena encompasses four tennis courts, a café, conference rooms, a gym, changing rooms, and technical facilities, marking it as the first PH-certified tennis arena. The success of this project is evidenced by continuous monitoring activities revealing a consistent indoor temperature of 18˚C throughout both winter and summer seasons. Initial energy consumption data from the first two years indicate minimal requirements for heating or cooling (Antonelli, 2016), showcasing the effectiveness of the PH approach even in non-residential constructions (PHI, 2014a).

Achieving the rigorous PH standard in a cold climate necessitated the implementation of high-performance building assemblies. Key features include 280 mm of XPS insulation under the slab, 306 mm of mineral wool insulation in the external walls, and 475 mm of mineral wool insulation in the roof, complemented by a triple-glazed curtain wall system. Notably, the project also achieved a remarkable airtightness test result of 0.13 air changes per hour (PHI, 2014b). These measures set a benchmark for sustainable construction practices in sports facilities.

Table 15. *Södra Climate Arena, Växjö.*

Typology	*Indoor tennis courts*
Location	*Växjö*
Country	*Sweden*
Floors	*1*
Structure	*Glulam*
Floor area	*3,600 m²*
Constructed	*2012*
Collaborators	*Architect – Kent Pedersen Arkitektfirma* *Timber - Södra*
Highlights	*Almost no energy required for heating or cooling.*

Large glulam rafters from Södra.

Highly reflective glazing treatment.

Certified Passivhaus arena.

HasleTre Office Building, Oslo

The HasleTre project stands as Norway's first all-timber office building explicitly designed and constructed for disassembly and reuse. With the aim of closing the material loop and fostering a circular value chain, this initiative embodies a fundamental shift towards the principles of the circular economy within the building industry. Recognized for its innovative approach, the project was awarded the prestigious Norwegian Building Industry's Timber Building of the Year accolade, highlighting its significance in advancing sustainable construction practices.

The HasleTre project was not only driven by the goal of promoting material efficiency but also mandated to reduce overall greenhouse gas (GHG) emissions by a minimum of 50% and achieve certification to the demanding BREEAM NOR Excellent standard. These ambitious objectives necessitated a collaborative effort from the property developer, the design teams, contractors, and planning authorities. Central to the success of the HasleTre project were the innovative design solutions implemented to facilitate disassembly and maximize material reuse. These included the development of timber-to-timber joints and connections, utilizing glulam columns and beams joined with hardwood dowels and CLT walls and slabs fixed using novel X-fix dove-tail connectors (Flindall et al., 2023). By minimizing the use of steel and simplifying separation processes at the end of the building's life cycle, these solutions not only enhance recyclability but also retain the value of materials for future use. Furthermore, the project integrates existing material components such as second-hand acoustic panels, ducting, sanitary installations, and flooring, demonstrating a holistic approach towards sustainable resource management. With adaptable open spaces and modular infrastructure, the HasleTre project offers insights into the potential of timber architecture in shaping the circular future of the built environment.

Table 16. *HasleTre, Oslo.*

Typology	*Office*
Location	*Oslo*
Country	*Norway*
Floors	*5*
Floor area	*3,000 m²*
Constructed	*2022*
Collaborators	*Architect - Oslotre architects*
Highlights	*All-timber office building designed and constructed for disassembly & reuse*

Design strategies for flexible spaces.

Novel timber connectors, such as a X-Fix dove-tail connection) used between CLT slabs (Flindall et al., 2023).

Designed for longevity and enduring taste.

TUMwood Group, Technical University of Munich

Sandra Schuster, who acts as both the chair of architecture and wood construction at the Technical University of Munich and the director of TUM.wood explained that TUM.wood is a project initiated in response to pressures from the EU. Its primary focus is on the development and assessment of timber panel constructions with a view towards future circularity and aims to determine the cascading potential of materials and their suitability for re-use in timber frame elements (TUM, 2023). Launched in 2013, TUM.wood operates in a highly interdisciplinary manner, involving collaboration among 11 professorships from various disciplines across the university. Circular timber construction in Germany is heavily influenced by political will, currently propelled by concerns surrounding climate change, wildfires, insect infestations, and the proliferation of foreign tree species, all of which exert pressures on forestry practices. There is uncertainty within the forestry sector regarding the availability of timber resources by 2100, underscoring the critical importance of resource efficiency. As part of TUM.wood's technical development efforts, timber frame elements are being designed to facilitate easy disassembly and re-use, as well as to enable the separation of wood-based materials at the end of their life cycle.

TUM.wood represents cutting-edge research in the field of circular economy for mass timber construction, tackling pertinent questions related to the application of circular principles in modern timber construction (BBSR, 2023). Interestingly, there are also several other industry organizations actively engaged in circularity initiatives, including European Union-backed projects Concular (European Union, 2020) and the RE4 project (RE4, 2020). Switzerland also serves as a hub for circularity projects, exemplified by initiatives like Baubüro in situ (Insitu, 2024). While in Australia, Revival Projects in Fitzroy (Revival Projects, 2022) stands out as a unique multidisciplinary practice dedicated to closing the material loop for construction projects, further emphasizing the global momentum towards circularity in construction practices.

Table 17. TUM.wood Group, Technical University of Munich.

Typology	*Research organisation*	 (TUM, 2023)
Location	*Munich*	
Country	*Germany*	
Collaborators	*Federal Ministry of Food and Agriculture (BMEL)*	
Highlights	*Develop circular timber frame elements considering technical, environmental and economic feasibility.*	

Passivhaus Institute, Darmstadt

At the Passivhaus Institute's (PHI) head office in Darmstadt, key staff at the institute described the work that had been done in in applying ultra energy-efficient (PH-certified) buildings in warmer climates. Jessica Grove-Smith, senior scientist and one of the board of directors of the PHI explained how the PH standard is a superb net-zero design approach for buildings located in hot climates. However, there are a number of cultural difficulties for applying the PH standard in hot and humid climates that should be considered, as buildings in these climates are culturally expected to be as open as possible for airflow. Though over the lifetime of the building, the likelihood of air conditioning being installed for active cooling at some stage is very high, which leads to non-optimal solutions due to high air infiltration rates. Grove-smith also described how the PH standard can effectively be incorporated into standards and policies to achieve very high energy efficiency in the urban building sector (Grove-Smith et al., 2018). The PH standard incorporates several tools that make it more appropriate than traditional net zero rating approaches when considering the occupancy density of the building and its climate-specific seasonal energy-use. Further information about this primary energy renewable (PER) approach can be found in the report by Steiger et al. (2022) and the article by Grove-Smith et al. (2016), while please refer to the authors thesis for further reasoning about why the PH standard is ideally suited for hot and humid climates (Strang, 2023).

Effective energy efficiency solutions in hot and humid climates were then discussed with Jürgen Schneider, director of the PHI. Schneider confirmed that extremely low cooling energy consumption could be achieved through careful application of the PH standard and included design elements, such as good levels of insulation, appropriate window sizing, quality and shading, excellent airtightness, low solar absorptivity of cladding, along with dedicated dehumidification and mechanical ventilation with enthalpy recovery. Active cooling system for highly energy efficient buildings in hot and humid climates should be able to automatically adjust their own sensible heat ratio (SHR) accordingly to the required sensible and latent cooling requirements. This is best achieved when de-coupling cooling and dehumidification to allow for a variable SHR. While additionally, these solutions need to have low investment to compete with conventional systems. The potential for building automation to avoid issues with commissioning the mechanical ventilation system was also discussed with Jürgen (Feist, 2023). Additional consideration about appropriate low energy systems for highly energy efficient buildings in these climates can be found in the in the report by Schnieders and Grove-Smith (2013) and the author's thesis (Strang, 2023).

Speaking with Susanne Theumer, senior consultant at the PHI about precedent international hot and humid case study projects and experiences, Theumer described a number of current international PH efforts in hot and humid climates. One project of interest was 20 PH single-family projects that were built in Mexico between 2015 – 2019 under the funding framework of the LAIF Component of the Ecocasa Program (Passive House Institute, 2012). Being one of the first programs that aims at the implementation and financing of social housing with high energy efficiency in a developing country, the aim of the project was to build houses under the PH standard to achieve a reduction of approximately 80% in greenhouse gas emissions. A cost analysis found that the considering the price of the houses and the subsidy that users may have to pay more capital at the beginning, though savings were available in the long term (Passive House Institute, 2022).

Table 18. *Passivhaus Institute, Darmstadt.*

Typology	*Research organisation*
Location	*Darmstadt*
Country	*Germany*
Highlights	*Meeting with key personnel at the Passivhaus Institute and discussing strategies and components to achieve highly energy efficiency outcomes applicable to hot climates.*

High-performance thermal break and window components.

Snøhetta Studio, Oslo

Snøhetta stands as a prominent global architectural firm, with its headquarters situated in Oslo, Norway. Renowned for its commitment to responsible design practices, Snøhetta approaches each project with a focus on fostering harmonious coexistence among people, plants, and animals while minimizing negative environmental impact. Meeting with Anne Cecilie Haug, a senior architect and project leader at Snøhetta, the firm's strong commitment to timber construction emerged as a prominent theme. Snøhetta places particular emphasis on designing buildings that pay back their CO_2 footprint over their lifetime. With a commitment to achieve carbon neutrality across all its projects within the next 15 years (Snøhetta, 2024a). Among Snøhetta's notable timber-centric projects are ASI Reisen's four-storey all-timber head office in Innsbruck, Austria (Snøhetta, 2024b), the Høyt Under Taket climbing centre in Skien, Norway (Snøhetta, 2024c), and House Dokka in Kongsberg, Norway (Snøhetta, 2024d).

Table 1. *Snøhetta Office, Oslo.*

Typology	*Architecture studio*
Location	*Oslo*
Country	*Norway*
Highlights	*Innovative architectural design studio focusing on timber design.*

Snohetta holds a strong desire to work with timber in new and innovative ways (Snøhetta, 2024e).

In-house exploration of traditional handicrafts and cutting-edge digital technology.

Adjacent to Snohetta, meadow planted with wild species designed to ensure spread of pollinating insects.

Diversity of International Mass Timber Projects

A number of other mass timber projects were visited as part of this study tour. While not necessarily best-practice projects in the terms of moisture management or energy efficiency, these 7 projects still presents the diversity, scale, and unique typologies that mass timber construction can be applied to, which may serve as inspiration of mass timber buildings in Australia.

Timber Pioneer, Frankfurt

Frankfurt's first CLT office building is hailed as a smart building with sensor technology, energy optimisation and CO_2 measurements. Where heating, cooling, sunshades and lighting are automatically controlled, and personal preferences are stored (UBM Development, 2023).

Table 1. *Timber Pioneer (UBM Development, 2023).*

Typology	*33 commercial tenancies*
City	*Frankfurt*
Country	*Germany*
Floors	*8*
Structure	*Glulam*
Floor area	*14,000 m²*
Constructed	*2024*
Highlights	*Frankfurt's first timber hybrid office building.*

Eva-Lisa Holt Arena, Karlstad

The Eva Lisa Holtz Arena, an indoor athletics facility located in Karlstad, was officially inaugurated in April 2022. Designed by Sweco Architects, this arena boasts a wooden frame construction and offers seating for up to 1,000 spectators. One of its notable features is a 58-meter timber beam, consisting of four parts each with a thickness of 1.4 meters, spanning a total length of 120 meters. Additionally, the audience bleachers are constructed using CLT panels. In terms of energy efficiency, the arena incorporates several key elements. The roof is insulated with 400mm of Structural Insulated Panels (SIPS), while the walls feature 300mm of SIPS insulation. Furthermore, the building is equipped with triple-glazed windows. Beneath the slab, there is 200mm of insulation. The structural components, including beams and columns, are sourced from Moelven Limtre, while the CLT panels are supplied by Stora Enso, located approximately 30 km away. To maintain indoor air quality and comfort, the arena is equipped with a high-performance SystemAir MVHR unit integrating heating capabilities, utilizing district hot water as a heat source.

Table 1. *Solar Arena stadium and Eva-Lisa Holt Arena, Karlstad.*

Typology	*Indoor track*
Location	*Karlstad*
Country	*Sweden*
Structure	*CLT & glulam*
Floor area	*9,000 m^2*
Constructed	*2021*
Collaborators	*Developer - ByggDialog* *Architect - Sweco*
Highlights	*High performance athletics facility constructed from mass timber.*

Norsenga Bridge, Kongsvinger

The Norsenga Bridge, situated in Kongsvinger, Norway, stands as one of the most substantial timber bridges in the country. Opened to traffic in 2017, this post-stressed two-lane bridge spans 95 m and includes dedicated paths for pedestrians and cyclists. To realize this impressive structure, approximately 710 m^3 of massive glulam beams were provided by Moelven (Nordic Steel, 2024). In the future, European bridge construction is expected to embrace untreated timber materials with a focus on passive protection measures. Strategies such as incorporating metal venetian blinds can help shield the bridge components from driving rain while still allowing for adequate ventilation and moisture management.

Table 1. *Norsenga's Post-Stressed Timber Bridge.*

Typology	*Timber bridge*
Location	*Kongsvinger*
Country	*Norway*
Constructed	*2016*
Highlights	*Metal capping for weather and water protection*

Holzhybridhaus, Frankfurt

Holzhybridhaus constructed in 2016 from 70% renewable raw materials, represents a sensible alternative to conventional concrete construction (Hirschmuellerschmidt, 2017).

Table 1. *Neubau Holzhybridhaus Taunusstraße (Hirschmuellerschmidt, 2017; Novak, 2016).*

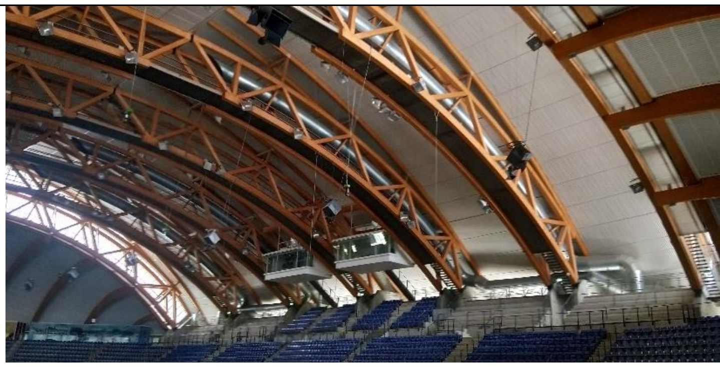
Typology	*25 multi-family residential apartments*
City	*Frankfurt*
Country	*German*
Floors	*4*
Floor area	*1,600 m^2*
Stucture	*Concrete and CLT*
Constructed	*2016*
Highlights	*"Special Recognition" award for "Exemplary Buildings 2017".*

Håkons Hall, Lillehammer

Håkons Hall stands as Norway's largest venue for handball and ice hockey events, accommodating up to 11,500 spectators. Since its completion, the hall has been a hub for various events, including tournaments, concerts, exhibitions, conferences, and banquets. Constructed specifically to host the ice hockey competitions during the 1994 Winter Olympics, Håkons Hall has become an iconic landmark in the region. The architectural design of Håkons Hall features a distinctive roof structure comprising four sections supported by double-trussed glulam beams. These beams enable impressive spans of up to 85.5 m, a total length of 120 m, and a maximum ceiling height reaching 40 m. Notably, the truss system incorporates steel plate and dowel connections, ensuring structural stability and integrity. To maintain optimal indoor air quality, Håkons Hall is equipped with a ventilation system capable of delivering airflow rates of 30,000 m^3/h under typical conditions. However, during full occupancy, such as during major events, the ventilation capacity can be increased to accommodate up to 200,000 m^3/h.

Table 1. *Håkons Hall, Lillehammer Olympic Park.*

Typology	*Hockey stadium*
Location	*Lillehammer*
Country	*Norway*
Floor area	*23,000 m²*
Constructed	*1993*
Collaborators	*Norway Olympic Committee* *Architect - Ståle Sletten* *Timber - Moelven*
Highlights	*Our tour was escorted along the service pathway in the rooftop glulam truss*

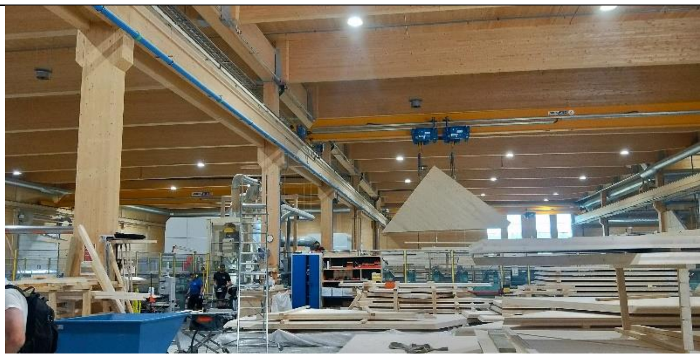


Splitkon, Åmot

Morten Johansen CEO of Splitkon took us for a tour around their CLT factory established in 1960. The factory produces 60-80,000 m³ of CLT product annually, where the demand in Norway is 200,000 m³. While explaining some intricacies of the manufacturing process, he mentioned that edge-gluing does have some benefits for reducing air convection through the CLT and its moisture protection, however their CLT panels are not edge-glued and will never be glued. This is because such an approach gives an indication where cracking may occur, in addition to giving a larger tolerance for movement within the CLT panel. Another difference compared to other CLT manufacturers was that no holes were drilled in the CLT panel for lifting, instead slings were used to reduce thermal bridging or air convection through the timber panel. Then once ready for transportation, trailers were used as storage with a plastic wrap only covering the top edge grain. Johansen did not have specific construction advice regarding stormwater management during construction, as in his opinion, an 8-storey building can be closed in 3 weeks. Being so rapid, he did not see moisture as an issue. However, if it does get wet, the panels should be dried slowly.

Table 19. *Splitkon CLT producer.*

Typology	*CLT manufacturing plant*
Location	*Åmot*
Country	*Norway*
Structure	*CLT and glulam*
Collaborators	*Building construction from mass timber from Martinson in Sweden*
Highlights	*Mass timber products wrapped before leaving factory.*



Norwegian Stave Churches, Oslo

A stave church is a medieval wooden Christian building once common in north-western Europe. The name derives from the building's massive timber structure of post and lintel construction. The Norwegian Museum reckoned to be the world oldest open-air museum to represent characteristic older Norwegian buildings. There are 28 stave churches still standing, with the earliest example being constructed in 1130 in Norway (Andresen, 2007). Pine trees selected were harvested to meet specific geometric requirements with buildings not traditionally treated. But in modernity, tar coatings have been applied for water proofing. However, this increases the risk of insufficient dry-out, if moisture ingress does occur past the tar layer.

Table 1. *Gol Stave Church*

Typology	*Church*
City	*Oslo*
Country	*Norway*
Floors	*1*
Structure	*Post and lintel construction*
Constructed	*1157–1216*
Highlights	*One of the oldest stave churches in existence.*

Recommendations

A number of recommendations are grouped into the themes of moisture protection strategies, as well as strategies for energy and materials efficiency. Where the recommendations are directed towards the Australian construction industry professionals that work on multi-storey mass timber buildings.

Recommendations for Moisture Protection Strategies

To alleviate the knowledge gap of moisture protection strategies in the Australian context, this section collates relevant moisture recommendations. Moisture should be managed according to control layer theory, using water, air, vapour, and thermal layers. Moisture risk assessment frameworks are recommended. Specifically, the industry standard ByggaF method (Figure 2), which is a method that guarantees, documents, and communicates moisture safety throughout the construction process, from planning to management (Lunds Universitet, 2022; Mjörnell and Gustavsson, 2016; SBUF, 2013). The method includes procedures and aids for all participants from developers, architects and other consultants, material suppliers, contractors to operations staff and managers. Where a full review of the project across the construction timeline is undertaken by moisture experts and a moisture safety officer (appointed by the developer) to review areas at risk of moisture damage with the manager of operations. As the reason for moisture damage arising in buildings could be due to a number of factors, from an ambiguous allocation of responsibilities, unclear requirements, lack of monitoring, unrealistic schedules, unclear communication, a lack of skills, inadequate procedures, or new types of structures, materials and components, which this standard aims to highlight and design out. Where there must be a strong focus on training contractors about moisture risks inherent to mass timber buildings and stormwater management strategies. Similarly, other international standards for moisture safety exist, such as the Norwegian Standard NS 3415 (2020).

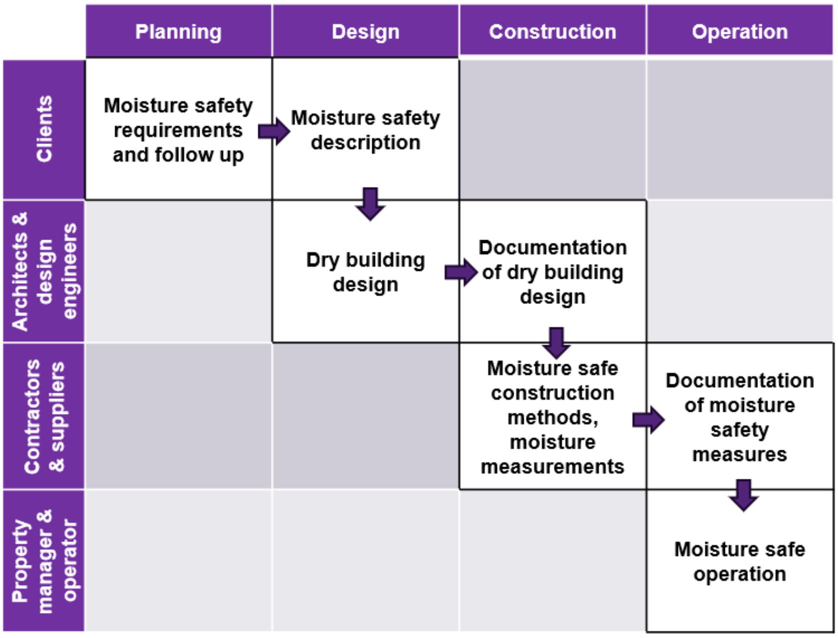


Figure 2. *Industry Standard ByggaF – Method for Moisture Safety of the Construction Process (SBUF, 2013).*

Table 20 below presents a summary of design recommendations and stormwater management suggestions that can be used by the Australia industry to inform prioritisation during the design and construction stages. A subset of these strategies was identified in the case-study buildings visited during this study tour period.

Table 20. *Summary of stormwater management strategies. Priority column gives suggestions to designers whether a specific strategy can be considered (low/medium priority) or must be considered (high priority) to ensure moisture-safety of CLT constructions in Australian climates (Strang, 2023).*

Type	Description of Strategy	Climate	Priority
Mechanical systems	• Mechanical ventilation to manage interior moisture levels.	Applicable to all climates	High
	• Dehumidification systems.	Subtropical and tropical climates	High
	• Slightly over-pressurising building by the mechanical ventilation unit throughout the year.	Tropical	Low
Control layers	• Drained and ventilated wall system. • Cladding should be the primary rain barrier. However, inclusion of a WRB and ventilated cavity adds redundancy. • Controlling exfiltration and infiltration using an air barrier to the interior of the insulation layer (exterior of insulation for tropical climates).	Applicable to all climates, including tropical climates	High

	• Placing insulation boards to the external of the panel, to prevent moisture from accruing within the panels.		
	• Internal insulation may be considered where an airtight WRB is durable to high temperatures and installed on the outside surface of the CLT. Thermal bridging must be mitigated, and close attention must be given to sealing junctions from stormwater behind a ventilated cavity. • Rigid WRB to withstand monsoon wind loads. Where WRB is adhered directly to the CLT or to a rigid sheathing board outboard of the insulation layer, this could be a material like OSB, fibre cement, or a proprietary product.	Tropical	High
Planning	• Execute an analysis of the risks for the CLT panels that may be exposed to moisture. • Just-in-time delivery of CLT panels. • Factory prefabrication.	Applicable to all climates	Medium
	• Keeping construction period within the dry periods of May to October.	Subtropical and tropical climates	High
Passive stormwater management strategies during construction	• Taping joints and seams of the WRB and airtightness membrane with solid acrylic tape. • Sealing end-grains of CLT panels before reaching the construction site through either the installation of capping joints during construction, or the sealing during manufacture with water resistant coatings. • Wrapping the face of CLT floor, wall (especially rough window openings), and ceiling panels exposed to rain or pooling water with diffusion open, membrane, suitable for use as moisture protection to prevent critical moisture-gain. • Water and airtightness champion on-site throughout construction to be responsible for quality checking implementation of building airtightness and weathertightness. Undertakes onsite induction of subcontractors to raise awareness for air control barriers risks for PH and moisture risks for CLT. Blower door test to check quality of WRB/air barrier implementation.	Applicable to all climates	High
	• Plumbing penetrations can be used to drain off excess stormwater during construction. Plumbing penetrations also considered during the operation of the building to drain internal plumbing leaks. • A temporary guttering system installed to sides of the CLT ceiling panels to assist in draining rainwater. • Once envelope is fully enclosed, the MVHR can be run on boost before building is occupied, to assisting in removing any construction wetting. • CLT manufacturers typically send CLT panels with 4 holes routed into the corners of panels to allow panels to be more easily craned into position with slings. Though penetrations should be avoided, and builder should instead install temporary eyelets for use with slings to crane into position.	Applicable to all climates	Medium
	• Preservative treatments. • Water repellent coatings.	Applicable to all climates	Low

	• Temporary tenting. • Enhanced durable materials.		
Active stormwater management strategies during construction	• Immediate removal of pooling water during construction using a broom. • Moisture content of CLT panels should be intermittently checked or continuously monitored with sensors, especially if exposed to pooling rain or rain events. • Installing a fan heater may also be considered to reduce the CLT panel moisture content to less than 18% before cladding internally. This is because, if a class 2 WRB and foam-based insulation is installed, dry-out capacity is significantly diminished. • Triggering of a water guard to shut-off water to rooms upon detecting moisture, in case of an internal leak.	Applicable to all climates	High

Recommendations for Energy and Material Efficiency Strategies

This section collates relevant energy efficiency recommendations for the Australian construction industry. Prefabrication practices can significantly assist both energy and material efficiency for mass timber projects and was thus highlighted by several projects, while circularity practices are also seeing increased demand in Europe. The PH standard is also well suited to highly energy efficient mass timber constructions, due to its inherently low thermal conductivity and ease of fitting external insulation and airtightness membranes to the rigid substrate of mass timber. Additional benefits of the PH standard are that it provides a net zero energy building framework that can readily be applied to the Australian context. While PH standard certification process provides a rigorous review and commissioning process to ensure that the building was constructed as per the design (PHI, 2022). The fundamental objective of certification therefore is quality assurance of the planning as a pre-requisite for successful construction and operation, as functioning buildings can only be built based on practice-oriented planning. This planning and coordination should take place as early as possible so that any errors can be corrected and suggestions for improvement can still be implemented. As getting it wrong locks in these mistakes for potentially the life-time of the building. With PH certification, the building owner can be sure that the building does achieve the expected level of efficiency and that the investment in better quality components will prove worthwhile. Where certified PH’s do not only feature supreme energy efficiency but also optimal thermal comfort, a very high degree of acceptance by users, permanent absence of structural damage, and are reliable in a future with increased temperatures. A formalised Design Stage Approval (DSA) requires that a PH Certifier checks the project documentation at a planning stage and confirms that the project will achieve the target energy standard if the building will be constructed according to the planning. Such a confirmation can be important for owners, designers, construction companies, and public financing bodies.

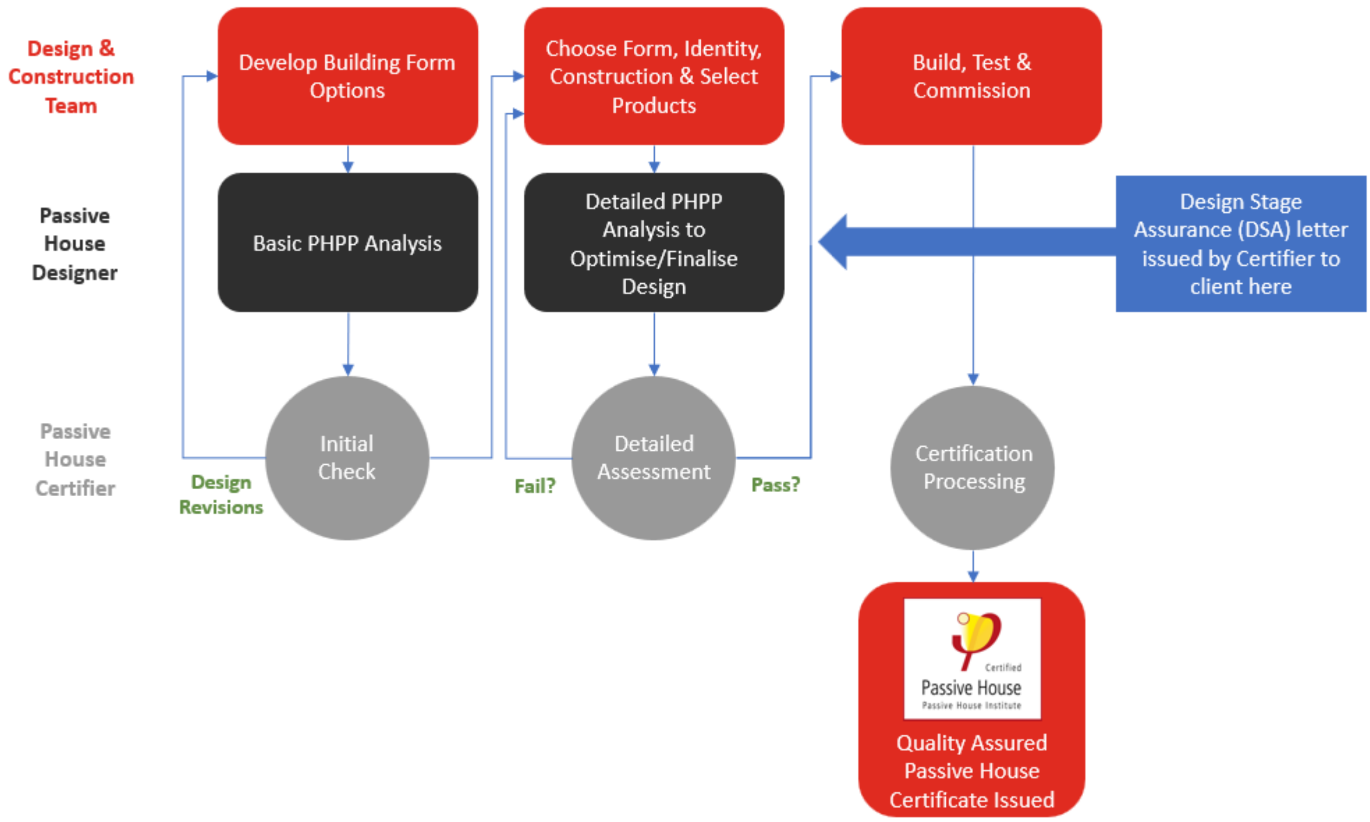


Figure 3. *The process for the Passivhaus standard.*

Table 21 below presents a summary of energy efficiency design recommendations suggestions that can be used by. A subset of these strategies was identified in the case-study buildings visited during this study tour period.

Table 21. *Summary of energy efficiency strategies for hot and humid climates. Priority column gives suggestions to designers whether a specific strategy can be considered (Strang, 2023).*

Description of Strategy	Climate	Priority
Highly airtight building fabric and mechanical ventilation.	Applicable to all climates	High
Automated window shading control.	Applicable to all climates	Low
Energy recovery ventilation to reduce ambient humidity loads.	Subtropical and tropical climates	Medium
Fixed exterior shading elements for windows or low windows-to-wall ratios to minimise direct solar gain.	Applicable to all climates	High
Exterior surfaces with low solar absorptivity to reduce solar radiation loads.	Subtropical and tropical climates	Low
Highly insulated envelope.	Tropical	High
Moderate insulation levels, while inclusion of insulation at the floor slab depends on the project's specific location.	Subtropical	Medium
Minimising internal heat gains through efficient appliances, reduced length of DHW pipes and ventilation ducts, and storage tanks outside of the thermal envelope.	Subtropical and tropical climates	High

Mitigation of thermal bridge.	Applicable to all climates	High for cold and medium for warm climates
Natural ventilation in subtropical climates when ambient temperatures and humidity is low.	Subtropical and tropical climates	High
Ventilated rainscreen façades to block solar radiation.	Subtropical and tropical climates	High
Glazing with solar control, moderate to high thermal resistance (double glazing), and high visual transmittance.	Subtropical and tropical climates	High

Conclusion

This report explores and identifies such stormwater management and energy-efficiency strategies used in a number of European best-practice projects. This is done to support the hypothesis that highly energy efficient multi-storey buildings constructed from mass timber are viable for adoption in the different climates of Australia and can facilitate the transition of the Australian construction industry towards carbon neutrality.

Mass timber elements are vulnerable to moisture, therefore there is an increased risk of biodeterioration for mass timber assembly during the construction stage. This is typically due to a lack of stormwater protection. However, wetting can be minimised or even eliminated by implementing stormwater strategies, such as prefabrication assembly processes or moisture content monitoring on-site. While low space conditioning energy consumption can be achieved through careful application of the PH standard and includes design elements, such as good levels of insulation, appropriate window sizing, quality and shading, excellent airtightness, low solar absorptivity of cladding, along with dedicated dehumidification and mechanical ventilation with enthalpy recovery.

The moisture risk assessment frameworks ByggaF method is highly recommended to guarantee, document, and communicate moisture safety throughout the constructed stages. While certification against the PH standard is also highly recommended to provide a rigorous quality assurance process to ensure that the building was constructed as per the design. These frameworks can assist the building owner in achieving the expected level of moisture safety, energy efficiency and that the investment in better quality components will prove worthwhile.

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