Mass Timber Buildings Moisture Monitoring and Management

A Comparative Study of Building Types, Design Techniques, and Climate Conditions for Enhanced Protection Plans and Best Practices

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Gottstein Fellowship Final Report

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About the Joseph William Gottstein Memorial Trust Fund

The Joseph William Gottstein Memorial Trust Fund, known as The Gottstein Trust, began in 1971. It is a national educational trust which encourages innovation and the pursuit of excellence through the people, processes and products within Australia's renewable wood products and forestry industry.

The Trust is the living legacy to honour Bill (Joseph William) Gottstein - who died in a tragic field accident in 1971 while visiting PNG. He was an exceptional, innovative man and was internationally respected. He was a scientist and a leader in the CSIRO forest products division.

The Gottstein Trust invests in capacity building which directly contributes to the success and evolution of Australia's wood products and forestry industry.

Governed by a board of Trustees - all with close industry links – every year the Trust calls for applications from interested candidates for Fellowships, Scholarships and Skill Development grant awards. These grants are awarded to individuals through a competitive selection process. The funding provided enables recipients to pursue projects, further their studies or undertake specific skill development. Regular short courses and industry field trips are also run each year, with a focus on understanding both forest science and wood science.

People involved in Gottstein activities have opportunity to build their knowledge and networks and expand their own capacity to contribute to the industry. The Trust is funded with the support of industry donations arising from an annual appeal and by investment earnings.

Further information may be obtained at www.gottsteintrust.org or email team@gottsteintrust.org

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Disclaimer

About the Author

Dr Maryam Shirmohammadi is an engineer who has worked on industrial research and development since finishing her bachelor's degree in 2006. She is passionate about developing practical solutions for industrial challenges that are tailored to the industry's needs and practical for adaption.

Over her research and academic career she has worked in various roles focusing on a range of different research topics including the impact of climate on technologies used in food and agriculture, product conditioning for optimum quality during and after harvest, impact of cellular structure on product response to environmental conditions, impact of strength in different scales (nano, micro and macro) on product quality from end user point of view, destructive and non-destructive assessment of product quality, impact microclimate on product conditions and service life, supply chain traceability and importance of traceability solution for ESG and EPD reporting.

In the past seven years her research has been focused on timber products, performance and service life. Her recent research has focused on the impact of conditional factors and climate on various properties of fibre-based materials including timber and engineered wood products in the Australian context. She has studied properties of Australian timber products exposed to various climate conditions as well as engineered wood products with layered structure. Her focus has been in understanding long term impacts of moisture exposure on product condition and methods to protect, detect, measure, repair and monitor for long-term service life of building elements.

The report presented here is the outcome of her study tour of Europe, Singapore, Canada and the USA focusing on moisture protection and safety planning for timber building. In this study tour she has focused on meeting experts in the field and discussing various aspects of the issue including impact of product type, climate conditions, building design, monitoring tools and effects of regulation in protection and prevention.

From this study tour she also is in the process of publishing a comprehensive comparison of cases she has visited and discussed, focused on best practice approaches and remedies recommended for prevention, protection and mitigation by the experts in the field.

This Gottstein Fellowship was awarded in 2023.

Acknowledgements

I would like to extend my heartful thank to all the experts, researchers, industry representatives and leaders for generously providing their time in-person or online during my research fellowship study tour. I am truly grateful for their time in sharing their expertise, knowledge and insights and providing direction and guidance that will enable me to navigate my research work and career moving forward. Their suggestions and introducing me to other laboratories, research teams, industry experts and projects made my fellowship tour much more practical and enhanced.

I would like to express my gratitude to The Gottstein Trust for awarding me this fellowship that provided the opportunity to travel internationally and engage with leading experts in my field of work. The fellowship opportunity has been both enriching and transformative and enabled me to deepen my understanding of key research topics, learn about emerging global best practices and strengthening my professional capabilities. This fellowship opportunity also allowed me to grow my professional network internationally, which has already contributed to increased outreach, starting new project conversations and opening doors for new collaborations and research projects.

I would also like to thank the Gottstein Trust management team for their support and understanding when medical advice I received meant the European leg my trip had to be postponed and for their patience when my birthplace made getting Visa's for the US leg a much lengthier process, which pushed the completion of my research travels into 2025.

Summary

This study aimed to visit global leaders and experts in the field of timber construction moisture protection, mitigation and monitoring from academia to manufacturers, industry, building designers and maintenance providers. The target outcomes were to develop a comprehensive review of existing solution development activities and technologies that can assist with prevention, detection/monitoring and remedies applied to address moisture issues in timber buildings. The author also took the opportunity to visit labs, meet academic leaders and senior industry members active in this area to develop a global network of existing expertise in order to access in future research and development activities and target collaboration.

From this project's learnings and observations, a comprehensive and comparative summary of outcomes in addressing moisture issues is reported in this document. This report aimed to summarise the learnings for the Australian timber industry sector as packages of short descriptive issues/topics and provide a snapshot of solutions applied, including from product manufacturing to construction site and end users/in-service. The report aims to provide information that will assist with the development of future discussions and project activities that lead to effective moisture safety planning and practice, building the industry's confidence to design and construct more resilient buildings that last the expected service life in Australian climate types.

More attention needs to be given to understanding moisture variation on building elements and their effective performance when exposed to weather and microclimates in buildings. There is a lack of standardised protocols for post-moisture exposure assessment, repair procedures and service life reassessment.

Overall project cost of the Vaxjo project in Sweden was reduced by 10% due to effective planning and design decisions to minimise moisture issues that led to faster interior construction completion. There were no delays or interruptions during construction due to bad weather events (645 mm rain during construction that was estimated to let 3,600 tons of water on the timber structure).

Drawing on global case studies and expert inputs the findings confirm that unaddressed moisture issues and lack of design focus are significant risk factors contributing to product quality loss, delay in construction processes, structural degradation, service life reduction, and costly repairs.

The study reinforced that moisture challenges are universal across climate zones, building typologies, design, and construction approaches. Success stories from around the world also demonstrate that these risks can be significantly mitigated through planning, early-stage design decisions, protective construction practices, continuous monitoring, and knowledge sharing across the industry.

The findings of this case study and to build upon their outcomes, the following areas are recommended for future work:

- Development of Australian moisture safety guidelines.
- Moisture risk assessment toolkit to develop practical tools for architects, engineers, and contractors to assess moisture risk in projects.
- Pilot demonstration of success stories and projects that illustrate best practice.
- Plan education and capacity building for the industry to deliver short courses and training modules for designers, builders, maintenance teams and building certifiers.

- Develop standards for measurement of moisture and product condition, sensor technology and monitoring data framework.
- Develop programs for long-term service life modelling.

Keywords: Moisture safety, climate zones, durability, service life, hygroscopic properties, prefabrication

Definitions

Moisture Safety consists of practices, strategies and plans put in place prior to the building construction process starting to minimise moisture impact on building process, material and building performance. It can include strategies to protect, prevent, detect, measure and mitigate any moisture-related exposures during and after construction. The goal of developing and implementing moisture safety strategies to minimise delays, avoid costly repairs and product rejection and replacement.

Moisture Content is determined as the percentage of moisture within the structure of timber at different depths. Moisture content measurement and monitoring is particularly important as the environmental condition that timber elements are exposed to changes due to factors such as weather changes during construction or plumbing leaks/condensation post-construction.

Water Ingress is defined as exposure of building materials to free water throughout the supply chain leading to moisture gain and increase in moisture content.

Engineered Wood Products (EWPs) refers to timber products that are engineered with adhesives under pressure with/without heat to enhance the performance of the timber itself and/or better use of resources for higher strength and service life performance.

Cross Laminated Timber (CLT) is an EWP made from layers of timber boards glued together that are stacked crosswise.

Mass Timber (MT) refers to EWP large panels that are manufactured for structural purposes, including flooring, walls, roofs and frames.

Light Timber Framing (LTF) are the timber boards that are manufactured for timber framing applications. They have required load strength to be used in wall, floor and roof design.

Service Life refers to the period that product is designed to fit for the specific purpose as a building element.

Environmental, Social and Governance (ESG) are factors that can be considered for the sustainability measurement of processes and products by investors or end users.

Environmental Product Declaration (EPD) is standard and verified documentation that provides clear and transparent information about product/service during its life to each stage of the supply chain.

Contents

Introduction

About The Gottstein Memorial Trust Fund

The Gottstein Memorial Trust Fund is an independent Australian education trust that promotes innovation and professional development opportunities by providing a competitive fellowship scholarship for people working in Australian forest and wood product industries. The trust was established in 1971 to honour Bill Gottstein who was an esteemed CSIRO forestry research scientist who lost his life during field work in Papua New Guinea [1]. The report presented here is the outcome of a Gottstein fellowship awarded in 2023 titled "Mass Timber Buildings Moisture Monitoring and Management, a Comparative Study of Building Types, Design Techniques, and Climate Conditions for Enhanced Protection Plans and Best Practices". The proposed study aimed to address the growing need for better understanding of moisture related challenges and moisture safety requirements in timber buildings. The study tour covered different aspects of the topic throughout the timber supply chain and a specific focus on moisture issues in mass timber and engineered wood product applications.

Background

Timber as a building material has been used in building construction for thousands of years [2]. In Australia, timber has been used in a variety of applications in buildings; as MT buildings and EWPs become more commonplace in the Australian built environment it is clear that the environmental conditions our buildings are situated in are often harsh. Because the challenges presented by the varied Australian climate are unique, an understanding of effective design, protection strategies, industrial best practices of EWPs and MTPs management from a variety of climatic regions around the globe is critical.

The insight and understanding of global efforts and case studies on moisture safety will advance Australian design, implementation and maintenance/management of timber buildings, enabling a durable, future-proof service life that fully captures timber's exceptional environmental benefits. The topic of durability and moisture safety for buildings and timber products is an ongoing discussion and topic of research and development projects globally. There are differences in opinion on how sensitive timber products are to moisture in different stages of the supply chain [3].

The case study outcomes reported here aim to provide a detailed summary of various moisture safety planning, practices and practical mechanisms applied globally. The report provides a comprehensive comparison of various project sites visited and discussions with experts in this field, focused on building types, design techniques, and climate conditions, shedding light on their role in managing moisture conditions post-construction.

This information has been presented in case study finding formats for industry to consider future protection plans and best practice development, providing construction and building design engineers with a summary of expert opinions and example outcomes from the case study as a foundation for the Australian industry to develop better moisture safety strategies and protection plans.

Moreover, this project aimed to provide a summary and feedback of expert opinions on commonly used protocols during manufacturing, handling, transport, off- and on-site storage, and during construction to the Australian timber and construction industries. The collected feedback can help the Australian industry to identify areas of improvement and implement measures/protocols/standards to define and enhance their moisture management practices.

Overview of the challenge

Water, heat and ultra-violet radiation are the three sources that degrade any building materials. Among the three, water is the most significant mechanism [4]. Almost all building types experience exposure to moisture or high levels of humidity throughout their service life. In Australia it is reported that water and mould damage account for 37% of insurance claims according to CARSI [5]. Moisture sources can be from exposure to weather changes (heavy rain and flash flooding) throughout the supply chain and construction stages, condensation, leakage and/or plumbing issues.

Timber as a building material offers many advantages such as sustainability, structural performance, and low-embodied carbon compared to other building materials. As a natural material, however, timber needs to be protected against any undesirable moisture exposure that can lead to product degradation and impact its designed service life. It is reported that almost half of the common causes of failure in timber buildings associated with design and planning including poor construction principles (14.1%), changes made on construction site (12.5%) and lack of appropriate design and protection against environmental factors (11.4%) [6]. As a result, all building assemblies need to be protected from exposure to moisture such as rain, ground water, air transport and vapour diffusion.

There are various solutions for protection against each of those exposure types including water barriers, air control layers, thermal control layers, air pressure control, ventilation for interior moisture control and dehumidification. It is important to have a clear understanding and expectation of supply chain complexities, climate variations and their impact on moisture changes during and after construction to put practical strategies in place for prevention, detection and repair/removal of moisture.

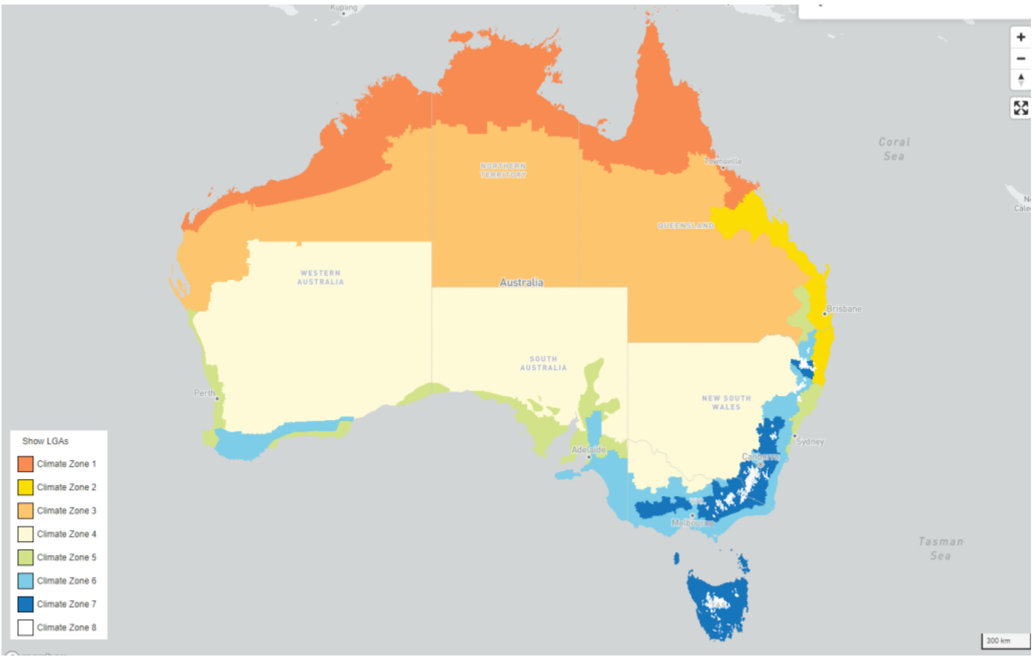

Figure 1: Climate zone map of Australia [7]

In Australia, construction zones have been defined by the national construction code (NCC) [7] as high humidity summer, warm winter to alpine (Figure 1). The average annual rainfall from 1991 to 2021 map is presented in Figure 2. Given the importance of climate types and moisture exposure on timber products' durability, it is crucial to develop building moisture safety procedures and planning that minimise undesirable exposure to water and high humidity pre- and post-construction.

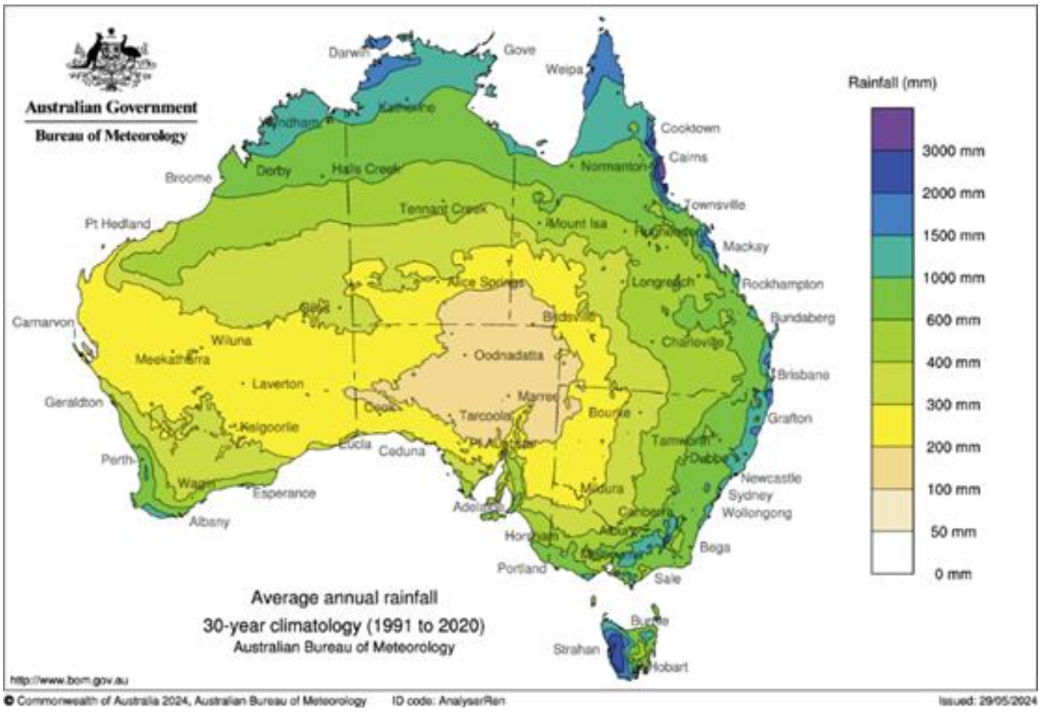

Figure 2: Average annual rainfall maps in Australia [8].

The study presented here aimed to understand the impact of climate, various types of moisture challenges and moisture safety protocols/procedures applied globally to provide findings for Australian industry adaptation and application.

Key themes and discussion topics

The project undertook a comparative approach and developed discussion points around the following topics to gather expert opinions and provide an overview of projects, activities and products in addressing moisture safety in timber buildings and construction. The following are topics of conversations throughout the case study.

- ***Climate, Timber Species and Regional Differences***

Considering Australia's diverse climates and their effect on moisture exposure of building elements during and after construction, the case studies aimed to discuss climate types, exposure duration and practical solutions that can be applied to various building and construction projects in order to minimise moisture issues.

The impact of product types including species, lay ups, adhesive types and gluing patterns were discussed with various industry representatives and research experts to develop a clearer understanding of important factors and protective solutions required that could contribute to and minimise moisture ingress and impact the type of drying required and speed of egress.

The topic of preservation and differences in treatment practices was discussed, as well as various physical solutions such as weather barriers, prefabrication, leak detection systems and monitoring solutions.

- ***Moisture-Related Failures in CLT/Timber Buildings***

Global experts' experiences with moisture in construction-phase and in-service leaks were discussed. The aim of these discussions were to identify the planning, design, protection and maintenance/monitoring factors from experiences that experts have had in similar scenarios. The common failure zones were discussed, and comparisons were made between similar types of moisture challenges and how different solutions have been developed to address a range of issues.

Examples of critical areas where more care is needed within the building fabric were discussed, such as flat roofs, terraces, wet rooms, ground floor panel bases and extra care needing to be communicated to post construction maintenance teams. The complexities of detection leading to the unexpected or delayed discovery of issues that moisture caused and possible structural decay in relatively new buildings were discussed. The aim of these discussions were to identify areas to better monitor, planning of short- and long-term maintenance required and possible insurance claim histories that can assist maintenance teams to better plan detection of moisture issues.

- ***Drying and Moisture Monitoring Practices***

In order to address the issues moisture can cause in timber buildings, various types of drying practices were discussed. The practices included passive and active drying and the possible limitations and practical applications for various scenarios depending on phase of building life (construction or post-construction) and scale of building vs scale of moisture issues. The discussion around complexities of drying, remedies required, and the importance of monitoring were highlighted and further technological advancements and required labour for static monitoring were discussed. The need for better communication and training for building and construction supply chain participants was raised and further discussion around education gaps and inconsistent practices on moisture measurement, prevention and management were discussed.

- ***Warranty, Insurance and Design Response***

It is crucial to consider the impact and importance of products and that they are used for the right applications and in best design scenarios so that the full-service life is achievable. The benefits of effective design and provided planned maintenance required to minimise expensive repairs and replacement were discussed. The impact of protection and moisture exposure prevention during construction was discussed. Construction management planning and moisture safety protocol development with defined responsibilities for supply chain participants were also discussed.

- ***Post-Construction and Occupant Behaviour***

The risk of excess moisture builds up considering the application of building sections and everyday activities (e.g., indoor clothes drying) and impact/requirement of climate types were discussed. The impact of construction practice and cultural considerations in building use and its impact on maintenance was also discussed. This was further highlighted in different case studies discussed. including examples of long-term decay from hidden leaks, condensation and lack of appropriate/regular maintenance and monitoring.

Methodology

The case study undertaken took a comprehensive approach to visit sites and discuss the topic with academic, research, building construction engineering, design and manufacturing industry representatives.

Overview of visited groups and sites

The project took a holistic approach by targeting discussions and site visits to a range of different global leaders in the field of building moisture and timber durability and service life*. Table 1 shows the list of organisations and areas of expertise consulted during the project's case study.

Table 1: Project's industry and academic visit list during the case study.

Country/Organisation	Type of industry	Area of expertise	Discussion topic
UK/ MB TRADA, NHBC, Engineering consultant	Consultancy/Timber research and development Timber building and construction engineering Timber building insurance and maintenance engineers	Timber Building design and service life Building insurance and repair engineers	"Understanding the Effect of Moisture on Cross-Laminated Timber" [9]
Belgium/ UGent	University research team	Continuous moisture monitoring and field trials	An experimental set-up for real-time continuous moisture measurements of plywood exposed to outdoor climate [10]
Germany/ Thunen Institute, University of Göttingen, Technical University of Munich, Fraunhofer Institute for Building Physics IBP	Research institutes Academic and university research groups	Timber durability, moisture movement, modelling timber service life, study of new and changing resource durability properties, moisture condition monitoring, field trials and impact of climate on timber product.	The combined effect of wetting ability and durability on outdoor performance of wood: development and verification of a new prediction approach & monitoring the "material climate" of wood to predict the potential for decay: Results from in situ measurements on buildings [11, 12] Building moisture monitoring, water ingress and moisture gain [13].
Slovenia/ InnoRenew	Research institute	Built and environment focused on material	Assessment of wood structural members

		processing and advanced efficiencies, engineering materials with focus on health and sustainability.	degradation by means of infrared spectroscopy [14].
Norway/ Norwegian Institute of Wood Technology	Timber engineering, research and development	Timber building moisture management, drying protocol testing and onsite moisture management.	A review on the protection of timber bridges [15]. Moisture safety strategy for construction of CLT structures in a coastal Nordic climate [16].
Austria/ University of Graz	University research group	Timber engineering and building physics experts.	BTZ laboratory at TU Graz was the early home of mass-timber research-building design and building physics [17].
Sweden/ Lund University, 1Ri.se Institute, KTH Royal Institute of Technology	University research Government R&D team Industry-focused research team	Timber construction, material science and service life laboratory research. Timber and moisture focused on degradation and service life. Building site monitoring and moisture condition improvement pre- and post-construction.	Methods for determination of moisture conditions in wood exposed to high moisture levels [18]. Moulds and mycotoxins in indoor environments—a survey in water-damaged buildings [19]. Moisture conditions in exterior wooden walls and timber during production and use [20].
Switzerland/ Moisture modelling and protection solution company	Building construction and service life moisture protection solution manufacturer	Moisture protection/airtightness solution developer and manufacturer for temporary and long-term protection.	Weatherproofing and airtightness for mass timber A technical guide to protecting building materials from the weather and delivering an airtight construction[21].
France/ Université Paris-Saclay	Research/university team	Wood moisture modelling	Evaluating moisture transfer properties of wood by inverse analysis of moisture content profiles determined during drying by X-ray attenuation [22]. Water migration in wood during imbibition

			assessed by X-ray imaging [23].
Singapore/ University, building authority	University maintenance and timber building management team Building Association Authority	Post-construction maintenance planning, management and repair. Regulator on building condition pre- and post- construction.	Singapore's largest MMC mass timber building takes shape [24].
Austria/ Stora Enzo	EWP manufacturer	Moisture in cross laminated timber.	Moisture management explained [25]. Understanding the effect of moisture on Cross-Laminated Timber [26].
Canada/ RDH Building Science Labs	Building science consultant	Building design, material behaviours, protective solutions, remedies after exposure.	Moisture and Materials, Moisture control handbook: principles and practices for residential and small commercial buildings & moisture in buildings [27-29].
Canada/ British Columbia Institute of Technology	Building Science and Design Research	Understanding timber building products and impact of design and climate on their service life and durability. Study of building sections/layer ups exposed to various microclimates monitoring wetting and drying.	Development of a whole-building performance research laboratory (WBPRL) for an integrated study of energy efficiency, indoor environmental quality and building envelope durability. Influence of cavity ventilation on the drying and wetting of plywood sheathing in the rainscreen walls in the coastal climate of British Columbia [30].
Canada/ Structure Monitoring Technology	Building condition monitoring and analysis	Moisture monitoring and detection systems from construction to the end of service life of the building.	Mass timber and water: Understanding the Risks [31]. Dry-out behaviour of cross-laminated timber (CLT) edge conditions in roof assemblies: A field study [32].
Canada/ Polygon Climate Control	Condition monitoring/ building optimum moisture/	Active moisture monitoring and detection system for	Protect building materials without

	microclimate monitoring	construction site and desiccant-based drying solutions.	compromising schedules [33]. Mastering moisture: The role of vapor pressure in wood and mass timber construction [34]. Managing moisture at mass timber student housing project [35].
USA	WoodWorks/ Wood Products Council	Association providing support and promoting use of timber.	Mass timber moisture management [8]. Mass timer moisture management during construction.
USA/ Colorado School of Mines	University research organisation	Moisture studies and monitoring.	Study of moisture conditions in a multi-story mass timber building through the use of sensors and WUFI hygrothermal modelling [36].
USA/ Oregon State University	University research team	Moisture monitoring in mass timber buildings.	Moisture exposure during construction The Forest Science Complex (Peavy Hall)- Oregon State University- [37].
USA/ International Mass timber conference	Conference	Mass timber building design. Moisture protection solutions during and after construction. Monitoring solutions. Case study of various timber building and moisture exposure.	Save the planet, build with wood. Mass timber at Skanska [38]. Mass timber protection: The New Zealand context, Lessons learned: Holistic moisture management in mass timber buildings, best practices for mass timber roof design and construction [39]. Wooden basements:hygrothermal performance analysis using in-field measurements and numerical simulations [40].

USA/ International Mass timber conference	Conference	Mass timber building design. Moisture protection solutions during and after construction. Monitoring solutions. Case study of various timber building and moisture exposure.	Save the planet, build with wood. Mass timber at Skanska [38]. Mass timber protection: The New Zealand context, Lessons learned: Holistic moisture management in mass timber buildings, best practices for mass timber roof design and construction [39]. Wooden basements:hygrothermal performance analysis using in-field measurements and numerical simulations [40].

*Note that the project focused on design aspects and methods to prevent, detect and mitigate moisture in timber buildings. The project did not include chemical treatment within its scope, as such treatments are not commonly used in all parts of the world due to regional differences in practices and regulations.

Findings

Timber is a globally preferred building material, and around the world, numerous projects are underway to better understand its properties and improve protection and building design for service life. A common focus across these initiatives and activities is developing improved durable timber products tailored to different building design, applications/service conditions and climate type.

Moisture safety and management is an important area of consideration for any building regardless of climate type and material used [29]. Throughout the study tour, discussions and visits with experts in the field highlighted the importance of moisture safety and planning including strategies put in place for protection, detection, mitigation and monitoring during the building service life. Moisture -regardless of material used for the construction- can enter buildings in different forms including liquid water, water vapour, liquid and vapour from soil and moisture built in construction elements [29]. Reported moisture ingress pathways into the building envelopes are shown in Figure 3. Any building throughout its life can be exposed to these sources of moisture and if adequate design, protection, detection and mitigation are not applied these can lead to damage from discoloration and surface degradation to mould growth and structural loss [41].

For timber products and buildings, moisture exposure risks across the entire value chain need to be carefully considered and management protocols put in place. The protocols include implementing moisture safety planning, protective measures, early detection and monitoring systems and appropriate drying strategies where required [3, 8, 9, 42-45].

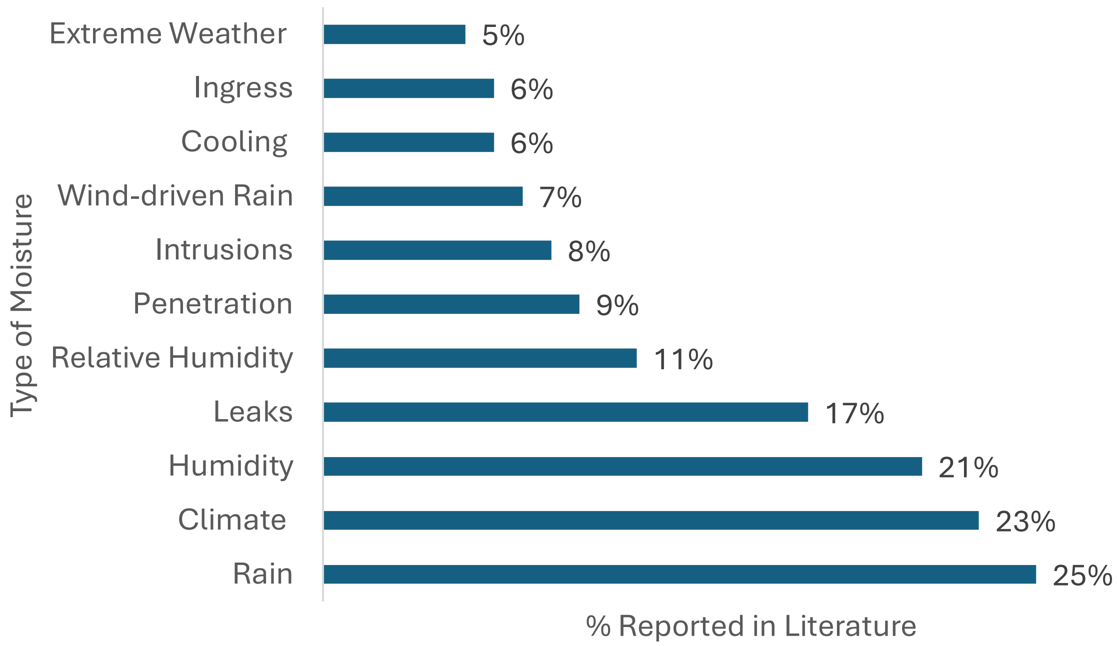

Figure 3: Summary of building construction exposed to moisture types reported in literature [41].

Planning for moisture safety throughout the construction timeframe as well as the entire timber product supply chain is becoming more commonly recommended by experts in the field [3, 16, 42, 43, 45-47]. Understanding the timber product supply chain (

Figure 4) and potential events that can lead to moisture gain and increased moisture content are being considered for deciding on construction timelines, level of protection applied, drying requirements and potential construction delays that can occur.

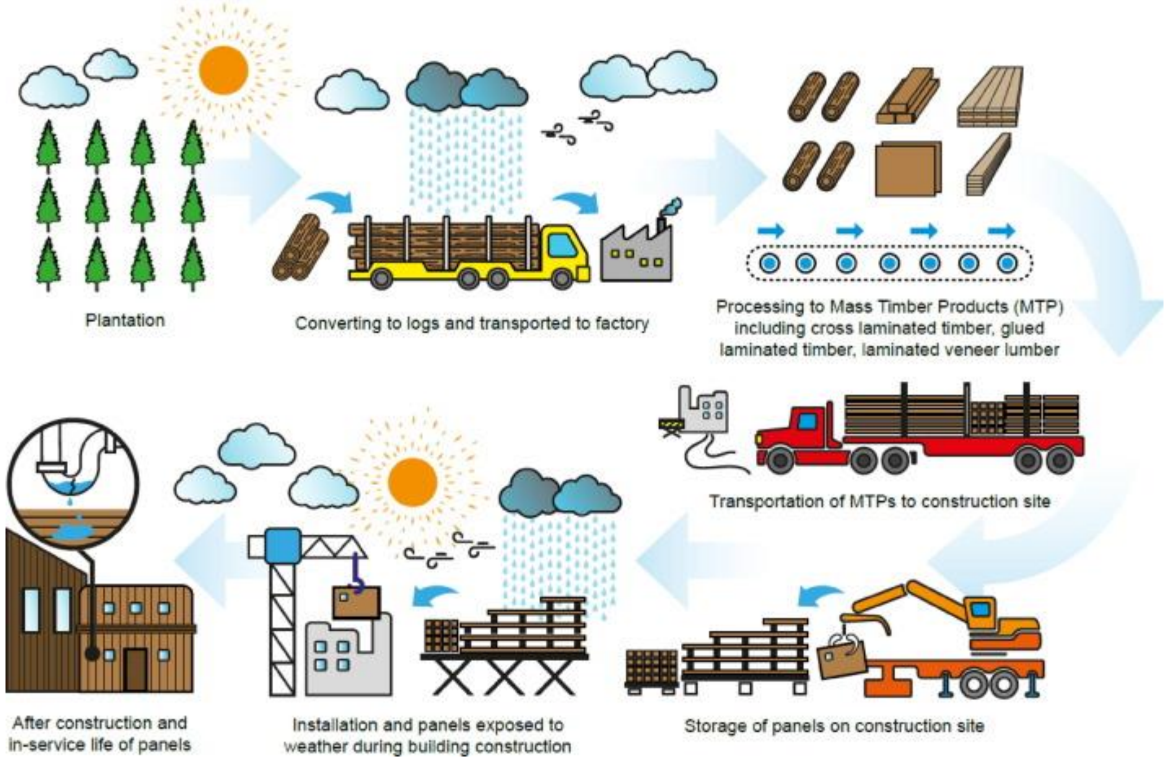

Figure 4: Diagram of moisture exposure throughout the supply chain of timber products from forest to service life [48].

There are various groups and teams across the world that work on the topic of moisture that focuses on better measurement, improving prevention, detection and developing more practical solutions where repair is needed. Some of the recommended steps in developing moisture safety planning include assessment of climate types, risk associated with exposure that leads to rapid moisture gain, development of moisture management plans (detect, measure, mitigate and monitor) and improving design for better moisture protection.

Below is a summary of project discussions and visit findings provided.

General

- If not addressed, moisture can be a problem in all climates and building types. Designers/builders/owners need to work together to understand the impact of moisture and address the issues it causes.
- Construction moisture management and moisture safety planning is crucial in minimising issues caused by moisture, in addition to targeting exposure to moisture before building completion.
- In various parts of the world there are specific requirements for building completion and sign-off to address moisture in a methodical way. Elsewhere the conversation is happening around better regulation and policies to manage moisture.
- The effectiveness of design and use of moisture protective solutions are important design considerations to eliminate damage, prevent expensive repairs and avoid drying processes.

Preconstruction

- From a manufacturing and product specification point of view, the differences between the product design, impact of layups, adhesive types and patterns were discussed. Critical areas such as openings, connections, edge gaps and overlaps need to be considered for appropriate moisture protection and monitoring. This highlighted the importance of moisture safety planning throughout the supply chain from manufacturing to service life.

Building design

- Better design and consideration of critical areas to protect is an important topic for any building type, especially for timber and mass timber buildings. Some recommendations are around wet areas, flat roofs, opening/areas exposed to condensation and high humidity exposure to building microclimates. Avoidance of flat roofs or redesign for slope and drainage, and caution with untreated CLT in exposed or wet areas have been recommended.

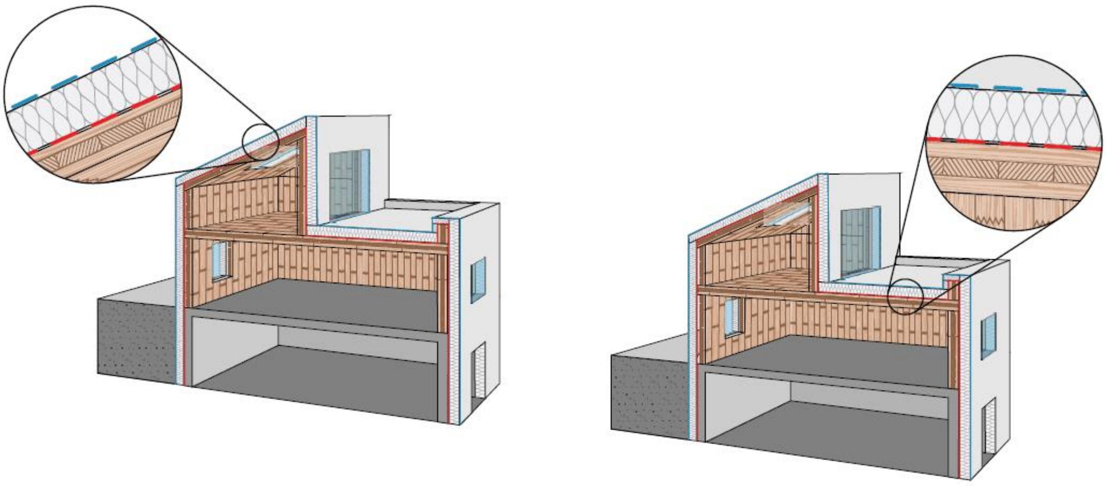

Figure 5: Roof protection layups for pitched and flat sections [49].

- The importance of perfect and better design to separate indoor from outdoor to eliminate any moisture issues were discussed. If designed correctly, the climate becomes irrelevant as the building elements are protected and will not be impacted.
- Prefabrication and impact of protecting prior to product arrival on site can eliminate moisture issues, improve construction process and speed of construction and reduce any possible need for drying.
- Appearance and surface changes due to exposure to varying conditions and high humidity.

Figure 6: Mould issues in building elements exposed to high humidity environment[50].

Construction phase

- During construction, monitoring of building elements is becoming more common with focus on varying climates and type of expected exposures.
- Methods of moisture monitoring on construction site.
- Monitoring technologies and leak detection systems are used more often in projects. Previously the use of technologies was more focused on repaired sections and after moisture issues occurred. However, with changes in building energy requirements, indoor condition monitoring and smart building systems especially in larger projects, the use of sensing and detecting systems is becoming more frequent.
- The use of temporary roof protection during construction was discussed in different case studies where the protection is applied at the beginning of the construction phase. The importance of planning and issues caused by no protection leading to higher cost of temporary roofing during the construction phase and construction delays were also discussed as lessons learnt from previous projects. In some cases the application of protection late during construction meant that the building was exposed to high levels of moisture during extended exposure. The drawbacks and costs were discussed.
- Various drying approaches have been applied and tested for pre- and post-construction issues with wetted building sections. It is important to determine the goal and initial condition of building elements, and monitor the changes and movement of moisture to achieve the targeted optimum condition. Once achieved, continued monitoring is required to maintain the required moisture condition and ensure no further moisture gain.

Post construction and service life

- Review of mass timber buildings across the world shows the need for more maintenance planning and integrated monitoring so issues can be detected early and resolved.

Building practice and training needs

- The need to develop educational programs and additional technical best practices information along with training opportunities for building operators and onsite workers' skill development were raised in many discussions across the case study. The importance of understanding timber properties, critical areas of exposure, impact of building layup when there is exposure to moisture and challenges reducing the speed of drying or blocking air circulation for drying were discussed on many occasions, especially on construction site visits.

- Targeted training for contractors, designers, and warranty assessors.
- Need for better tools and standards for moisture measurement and drying.
- Impact of weathering and degradation of moisture changes in products.
- It is important to define the type of exposure and prevention for moisture issues and levels. Definition of moisture gain and exposure to high humidity that can cause mould and lead to decay development need to be developed and communicated to the construction operators and building maintenance teams.

Solution development and research

Moisture risk in building and timber products depends on the duration of wetness, and not just the amount of sustained exposure in a wetting event. The duration and frequency of exposure especially during construction when exposed to weather changes, and post construction when exposed to condensation and leakage are more critical than total water absorbed. Case studies have shown that issues with structural loss and decay can begin from as early as four months if moisture is not detected and issues are not addressed.

Figure 7: Field trial set up at the University of Ghent monitoring continuous moisture changes of timber sections exposed to weather.

Timber products can be at risk if the moisture issues during construction are not addressed. The greatest risk period is before the roof is installed. Various solutions can be applied including prefabricating moisture barriers and installing semi-finished building sections rather than exposing timber elements to weather and applying solutions on site.

Figure 8: Prefabricated building sections arriving at site protected for any weather change and moisture exposure, Switzerland.

Inadequate protection during the construction phase and lack of monitoring can lead to severe delays or hidden decay especially if building sections are closed before drying. The lack of moisture safety protocols and monitoring could lead to costly remedies such as the need for removing sections and replacement. As the enclosed systems have limited drying capacity, there are risks for decay within critical areas of the building and longer-term drying requirements, which will cause further delays in building structure.

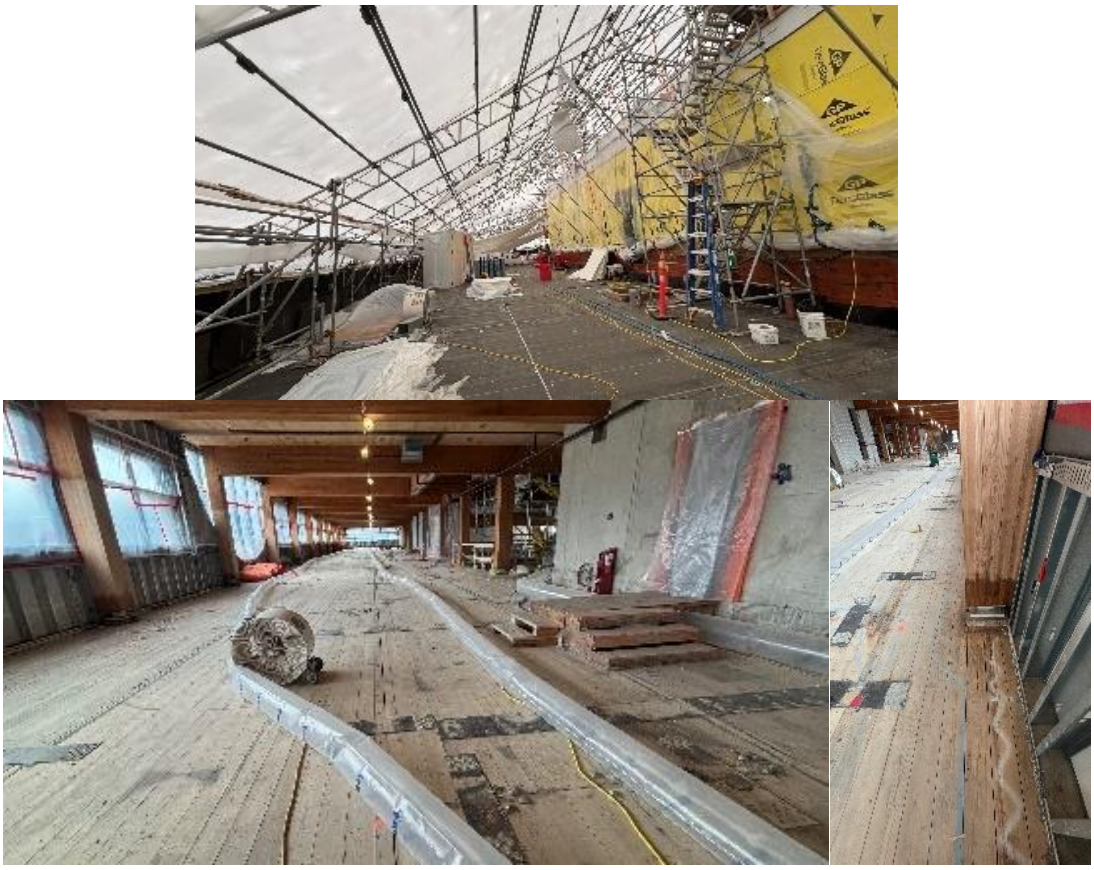

Figure 9: Building with moisture exposure and no monitoring of conditions that led to construction delay and protective roof applied later with need for major drying and some decayed sections.

Figure 10: Example of drying process on construction site focused on reducing moisture content using desiccant drying (top) and tunnel fan drying (bottom) [51].

Attention to site requirements and effective building design addressing climate and construction type can reduce or eliminate the need for further remedies (such as temporary roofing, drying and section replacement). Effective design features providing some of protection are overhangs, increased ventilation, appropriate species selection, application of surface protection and prefabrication of sections.

Figure 11: Laboratory study of building sections exposed to various moisture scenarios.

Figure 12: Large scale testing of timber building section set up with different layer up exposed to post-construction (leak/condensation) moisture.

Figure 13: Large scale experimental set up at TalTech testing the moisture changes in timber structures (CLT and timber framing) using real-time data collection.

Moisture monitoring solutions are becoming more advanced and available for various stages of building life from manufacturing to service life. Wired and wireless moisture sensors are now developed with monitoring analysis packages providing information for building designers, maintenance teams and owners about internal and external conditions as well as detecting peaks in moisture content potentially causing mould or decay issues in buildings.

Figure 14:Large scale indoor and outdoor condition monitoring of timber structures using different types of sensors at TalTech.

Figure 15: Leak detection systems applied on outer surface of roofing.

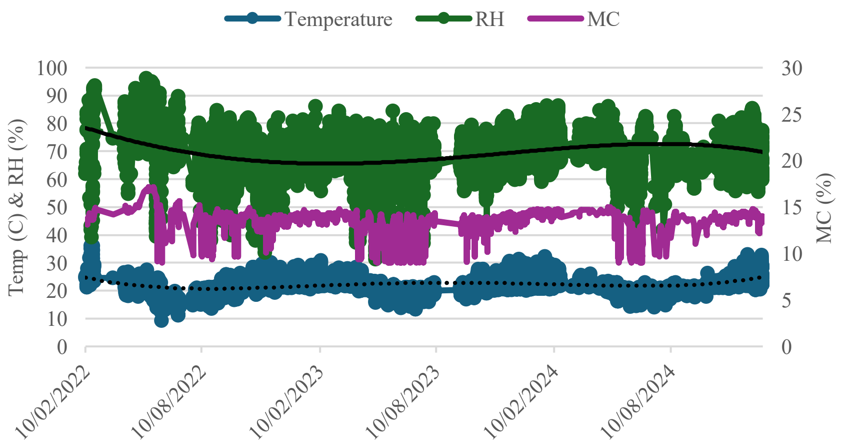

Figure 16: Condition monitoring of mass timber building using wireless sensors focused on building design, critical areas exposed to moisture and indoor/outdoor conditions [52].

In addition to moisture monitoring for timber moisture content, more advanced leak detection systems are also being used in critical areas of buildings where exposure to moisture can happen due to various design features such as flat roofs, wet crowded/public areas and green roofs/gardens. Microclimate monitoring within the building structure provides practical information about critical areas, types of end-user impact and targeted sections for moisture monitoring. The building interior environment and impact of high humidity studies recommend relative humidity ranged from 30-50% to maintain the optimum durability performance of mass timber product [43]. This highlights the importance of implementing effective design, application of humidity control to regulate indoor climate as well as monitoring technologies to address any critical change in product condition. Tracking internal conditions (e.g., RH, temperature, UV) can assist with information to be used as an early-warning system for moisture risk, especially when embedded moisture sensors are not feasible. The information can be collected for various building products, design considerations and building performance monitoring.

Figure 17: Internal building condition monitoring of different design and layer up

Delayed detection of any moisture issues can lead to further construction delays and structural damage to the building elements. The existing detection systems can provide active and real-time moisture analysis data to the building operators during and after construction, providing recommended drying needed for each specific stage of the building process. An active moisture measurement system can be used to alert the building team about possible leakages, moisture pooling on the surface and movement of moisture within the structure. The active monitoring data can also be used to focus on critical high humidity levels which lead to mould development and aid planning for increased ventilation of dehumidification as required.

Various drying and dehumidification

Figure 18: Sections of mass timber building exposed to outdoor environment and maintenance in progress addressing various moisture issues.

There are gaps in existing regulatory requirements and design protocols ignoring moisture safety during and post construction. Current standards are still evolving, however, more attention needs to be given to understanding moisture variation on building elements and their effective performance when exposed to weather and microclimates in buildings. There is a lack of standardised protocols for post-moisture exposure assessment, repair procedures and service life reassessment. Wood as a porous and hygroscopic material can absorb moisture from the environment; rain and pooled water on construction sites can increase the moisture content of mass timber elements during construction. Construction site drying can be challenging due to access, building construction stages and space/logistic requirements. Therefore, the effectiveness and efficiency of drying methods play an important role in minimising delays, cost as well as any potential surface changes or degradation. Various drying methods and setups are used depending on project size and climate type. Some of the considered factors when selecting the drying method are effectiveness at low temperatures, efficiency (cost related to duration and energy requirements) and drying speed with minimum impact on material degradation, energy cost and effective removal of moisture.

Figure 19: Desiccant drying on construction site.

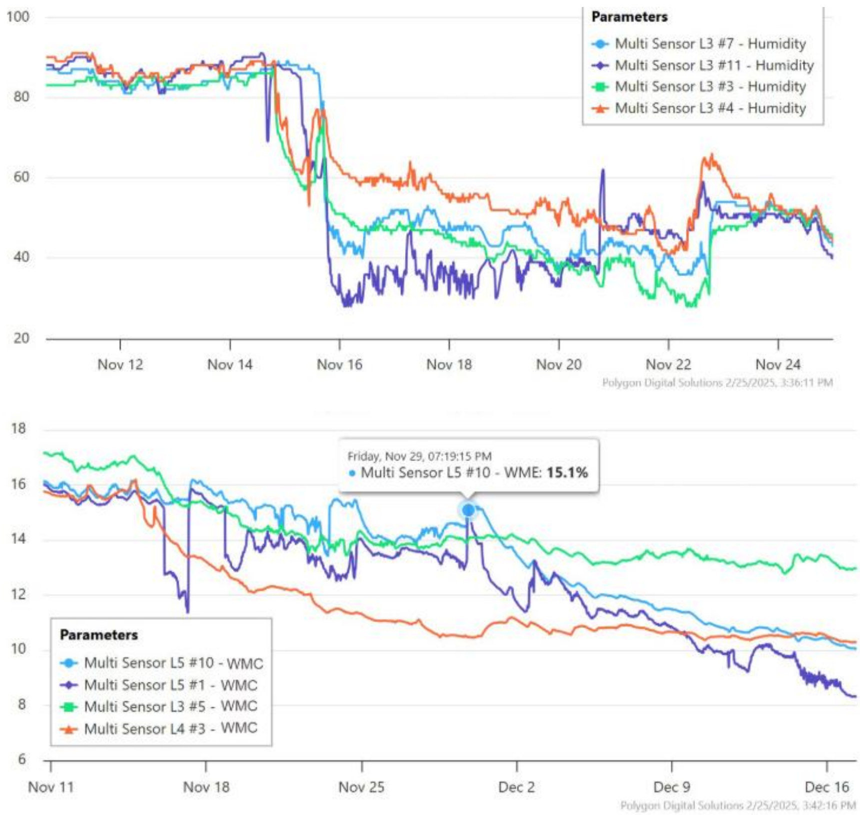

Figure 20: Monitoring of drying panels using desiccant drying technology in a case study building exposed to prolonged rain and water pooling [35].

The combination of effective drying and climate monitoring systems allows informed decision making during the repair and drying process. The gathered data will provide effective information about any changes in air humidity and timber element moisture content monitored at different depths to achieve the targeted optimum moisture condition. The gathered information can also be used in determining estimated drying time required, energy consumption and effectiveness of approach. This provides valuable insight into climate, building type, exposure level and required effort to address moisture issues for future project planning, moisture safety and management.

Figure 21: Fan drying using air tunnels in both sides of panel (top) and targeted fan drying in mould areas (bottom).

Encouraging International Case Comparisons and Sharing of Lessons Learnt Approach

Examples from international case studies with focus on design factors, decision making and construction/post construction factors can help the development of comprehensive and informed practices for future moisture safe project plans. Europe, Canada, Australia, New Zealand, and the U.S. show a wide variation in design practices, climate impacts, and regulatory responses when it comes to moisture management in building construction. Long-term outdoor exposure to moisture and testing of its impact have revealed both surprising resilience and serious vulnerabilities across different case studies. The discussion throughout this study tour with experts in different fields highlighted the need for a standardised approach and inclusion of external and construction processing factors in minimising moisture exposure as well as when drying/restoration is required and planned. In many cases the decision for overall protection (such as temporary roofing and covering large sections), regular/real-time moisture measurement and identifying critical areas for mould and decay development, was delayed due to a lack of technical knowledge/experience of material response, climate impact and factors required for degradation. In some cases, the delay to decide on a protective approach and discover areas prone to degradation caused costly repairs and lengthy delays in project completion.

Regulation and examples to learn from

Växjö Station project

Weather and moisture protection planning took place during the construction planning process for the Växjö railway and town hall project in Sweden. The project which is called "the greenest city in Europe" was built from 1,100 m^3 of glulam and 3,100 m^3 of CLT in an area of 17,000 m^2 [53]. Moisture safety and management was considered as a key factor in project planning for the Växjö project. This decision was made based on recent studies' recommendations for mould growth as a significant risk in building construction in the Swedish climate [54, 55]. A weather protection tent was mounted above the project as shown in

Figure 22. The protection was designed to shield the entire construction project from moisture ingress as well as provide a safe work area for construction workers. Other gains from the decision made to protect the entire construction site were faster construction processes especially in interior work as the protective measures made the starting of internal work possible earlier even without the full envelope construction.

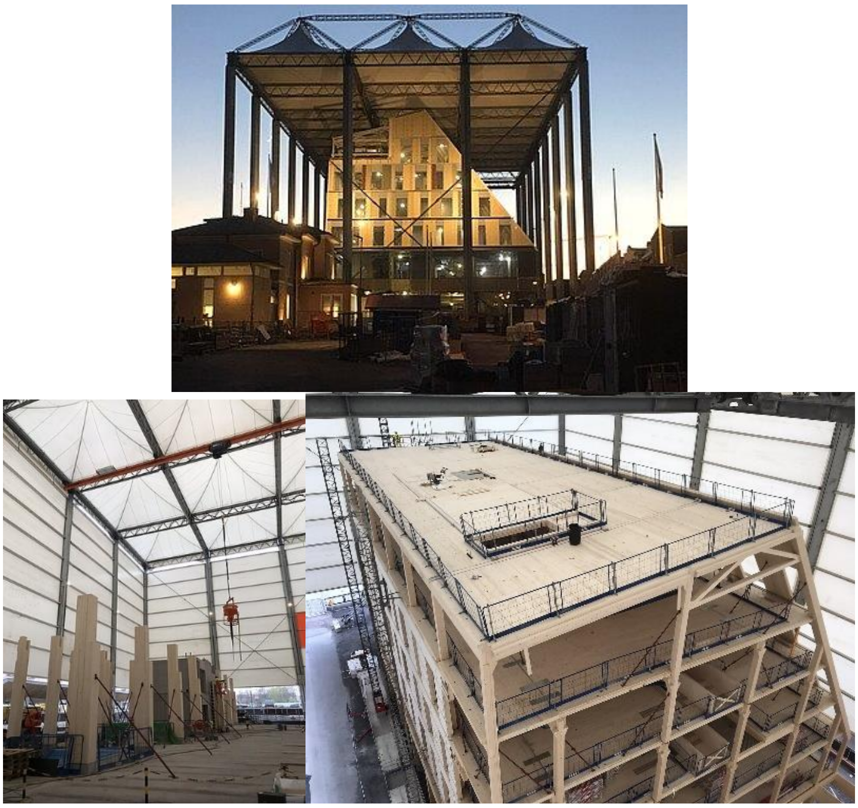

Figure 22: Växjö project with moisture safety planning and protection applied throughout the project construction phases [56].

The project moisture safety protocol was developed using moisture readers to monitor moisture content, and protective covers and roof to minimise dimensional instability due to weather exposure. Based on Swedish sustainability standards focusing on moisture monitoring, indoor climate quality and energy efficiency, the project achieved Miljöbyggnad Gold certification. The overall project cost was reduced by 10% due to effective planning and design decisions to minimise moisture issues that led to faster interior construction completion. There were no delays or interruptions during construction due to bad weather events (645 mm rain during construction that was estimated to let 3,600 tons of water on the timber structure [57]) as the roof allowed a safe and protected work environment for the operators. The application of roofing to protect the entire project from moisture had a significant impact in project on-time completion [57].

Canadian Leaky Condo Crisis (CLCC)

In 2008 it was estimated that over 72,000 wood frame units built since 1985 to early 2000 in Canada had leak issues, costing over $1 billion in repair, with 50% of the reported cases being condominiums [58]. The issues reported were a lack of attention to building design and climate requirements, a lack of drainage systems within the building envelope, use of unbreathable layers of materials, and no maintenance or detection scheduled leaving the moisture issues for prolonged period as the problems were invisible. The building designs were based on designs originating from much dryer climates such as California. The lack of appropriate design, detailing, detection and maintenance led to major issues such as mould growth, structural failure and large repair/replacement bills. The outcomes of years of investigation launched by the Canadian Mortgage and Housing Corporation led to regulations requiring higher construction, material quality, inspection regime and design standards which apply to the building industry in Canada today [58].

The issues caused by the CLCC years led to further work in development of moisture focused strategies, construction moisture management practices and education programs for the building industry [59].

Table 2: Summary of changes made, and lessons learnt from CLCC.

Issues Identified	Solutions Developed
Rain Screen Principle	Utilisation of drained and ventilated rain screens in wall design to manage bulk water away from structures. BC Building Code (2006) and National Building Code of Canada (NBC) began requiring rainscreen assemblies in wet climates.
Envelope Engineering	Importance of envelope design for buildings was recognized as required element for building certification and led to involving engineers to calculate, design and ensure durability and moisture resilience for building design and service life. The requirement for building envelope consultants was highlighted and become a routine practice for building design and inspection.
Building science incorporated in educational programs	The focus was directed to train practitioners such as architects, builders, and inspectors on how to measure/detect/monitor moisture movement, vapor diffusion, and thermal bridging. Practical solutions and training were developed and are now offered through British Columbia Institute of Technology (BCIT), where both R&D projects can test new product performance and building operators can also get trained with hands-on courses related to building layer ups and design factors.
Knowledge of material types	The use of breathable weather barriers, capillary breaks, and moisture tolerant materials has become a common practice where materials are tested for design and climate types. The concept of face-sealed building elements such as cladding systems was studied and discussed so that they are only used for specific applications.

Inspection requirements from expert third party for insurance and warranty programs	It now has become a common practice to have third party experts review and assess the building envelope details for specific service life durability purposes. Building condition assessments have now become a process to continuously monitor and address any issues prior to them becoming major problems. Warranty programs developed for BC include two years on materials/labour, five on building envelope, and 10 on structure of the building.

NZ Leaky Building Syndrome (LBS)

In New Zealand, it was estimated that between $11-23 billion damage is expected from around 80,000 homes experiencing the leaky syndrome problem. Faulty building envelopes, water penetration at high rainfall and moisture finding its way into the building fabric were listed as the major issues with the LBS in NZ. The building fabric remaining at high moisture level for long periods of time led to structural loss and health issues for the occupants. The design issues were a lack of appropriate flashing, draining the moisture away from building fabric, lack of attention to cladding design/requirements, failed sealing materials and wind driven water entering the building fabric through balconies without the required design features [60].

In NZ further investigation into the LBS led to changes made to enhance the building conditions and protection against moisture issues. The list of those changes are summarised in Table 3.

Table 3: Summary of actions taken in NZ after lessons learnt from LBS.

Timber treatment requirement	In 1995 the NZ standard included the change to require treated timber for wall framing.
Department of building and housing (DBH) developed	In 2004 DBH replaced the NZ building industry authority (BIA) which is focused on enforcing building standards and addressing any regulatory gaps that could lead to service conditions such as moisture issues in buildings.
Regulation for weathertight homes Act 2006	This was developed to assist end-users/owners with issues related to weathertightness, building design and material selection.
Building code provisions enhanced	Further requirements for external moisture management included design features, selection of materials and detailing.
Licenced building operators required	This requirement promotes the need for further skills and experience needed for the building industry to deliver buildings that comply with existing requirements and standards.

Conclusion and recommendations

This report presents the findings of a case study tour of timber buildings and global industry experts focused on moisture safety during and after construction. The report outcomes highlighted the critical importance of integrating moisture safety planning throughout the life cycle of timber products and buildings, from product specification and prefabrication to construction, occupancy, and end-of-life. Drawing on global case studies and expert input from leading research institutions, manufacturers, consultants, and building authorities, the findings confirm that unaddressed moisture issues and lack of design focus are significant risk factors contributing to product quality loss, delay in construction processes, structural degradation, service life reduction, and costly repairs.

The study reinforced that moisture challenges are universal across climate zones, building typologies, design, and construction approaches. However, success stories from around the world also demonstrate that these risks can be significantly mitigated through planning, early-stage design decisions, protective construction practices, continuous monitoring, and knowledge sharing across the industry. Countries such as Sweden, Canada, and New Zealand have turned past failures into opportunities by embedding lessons learnt into standards, codes, best practices, application of new technologies and educational programs.

For Australia, adopting a proactive and holistic approach to moisture safety in timber construction will be vital in ensuring long-term durability and public confidence in timber buildings. This includes clear protocols that address pre-construction protection, drying and monitoring strategies during construction, and post-occupancy maintenance scheduling and regular checks. The findings in this report provide a strong foundation to inform national discussion, project planning, and regulatory reform.

From the findings of this case study and to build upon their outcomes, the following areas are recommended for future work:

- Development of Australian moisture safety guidelines that translate international best practices into Australia-specific technical guidance documents and design protocols tailored to local climate zones and construction methods. The guidelines will enable collaboration with national industry associations and organisations to provide support to broader industry representatives leading to the establishment of formal moisture safety standards.
- Moisture risk assessment toolkit to develop practical tools for architects, engineers, and contractors to assess moisture risk in projects as early as possible and integrate mitigation strategies into planning and procurement.
- Pilot demonstration of success stories and projects that illustrate best practice. Partner with construction industries, consultants and government agencies to implement moisture safety protocols in selected demonstration buildings and provide educational materials for broader industry training and implementation. Develop outcomes documents and reports that validate the short- and long-term benefits of practical design, planning, use of monitoring technologies and best practices in achieving best outcomes on durability/service life, insurance claims reduction, and construction efficiency.
- Plan education and capacity building for the industry to deliver short courses and training modules for designers, builders, maintenance teams and building certifiers. The training materials need to focus on moisture safety throughout the service life, timber moisture behaviour, monitoring technologies, and drying strategies. Incorporate lessons from existing case studies globally including Canadian and New Zealand education models, which successfully raised industry standards post-failure.
- Develop standards for measurement of moisture and product condition, sensor technology and monitoring data framework. This can be achieved through national case studies on the performance of embedded and wireless moisture monitoring systems. The outcomes will assist in the development of a standardised framework for collecting and interpreting moisture-related data across various project scales, product types, building designs and climates.

- Develop programs for long-term service life modelling that undertake research to investigate the moisture changes throughout the product/building life that affect their mechanical and physical performance. This modelling will inform and support life cycle assessment (LCA) of products and buildings, insurance frameworks, and circular economy initiatives.

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