Fellowship Project Report

Gottstein Trust
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The Global Perception and Understanding of Vibration and Acoustics in Timber Structures

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Gold Coast

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Image: CSTB Acoustic Testing Facility in Paris, France. It showcases the breadth and depth of testing environments needed for acoustic assessment of building materials.

The Gottstein Trust

Joseph William Gottstein Memorial Trust Fund (The Gottstein Trust) was established in 1971. It is a national educational trust to support Australia's forest and forest products industries. The purpose of the fund is to; create opportunities for selected persons to acquire knowledge which will promote the interests of Australian forestry industries for the use of forest and forest products.

Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products within the Commonwealth Scientific Industrial Research Organization (CSIRO) when he was tragically killed in March 1971. The accident occurred as he was photographing a tree-felling operation in Papua New Guinea. He was held in such high regard by the industry which he'd assisted for many years, that substantial financial support was successfully raised from donors in order to create The Gottstein Trust. This educational trust fund honours him and it ensures his legacy keeps on going.

The Trust's activity in support of the forests and wood products include:

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4. *Study Tours:* Whether they be national or international facing, the trust supports a range of study tour opportunities for early-to-mid career professionals and researchers to build upon their passions and accelerate their professional development.

Further information

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Finally, the author would like to thank all those from the various countries who generously donated their time, and for their overwhelming hospitality when meeting with the author. Without them, the findings of this study tour would not nearly be as impactful.

About the Author

Adam Faircloth is a Forest Product Researcher, with a particular interest in wood product quality evaluation approaches for the sake of improved quality prediction methods and comfort for those working and living around wood products.

Adam has close to seven years of experience in the Australian forest product industry working directly with industry through the Queensland Department of Primary Industries (DPI). His duties range from laboratory management of one of Australia's few NATA accredited wood product testing facilities, participation in numerous overseas support activities in both Laos PDR and Fiji, and a series of projects working directly with, and in, the Australian timber industry. Adam has received several professional development grants and awards including the "3rd Australian Young Researchers Conference" Award by the Institute of Structural Engineers in 2019, and the Timber Queensland "Growth Scholarship (Kennedy Award)" in 2022.

Adam has a Bachelor of Engineering (Mechatronics) received from Griffith University in 2017 and has gone on to complete a Master of Philosophy while working directly with DPI (received from Griffith University in 2022).

He is now undertaking a PhD program with Griffith University while working with DPI.

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Executive Summary

Mass timber buildings are becoming more common globally, but challenges remain, particularly with timber's performance when exposed to low-frequency vibration and acoustics. Timber's lower density compared to concrete and steel results in lower natural frequencies comparatively that can be excited more easily by footfall induced events. If unmanaged, this could lead to occupant discomfort and at times structural issues. However, it is not suggested that mass timber floors are non-conformant, instead the concern and drive behind the author's research has been the overly conservative design practices that may be occurring as a result. This could lead to excessive material usage, and costly builds when proposing mass timber.

The aim of this study tour has then been to visit a series of practitioners related to mass timber panel production, designers/ builders of mass timber structures, and researchers focusing on the challenges related to mass timber floor vibration and acoustics.

The information collected as part of the study tour has been obtained from 13 countries, 112 practitioners, and summarised as being related to aspects of product design, product performance, and regional variations:

- ***Product Design***: Discussions with practitioners identified that 75% of MTP producers noted an increasing demand for design information from builders/ designers; 61% of designers stated facing challenges during the design phase of mass timber floor systems; 44% of consultants raised concerns over vibration and acoustics in mass timber floors; and 17% of the visited builders reported receiving complaints about vibration and acoustic performance from occupants.
- ***Product Performance***: A detailed analysis of the 16 most prominent mass timber floor design standards led to the development of a usefulness rank, comparing practitioner preferences with the frequency of each standard's occurrence in the literature. This revealed several cases where the most frequently cited standards were not rated as 'highly useful' by practitioners, and conversely, some less frequently cited standards were considered more valuable by practitioners.
- ***Regional Variation***: A significant factor behind the regional variations observed is the level of detail, or lack thereof, in some design standards from various regions. This was reflected in 27% of practitioners reporting challenges with selecting appropriate standards or design guides and 71% highlighting that comfort perception measurements are under-represented in most existing standards and guides.

The study tour identified three key under-developed researched areas: (1) novel mass timber floor systems (i.e. long spanning floor systems), (2) discrete material properties for mass timber products, and (3) the discrepancies between various testing stages (under construction through to completion in-situ) and environments (laboratory compared to in-situ). These are planned to be addressed as part of Mr Faircloth's PhD studies.

Definitions

Acoustics: For the purpose of this study tour and context in this report, the term "acoustics" refers to the sound generated from the footsteps or footfall event referenced in the above definition. The volume at which the acoustic energy (noise) is measured is related to the impact force caused by the person walking.

Cross Laminated Timber (CLT): A type of mass timber panel, CLT follows the construction strategy of plywood using sawn boards, where each layer of boards is orientated perpendicular to the proceeding layer. Adhesives are commonly used to bond each layer and sometimes to bond between boards as well. It is also not uncommon for the laminates to include finger joints.

Engineered Wood Products (EWP): For the purpose of this report, Engineered Wood Products (EWPs) can be defined as timber composites made from a combination of various wood components and, in some cases, non-wood materials like plastic or metal, bonded together with adhesives. The wood components (sawn laminates, veneers, strands, particles, flakes, or fibres) are reassembled with adhesives, typically using heat and/or pressure, to create products suited for both structural and aesthetic applications.

Glued Laminated Timber (GLT): GLT or Glulam is produced from sawn boards layered sequentially on top of each other, all orientated in the same direction. Adhesive is commonly used to bond each layer together. It is also not uncommon for the laminates to include finger joints.

Hybrid Materials: The term "hybrid" in this context relates to the combination of wood-based products and a non-wood product. Common structural floor systems that can be classed as hybrid would be a CLT substrate with a concrete overlay. However, hybrid can also be used to define a multi-layer floor system (CLT, carpet, particleboard, etc).

Vibration: For the purpose of this study tour and context in this report, the term "vibration" refers to the result of footsteps or a footfall event occurring on a floor system. The rate of vibration is dependent on the pace of the person walking.

1 Introduction

This project titled "*The global perception and understanding of vibration and acoustics in timber structures*" was developed to be complimentary to the authors roles and responsibilities within his workplace, the Queensland Department of Primary Industries (formerly Department of Agriculture and Fisheries), as a researcher as well as his ongoing higher degree by research through Griffith University as a PhD candidate. In 2018, the United Nations Sustainable Development Goals were created, identifying 17 areas that have an elevated risk of worsening the globally changing climate conditions [1]. One of these 17 areas is the built environment which contributes close to 40% of the globally measured greenhouse gas (GHG) emissions [2]. Methods to reduce the GHG emissions generated by the built environment are of high priority for governments and researchers globally with timber or timber composite products considered a potential solution [3]. Additionally, and more recently, the Australian Government Productivity Commission [4] has released a detailed report analysing the current challenges of Australia's housing sector. The report reveals a suite of statistics related to the current and relatively unchanged building practices (slab on ground, light weight framed single dwellings, etc), which are proposed causes for the lack in productivity measured and highlighted throughout the report. One such measurement is the 53% decline in the number of dwellings completed by hour over the past 30 years [4]. The release of this Productivity Commission report is very timely in emphasising the need for the information and research discussed in this report to be reviewed and addressed.

Recent innovations in mass timber panels such as cross-laminated timber (CLT), glued laminated timber (GLT), and other composites present opportunities to compete with conventional building materials like concrete and steel on a low-to-mid-rise scale, thus supporting the sustainability aspects and need for dwellings Australia is faced with [5-8]. As a result of extensive investigations, mass timber panels present comparable structural performances to concrete and steel, solutions for timbers' stability concerns, cost effective design, easy installation, and often less trade on site [9-11]. Mass timber panels are also a natural carbon sink, allow for rapid installation, often require a smaller building foundation/ footprint, and a host of biophilic benefits that come with working/ living in 'green spaces' [7, 9, 10, 12]. An area that still generates significant interest for mass timber panels is their performance against occupant induced vibration and acoustics [13-15]. Due to timbers low density (relative to concrete and steel), it often performs poorly at low frequency vibrations and acoustic events; those commonly excited by footfall loading (walking vibrations) and impact noise [16]. This poor performance can lead to excessive deflections, uncomfortable or continuous motions, and excessive noise transfer between floors and rooms [13, 16]. Several articles have documented the additional information designers and builders still seek to confidently use mass timber panels and overcome their challenges with respect to low frequency vibration and acoustics [17-19]. The desire for design information comes from the lack of clarity that exists globally on the use of mass timber panels in construction due to limited research on their *in-situ* application [13, 20]. Researchers have significantly contributed to this through product focused research. However, they often do not capture the specific challenges of today's mass timber industry and newer timber composite product options.

Through the summarised literature above and the authors' existing knowledge of the perceived challenge in designing mass timber structures to meet vibration and acoustic performance indicators, a number of gaps were identified, which this project was developed to address:

- Approaches to mass timber panel **design** internationally.
- **Perceived importance** of vibration and acoustics in mass timber structures.
- Methods of **characterising the performance** of mass timber floors.

These three points were considered with an added layer of **regional variation** by considering the impact the different regions visited had in noted variations. Considering the breadth and depth whereby these issues may apply, the project scope and visited regions/ organisations were defined and are listed in the **methodology**.

It is important to mention the contribution an earlier Timber Queensland funded study tour has had on the scope and direction of this project. This study tour is summarised in the following section.

2 Context from Timber Queensland Learning Project

In 2023, a learning project funded by Timber Queensland (TQ) (Growth Scholarship) was conducted by Mr Faircloth to consolidate local industry knowledge regarding vibration and acoustics in mass timber or hybrid structures across the Tasman between Australia and New Zealand. The consolidation of this knowledge was then brought back to Queensland to better direct current and future research efforts in the field of research relevant to improved product design for vibration and acoustic performance.

The TQ learning project also acted as a foundational point for the now completed Gottstein Fellowship study tour by providing the contextual knowledge on the local design practices and regionally specific limitations, opportunities, and barriers to increased use of mass timber panels in the built environment. To ensure the information being collected was representative of the majority of the industry, approximately 40 contacts were targeted across Australia (Queensland, New South Wales, Tasmania, Victoria, South Australia, and Western Australia) and major cities and towns in New Zealand (Auckland, Rotorua, Wellington, and Christchurch). The learning project identified 4 major areas of significance as noted by the local industry.

These included:

Boundary conditions: Boundary conditions (BCs), which significantly affect a material's response to excitation, differ between isolated lab tests and in-situ performance, as shown by Faircloth *et al.* [21]. Industry highlights the need for better understanding of practical installation aspects, such as spanning lengths, joint stiffness, and connection effects, for accurate vibration and acoustic assessments [22-24].

Novel materials: Experimental testing is vital for refining standards and guiding the industry, with research largely focused on lab-based mass timber performance [22, 25, 26]. Hybrid materials like cross-laminated timber with concrete screeds remain underexplored in depth, prompting industry interest in expanded testing on layering stages, local species, and optimizing properties like grain direction and density.

Standards and policy: Australia and New Zealand's standards, adapted from overseas, need refinement to reflect regional conditions and address gaps in performance measurement for new materials [13]. Studies by Kremer *et al.* [10] and Karampour *et al.* [13] highlight these issues, with industry advocating for alternative approaches like Timber Design Guide (TDG) 49 [24] and TDG 44 [27] to support mass timber development.

Education: Practitioners emphasized the need for better knowledge on vibration and acoustics and how this knowledge can be integrated with linked properties and existing design preferences in multi-storey buildings. Further research into material properties, especially for Australian timber species, and their impact on structural performance is crucial for advancing sustainable construction, with opportunities like the 2032 Olympics construction program available to showcase innovation in the industry.

The outcomes of the learning project also led to the initiation of Mr Faircloth's PhD studies. Further details on the learning project and the final report prepared by Mr Faircloth are available [28].

3 Methodology

The information and details described in this report are due to a combination of site visits, industry discussions, and literature review. Most of the study tours and discussions were undertaken with stakeholders in North America, Europe, and to a lesser extent, Asia. The North American countries included Canada and the USA. The European countries visited included England, Norway, Sweden, Germany, Austria, Italy, Switzerland and France. Both Canada and the USA were included in the North American tour. China (Chongqing) was the only region in Asia included in this study tour. Table 1 presents the experience location and organisation, a brief description of the activity, and its relevance to the Australian forest products industry.

Carried forward knowledge and findings from a similar exercise funded by TQ, as noted in the previous section, are also touched on in this report, with industry knowledge gained from Australia and New Zealand. The visited organisations as part of the TQ activities are not noted in Table 1, for further details on these organisations see Faircloth [28].

Table 1: Summary of experiences achieved from study tour.

Location/ Organisation	Activity	Relevance to Australian Forest Products Industry
Oregon State University (USA, Oregon, Corvallis)	Discuss the use of mass timber panels in the north American landscape.	Greater understanding of regional challenges will provide context to advise Australian mass timber panel producers on global challenges and changes.
Hexion Adhesives (USA, Oregon, Eugene)	Review current advances being made on adhesive systems for mass timber panel manufacture.	Advances being made could be translated to the Australian mass timber panel industry and support research activities being planned in collaboration with mass timber panel producers.
Simpson Strong Tie (USA, California, Stockton)	Understand testing capacity and importance of mass timber panel connection systems.	Review range of connection options and R&D activities underway to address dynamic performance of mass timber panels (vibration and acoustics in floors caused either by occupants or seismic).
United States Department of Agriculture Forest Products Laboratory	Discuss condition monitoring and non-destructive evaluation methods for mass timber panels.	Foundational skills will be focused on based on the advice received by the practitioners on wood product characterisation and evaluation.

(USDA FPL, USA Wisconsin, Madison)		
University of British Columbia (Canada, BC, Prince George)	Witness and discuss the testing approaches being undertaken for hybrid floor systems.	Start to build database of material and product types that could become part of an Australian solution for hybrid mass timber panel floor systems.
University of Victoria (Canada, Victoria Island)	Review approaches to finite element modelling of mass timber structures.	Evaluate and understand the skills needed to effectively model alternate floor systems.
Lincoln University (UK, Lincoln)	Discuss the groups work to date on floor vibration, mitigation methods, and regional variations.	Approaches to setting up a large-scale floor system for experimental vibration measurements to feed into new R&D activities.
Exeter University (UK, Exeter)	Understand differences of approach for occupant perception to floor vibrations.	Differences of approach for documenting perception and comfort important to then detail floor designs and vibration thresholds.
Calmfloor™ (UK, Exeter)	Witness world first active mass damping systems in action and discuss applications.	Document the advances being made for active mass dampers and how these can be applied back to the Australian context and for mass timber panels.
Newcastle University (UK, Newcastle)	Review approaches to floor vibration laboratory testing and weighting of perception in assessments.	Perception differences of the same material type and setup between regions can have important Australian impacts when evaluating design guide thresholds.
Mjøstårnet (Norway, Brumunddal)	Discuss development challenges faced for one of the largest mass timber structures in the world.	Detail the approaches taken for the development of Mjøstårnet that could be transferred to Australian developments in the future.
Prefab Samland (Alvesta, Sweden)	Review different manufacturing approaches and methods for hybrid mass timber panels.	Conceptualise the various scales of manufacturing that exist globally for mass timber panels and hybrid materials.
Royal Institute of Technology (KTH University, Stockholm, Sweden)	Understand the application of alternative standards and design guides for floor vibration performance.	Begin to rank and evaluate the wide range of design guides based on impact, scope, and regional differences.
GERB Vibration Control (Berlin, Germany)	Discuss applications of tuned mass dampers with leading global producer.	Document the advances being made for mass dampers and how these can be applied back to the Australian context and for mass timber panels.
Stuttgart University (Stuttgart, Germany)	Exchange approaches to novel floor and mass timber panel designs to address vibration/ acoustic performance.	Greater understanding of regional challenges will provide context to advise Australian mass timber panel producers on global challenges and changes.

Biberach University (Biberach, Germany)	Review current approaches to long spanning floor systems and advances being made on new euro code revisions.	Establish greater database of practitioners on floor vibration testing and update understanding of current activities and focus.
Department of Natural Resources and Life Sciences (BOKU, Tullin, Austria)	Understand alternative and novel approaches to mass timber panel manufacture being proposed.	Review knowledge that can be transferred to Australian mass timber panel sector given the R&D occurring here on adhesion systems.
Graz University (Graz, Austria)	Discuss developments being made in mass timber panel designs and approaches to best optimise resource for performance.	Discuss origins of CLT to determine drive and reasoning behind its conception to document approach for future mass timber panel systems.
Stora Enso (Leonhard, Austria)	Witness mass timber panel production scale in Europe across a number of different product options.	Conceptualise the various scales of manufacturing that exist globally for mass timber panels and hybrid materials.
University of Trento (Trento, Italy)	Exchange approaches to novel floor and mass timber panel designs to address vibration concerns and future work.	Establish greater database of practitioners on floor vibration testing and update understanding of current activities and focus.
Rothoblass HQ (Trento, Italy)	Understand priority areas for organisation and internal R&D focus for mass timber panels, connections, and vibration/ acoustics.	Review range of connection options and R&D activities underway to address dynamic performance of mass timber panels (vibration and acoustics in floors caused either by occupants or seismic).
Rubner (Trento, Italy)	Witness mass timber panel production scale in Europe across a number of different product options.	Conceptualise the various scales of manufacturing that exist globally for mass timber panels and hybrid materials.
Swiss Federal Laboratories for Materials Science and Technology (Empa, Zurich, Switzerland)	Exchange approaches to novel floor and mass timber panel designs to address vibration/ acoustic performance.	Different approaches to measure vibration and acoustics will be critical in bridging knowledge gaps in measuring these critical properties for mass timber panels.
Bern University (Bern, Switzerland)	Discuss the use of mass timber panels in the European landscape and manufacturing approaches being introduced.	Review knowledge that can be transferred to Australian mass timber panel sector given the R&D occurring here on adhesion systems.

Centre for International Research into Agricultural Development (CIRAD, Montpellier, France)	Review the advances being made on material property characterisation for acoustic performance testing.	Foundational skills will be focused on based on the advice received by the practitioners on wood product characterisation and evaluation.
The Scientific and Technical Center for Construction (CSTB, Paris, France)	Witness the scale of a commercial acoustic experimental testing facility.	Commercial approaches to the scale and speed of testing will be recorded to then advise project development on method establishment.
Chongqing University (Chongqing, China)	Discuss regional and internationally focused research on mass timber panel performance requirements and occupant comfort perception approaches.	Greater understanding of regional challenges will provide context to advise Australian mass timber panel producers on global challenges and changes. Further, novel approaches to considering occupant perception is critical to traversing current challenges and barriers.

As can be interpreted from the details in Table 1, the represented groups of those visited during both this study tour and the learning project funded by Timber Queensland (Section 2) included producers/ manufacturers (18%), researchers (23%), designers (15%), builders (15%), consultants (17%), and government organisations (12%).

Figure 1 combines the visits conducted during the Timber Queensland learning project (Faircloth [28]), with those listed above in Table 1 to display the regions/ countries toured and the relative number of practitioners in each visited region/ country.

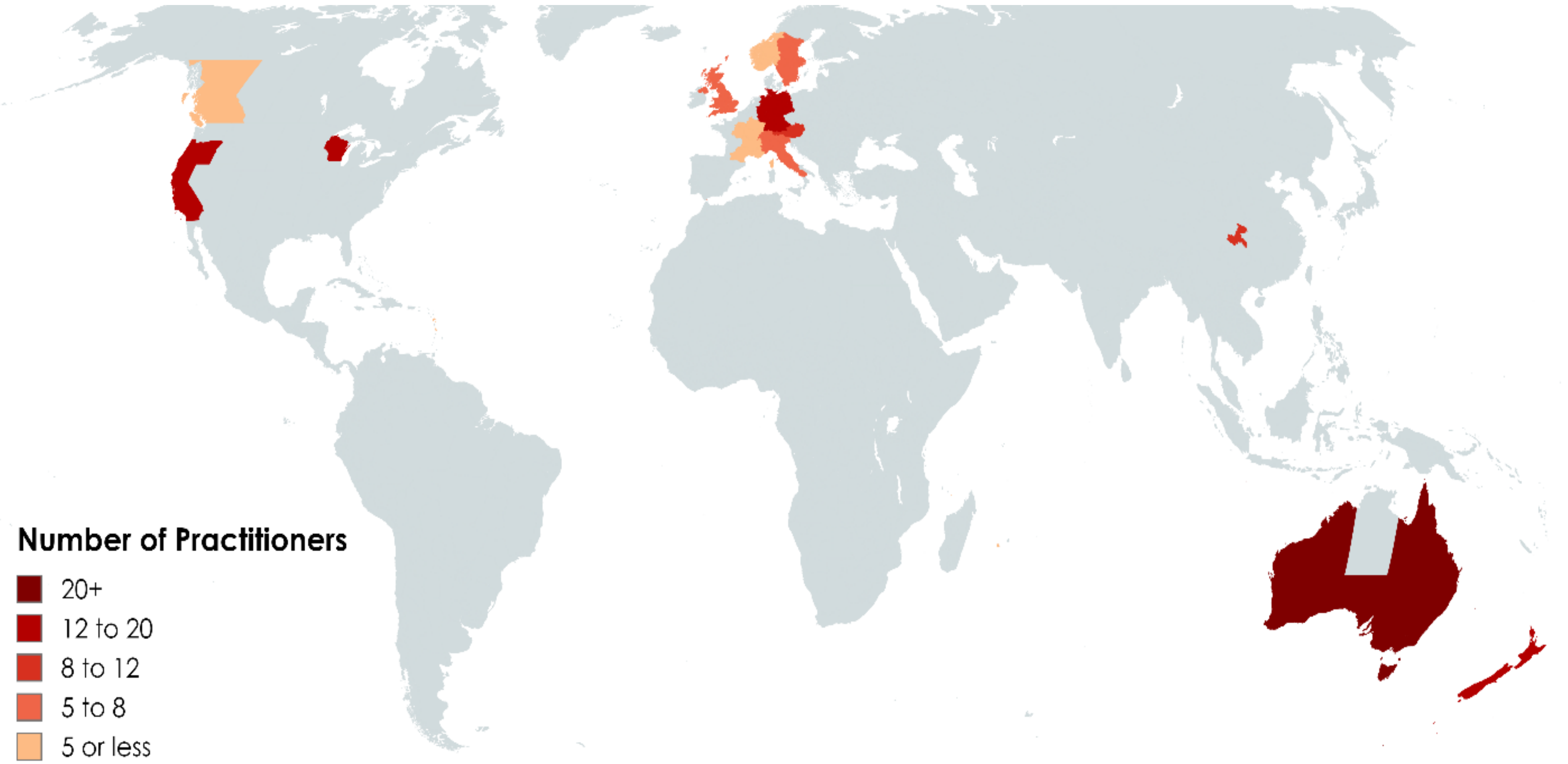


Figure 1: World map indicating places visited [29].

4 Findings

The outcomes of the visits as noted in Table 1 consisted of 112 discussions with practitioners from a wide range of the supply chain, spanning across resource processing, product performance, material specification, and structure design. The findings from the discussions at each of the organisations noted in Table 1 have been summarised into three grouped themes of findings. These themes consisted of responses related to product design (Section 4.1), product performance (Section 4.2), and regional variation (Section 4.3).

Twenty-nine percent of practitioners emphasized compliance with vibration and acoustic standards as a key mitigation strategy. Scaled/ laboratory (24%) and in-situ testing (19%) were noted as valuable but often impractical. A lack of mass timber panel performance data (21%) highlighted the need for corrective measures to meet occupant expectations. Priority areas included floor systems (63%), connections/junctions (27%), building services (7%), and other concerns (5%). Given the focus on floor systems, this review prioritizes design, evaluation methods, and corrective measures in this area.

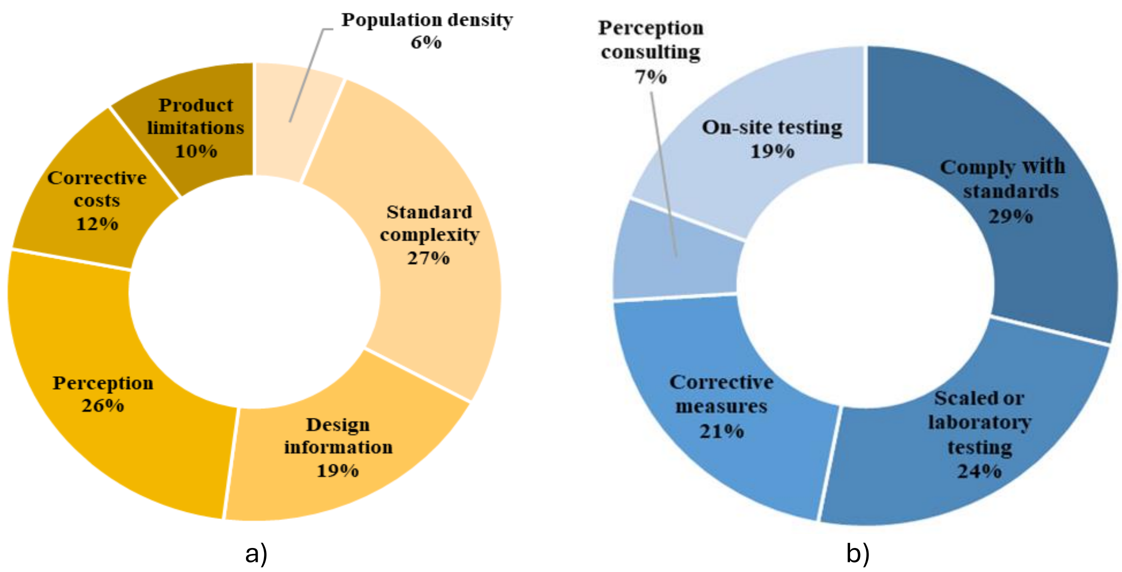


Figure 2: Responses indicating the a) perceived barriers to increased use of mass timber panels, and b) design mitigating methods for vibration and acoustics [29].

4.1 Product Design

4.1.1 Production & Manufacturing

While the properties being considered by this study are related to the performance of mass timber panels *in-situ* (while being used), the product itself and decisions made by the producers and manufacturers can contribute to that final performance. Therefore, it was deemed necessary to consider this stream of practitioners as part of the study tour. Issues raised by the producers and manufacturers have been compartmentalised into either global or local challenges. The report defines global challenges as those echoed across all (or most) of the visited regions, while local challenges are defined as being more specific to a single region.

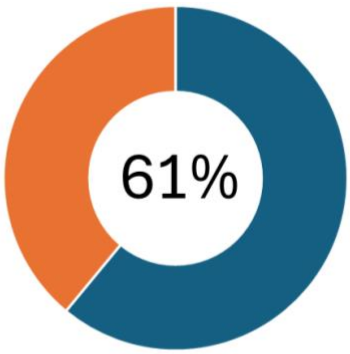
- ***Global Challenges:***
    - *Standard Complexity*: Producers of mass timber panels are facing ever growing demands for greater design information from builders. Mass timber panel characteristics such as strength, durability, and fire resistance appear further developed upon and understood than vibration and acoustics, which continues to limit the use of mass timber panels in the built environment. This onus placed back on the producers to specify how their products should be used to achieve a particular performance results in producers then being challenged by the method by which their product should be characterised against.
    - *Finished Material Performance*: It is uncommon for mass timber panels, such as CLT, to be used in applications where both sides are exposed. The performance of the finished floor is influenced by each additional layer, such as carpet, screeded concrete, or raised access ceilings. However, current vibration, acoustic and floor performance/ design standards fail to fully capture or differentiate the performance characteristics of these added materials.
- ***Local Challenges:***
    - *Material Properties*: Variations in timber species and access to them are the primary reasons for differences in product performance across regions. Factors such as growing conditions, seasonal variations, and rotation ages significantly impact material properties like density and stiffness, creating differences between Europe, North America, and Australasia. Additional challenges, such as limited access due to seasonal weather conditions or government policy decisions, are typically viewed as business-specific constraints and are not commonly addressed through research.
    - *Resource Constraints*: Differences in material properties and constraints on domestic timber supply in certain countries, such as Australia, can have significant effects on the supply chain. These effects often lead to: (i) increased reliance on imported or non-wood products linked to a higher demand for EWPs, (ii) through working towards a commodity type supply and demand, there are limited opportunities for considering novel systems, or (iii) the emergence of alternative, less-developed EWPs either using underutilised forest resources or new composite material combinations. While the third option encourages innovation within the industry, most regions facing such constraints tend to default to options (i) and (ii).
    - *Feedstock Conditioning*: Timber's hygroscopic nature means its performance varies with changes in moisture content. To address this variability, most European producers condition their feedstock before manufacturing in large environmental chambers. However, this level of control is not commonly practiced in many Australasian production facilities with environmental conditions often driving the feedstock conditions at the time of manufacture. Consequently, manufacturing tolerances must remain adaptable to account for fluctuations in environmental conditions.

Of the 20+ timber producers visited, approximately 75% reported increased demand for design-related information, such as installation and application details, compared to the traditional commodity-style raw materials they typically supply. This shift is partly attributed to a global challenge labelled "standard complexity" and a lack of experience among designers and builders working with mass timber panels.

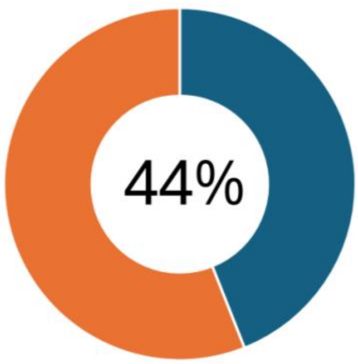
As a result, performance targets are often over-prescribed, leading to overly thick panels, shorter spans, or lower ceilings to address concerns about vibration and acoustics. Design standards, both globally and locally, impose limitations on materials, reinforcing this conservative approach. However, the discussions suggested efforts are underway to address these challenges, including stiffening floor panels and improving timber's acoustic performance at low frequencies.

4.1.2 Designers & Builders

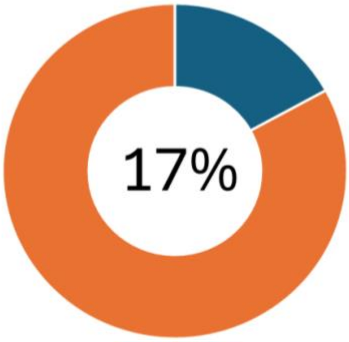
Of the developments witnessed during the TQ learning project (Section 2), there appears to be a large emphasis on mid-scale commercial developments often used for office spaces with many from 10 stories and greater. Those visited included: 25 King St (10 stories [30]), Brisbane, Queensland; T3 (14 stories [31]), Collingwood, Victoria; and WS2 (12 stories [32]), Perth, Western Australia. These structures showcased diverse design approaches and motivations for utilising mass timber panels, tailored to achieve specific structural and vibration/ acoustic objectives. Examples include the use of glulam and laminated veneer lumber (LVL) in manufactured beams to overcome cutouts and meet stiffness requirements (25 King St), extending the height of an existing building while adhering to strict weight limits (T3), and implementing reduced floor panel thicknesses combined with tuned mass dampers controlling annoying floor vibrations (WS2). These innovative solutions highlight the local industry's commitment to addressing complex challenges through creative and forward-thinking design. Insights gathered from discussions with the designers and builders revealed the following key observations.



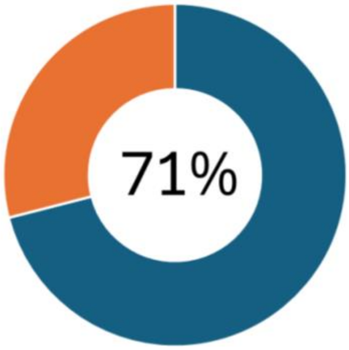
Of the designers and builders visited as part of the study tour, **61%** had noted challenges when progressing through the design stages for various floor configurations. These challenges presented as additional time taken to predict performance and consequently prescribe material types/ thicknesses for the final build up.
Specific causes were either related to i) lack of material data or experience with mass timber panels, or ii) challenges in selecting appropriate design guidelines/ standards.



Following this, **44%** of the vibration/ acoustic consultants included in the discussions noted that, at times, they had raised concerns over designs. These observations were mostly linked with structures nearing completion.
The concerns in question ranged from overly prescribed thicknesses of mass timber panel floor systems leading to floor system performance when measured against vibration, and at times, acoustics being consistently exceeded. While not a performance issue, it presents a potential area for further research to lead to material, sustainability, and cost savings.



A complex response came from builders who have received complaints regarding perception. Of the builders this was discussed with, **17%** noted receiving complaints related to either floor vibration or acoustic transmission from occupants. These complaints from tenants occurred at an undisclosed period of time after hand over, however this still presents a conflicting statistic from the responses of designers and builders suggesting floors are 'overly compliant'.



This then contributed to an almost unanimous finding that **71%** of all participants discussed with considered the study and understanding of comfort perception to be under-represented. This led to a series of sub-discussions around relationships lacking between measurements taken in the field (building or in-situ) to peoples perceived comfort levels, and relationships lacking again between these in-situ measurements with laboratory-controlled testing.

4.2 Product Performance

As highlighted in Figure 2, the ability for practitioners to comply with the available standards/ design guides and the related complexity faced in doing so is a significant challenge many encounter. For vibration alone, 16 standards exist for designers to choose from with each region presenting a varying level of detail to be overcome. From these 16 standards/ design guides, a comparative exercise was conducted comparing the most used methods as reported in literature compared with the most commonly used methods as discussed during the various meetings from the study tour. Figure 3 shows that for several standards (listed as 1 to 16) there are situations where the responses from the practitioners and the frequency of use in the literature are complimentary (ranked from 1 to 5 where 1 – used less, 5 – used often). However, there are also several of the methods (particularly 2 and 4) where the commonly referenced standard/ design guides in literature is less desired by the practitioners, and vice versa.

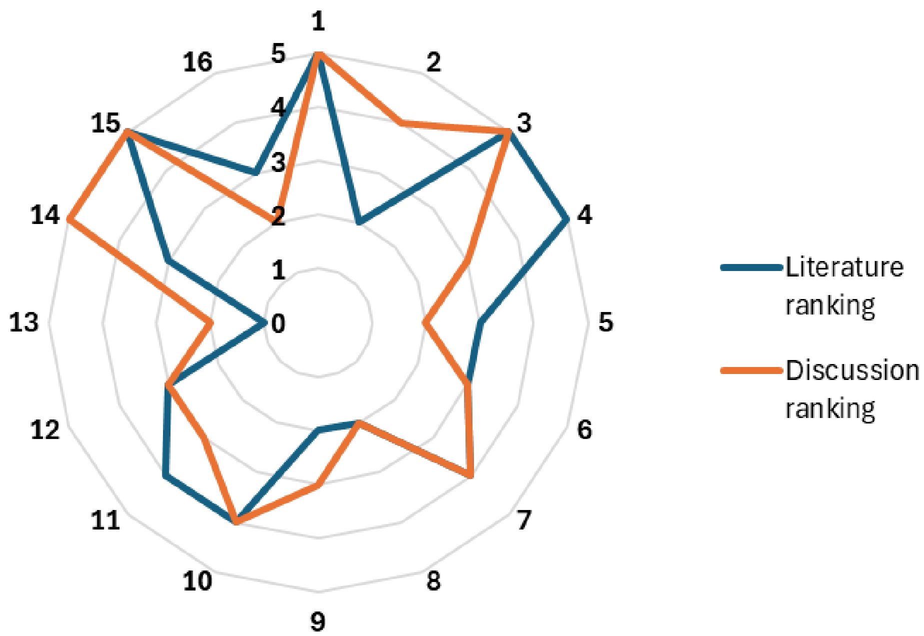


Figure 3: Comparison of most used standards (1 to 16 different standards) and their ranking (1 to 5) differences [29].

This not only reflects the challenges in specifying systems correctly but also complicates approaches to product evaluation and the benchmarking of novel product types. **Of the approaches to system evaluation viewed during the study tour, 85% of the focus appears to be laboratory concentrated with few researchers focusing on performance testing of products in-situ.** This weighting towards controlled laboratory experiments has led to prescriptive methods being calibrated from laboratory obtained results, often different to the expected and measured in-situ performance.

This is only further exacerbated when considering perception (comfort) measurements and the thresholds for targeting specific comfort levels as used in a series of the 16 standards and design guides. Most of these datasets are also founded from laboratory testing. The standards noted in Figure 3 present varying levels of detail, with some prescribing several material properties to either design for, or act as, a threshold for conformance. Other standards, however, may only prescribe a single design parameter. This suggestion alludes to the cause for the design complexity noted by 27% of all practitioners in selecting appropriate standards to design mass timber floors. This challenge was not isolated to industry professionals with a number of researchers also sharing their confusion in appropriate standard selection. While these various design methods and approaches focus on the consistent goal of floor conformance for vibration and acoustics, they differ in the path taken to get to the end goal. The main categorisation used for the various methods is whether they are deterministic or probabilistic. While deterministic approaches prescribe performance through calculated values, probabilistic ones consider a range of performances that can be achieved [33, 34]. Considering the variability that comes with floor design, a probabilistic approach appears more appropriate to some practitioners. This is shown by the ranking scale in Figure 3 showing greater interest from practitioners for probabilistic methods (method 2) compared to those of researchers, at the time of writing.

The following example illustrates the compounding challenges of i) selecting appropriate standards or design guidelines to address vibration and acoustics, and ii) aligning compliance with these standards to meet the occupants' perceived comfort. In Chongqing, China, a light rapid transit (LRT) system runs through the centre of a mixed-use building (combining residential, commercial, and office spaces), generating significant public interest (Figure 4). This structure was a focal point of the study tour due to its distinctive design and occupant specific challenges. The levels above the station and nearby buildings are predominantly residential, with commercial businesses and office spaces integrated into the environment. Xie, *et al.* [35] conducted a survey of the building's residents to assess their perceptions of the vibration and noise caused by the LRT system. Acoustic measurements revealed noise levels exceeding national regulations by more than 15 dB, while fewer than 20% of residents reported implementing mitigation measures, such as double-glazed windows. This example highlights the critical importance of carefully balancing structural functionality with the perceived comfort and liveability of occupants.

Figure 4: LRT system in Chongqing, China (image taken by A. Faircloth).

The structure highlights the importance of developing optimised and refined design guidelines that address both the measured performance characteristics (vibration, damping, acoustics) and the comfort characteristics of the occupant (comfort perception). A key challenge observed during the study tour, particularly with perception assessments in laboratory research, was the difficulty of replicating real-world conditions. Accurately simulating the behaviour of an actual floor system in situ is inherently challenging from a measurement perspective. Moreover, participants often perceive the test environment differently from how they would experience a real office or residential space, further complicating the assessment of perceived comfort and performance.

Of the 25 researchers visited, several were exploring new and innovative methods to assess the perceived comfort of floor systems. These approaches include: (i) utilising virtual reality (VR) and augmented reality (AR) to simulate the occupant's environment (H. Karampour *et al.*, Griffith University, Australia), (ii) monitoring neural activity to understand human responses (X. Zhang *et al.*, Chongqing University, China), and (iii) evaluating the range of effects across long-span floors (P. Hamm *et al.*, Biberach Universität, Germany). Despite these advances, ensuring that floor spaces perform as intended remains a significant challenge. The VSimulator experimental facility at the University of Exeter (Figure 5) offers a promising solution. This facility can physically replicate a wide range of floor dynamic responses through controlled incremental displacements, enabling researchers to simulate floor response factors, accelerations, and damping ratios based on either design calculations or real-world measurements from other test sites. Managed by Professor Aleksandar Pavic, the VSimulator is currently being used to study how floor vibrations induced by walking affect participants' working habits. This research is anticipated to establish critical connections between measured floor vibrations and perceived occupant responses, contributing to a deeper understanding of vibration-related comfort.

Figure 5: Exeter University, UK. VSimulator experimental floor facility a) view of floor system, b) under-view of floor system (Images supplied by A. Pavic).

4.3 Regional Variation

From the regions visited during both the TQ learning project (Australasia) and the Gottstein study tour (North America, Europe, Asia), only China was not actively producing mass timber panels. This lack of production combined with anecdotal inputs, suggested that the local industry in China is not yet ready to substitute or blend common construction materials like concrete and steel with mass timber panels. It is important to contextualize this observation that, while occupant perception of material performance is a key consideration, the construction landscape in China differs significantly from that of other regions visited. This distinction highlights the value of having considered regional variation through this study tour. For example, China's construction practices are shaped by its very large population, resulting in densely populated cities with views dominated by tall skyscrapers for residential and commercial use; a scale mass timber panels have not yet been tested for.

In contrast, countries like Australia and New Zealand, with smaller populations and different resource availability, have historically relied on lightweight framed construction methods. Discussions with practitioners during the study tour revealed several recurring themes influenced by regional differences. These included **(1)** the application of various design standards (as outlined in Section 4.2), **(2)** the weighting of perception based on the local/ societal context, and **(3)** the capacity for industry innovation and adoption. These themes reflect how regional factors, such as population density, resource availability, and historic construction methods shape approaches to design and performance standards across different parts of the world. Table 2 summarises some responses to the previously mentioned discussion topics for each region.

Table 2: Regionally sensitive practitioners' responses.

Region	***Responses***
(Australasia) Australia/ New Zealand	***(1)*** Interestingly, of the 16 standards noted from Figure 3, **24%** of them were developed in Australia/ New Zealand. However, when looking at the national standard for floor vibration, it was last reviewed in the year 2000.

	It also has minimal requirements to measure conformance when compared to other more defined standards. As a result, **53%** of practitioners reported using international guidelines in their designs. ***(2)*** Discussions highlighted several perception studies conducted across the region, focusing on extracting meaningful data from subjective measurements rather than adhering to standardized layouts. This avoidance of the standard structured experiments was found to be due to consistent lack of linkage between measured and perceived performance, as noted overseas. ***(3)*** Numerous domestic challenges (political and other) have meant the local forest and forest product sector in the region have had to be ready to adapt and respond to change. Rapid increases in demand and a housing shortage have added to the pressure domestic timber/ timber product producers face resulting in two conflicting outcomes i) a strict focus on meeting current demands (business as usual), and ii) investigations into new resource streams to meet the increasing demand using available forest resource that may be underutilised (innovation). The term 'conflicting' has been used as the two points appear to both hinder and foster innovation in the industry. This fostered innovation originates in industry as a result of limited detail in national product design standards or constraints on desired access to certain materials/ grades – which appears to have a positive effect, leading to more industry led standard revisions.
(North America) America/ Canada	***(1)*** This region contributed to **16%** of the standards noted in Figure 3, spanning from 1951 to 2024. Vibrational performance of floors was the primary focus of all these standards and design guides, with acoustics being viewed as a slightly lower priority. This trend has also been observed in other regions, as vibration events are often linked to acoustic discomfort and therefore it is often concluded that by addressing one, the other is also addressed. ***(2)*** While most practitioners considered perception important, some believed that current design standards adequately capture occupants' perceived comfort. However, this view conflicted with the majority, who felt that the standards only target the performance of the bare system. With additional material layers added during finishing, performance is generally expected to exceed the design target. ***(3)*** Based on the visited locations within the region, there appears to be strong collaboration between researchers and industry leading to innovative project outcomes from researchers being readily adopted. The region appears to be transitioning through a resource and product focus shift in the west to more veneer-based mass timber panels. From discussions conducted with the visited groups local producers are eager to capture the advantages veneer processing offers through recovery efforts. The region also presents unique challenges with respect to natural disasters (hurricanes, earthquakes) leading to much of the current vibration research focus being seismic related rather than comfort related.

(Europe) **UK/ Norway/ Sweden/ Germany/ Austria/ Italy/ Switzerland/ France**	***(1)*** Since 1996, Europe has led the development of international standards, focusing on floor vibration, perception frameworks, and probabilistic design approaches. Europe has been responsible for **60%** of the standards referred to in Figure 3. However, even within the region itself there is variation in design standard development, performance targets and methods to use (deterministic or probabilistic). ***(2)*** Perception is highly emphasized across Europe, with many countries encouraging, or even specifying, the inclusion of vibration and acoustic expertise in structural design and planning to ensure appropriate measures are taken and accounted for from the early stages of design. Despite this, challenges persist, particularly in defining the relationship between laboratory and in-situ performance and perception results. ***(3)*** While the production volumes of mass timber panels combined across Europe surpass 1 M m^3 for CLT alone, the region and industry appear to be more driven by regulation requirements than through industry innovation. Conversely to Australia/ New Zealand, Europe's industry at times may commonly rely on its strong research network to initialise innovation and novel approaches to product development/ application before themselves investing. The European model of a single or small set of prescriptive guides/ standards to govern multiple nations can also be restrictive for some countries within the Union.
(Asia) **China**	***(1)*** As mentioned earlier, mass timber is not widely used in China at the time of writing. Therefore, discussions with local practitioners focused on comfort design protocols for all building materials. In terms of design standards, practitioners rely on locally developed regulations, though these were not accessible for review at the time of producing this report. ***(2)*** While perception was considered important by local practitioners, it was difficult to confirm this through local publications. Relevant studies on vibration and acoustic comfort often reported discrepancies between expected and measured performance. However, this discrepancy was not uncommon to the findings of other regions. Understanding influences of perception appeared especially of interest for the researchers visited trialling alternative methods of monitoring impacts of disturbances related to excessive vibration and/ or acoustics. ***(3)*** Despite mass timber's limited use and production in China, local research efforts are increasing. These efforts aim to encourage greater investment from local industry and government by showcasing the benefits of mass timber. As a result, 8% of the literature that has been compiled as part of the literature review conducted in parallel to this study tour originated from studies conducted in this region.

5 Outcomes of the Fellowship

The following section summaries the outcomes of the fellowship activities and/ or recommendations to better direct research efforts. This section also provides details on personal impacts the fellowship has had for Mr Faircloth, during, and post its completion, inclusive until the submission of this report.

5.1 Industry Impacts

Comparing the findings from the previously discussed key themes with some highlighted themes extracted from a literature review of 100+ articles, complimentary areas, and areas requiring further development were identified (Figure 6).

The figure should be interpreted by considering perfect alignment between the "Practitioner areas of Concern" as extracted from the discussions from the various practitioners, and "Literature Linkages" extracted from the aforementioned literature review, as examples of good collaboration and interaction between industry and academia.

Following this, points that land further to the left on the diagram into the "Literature Linkages" section are considered saturated research fields where this is less of a priority for industry, based on the practitioners consulted. Finally, for the points that land to the right of the figure in "Practitioner areas of Concern", these are themes that appear of greater interest and concern for the practitioners consulted and appear to be less focused on by the published or ongoing research efforts.

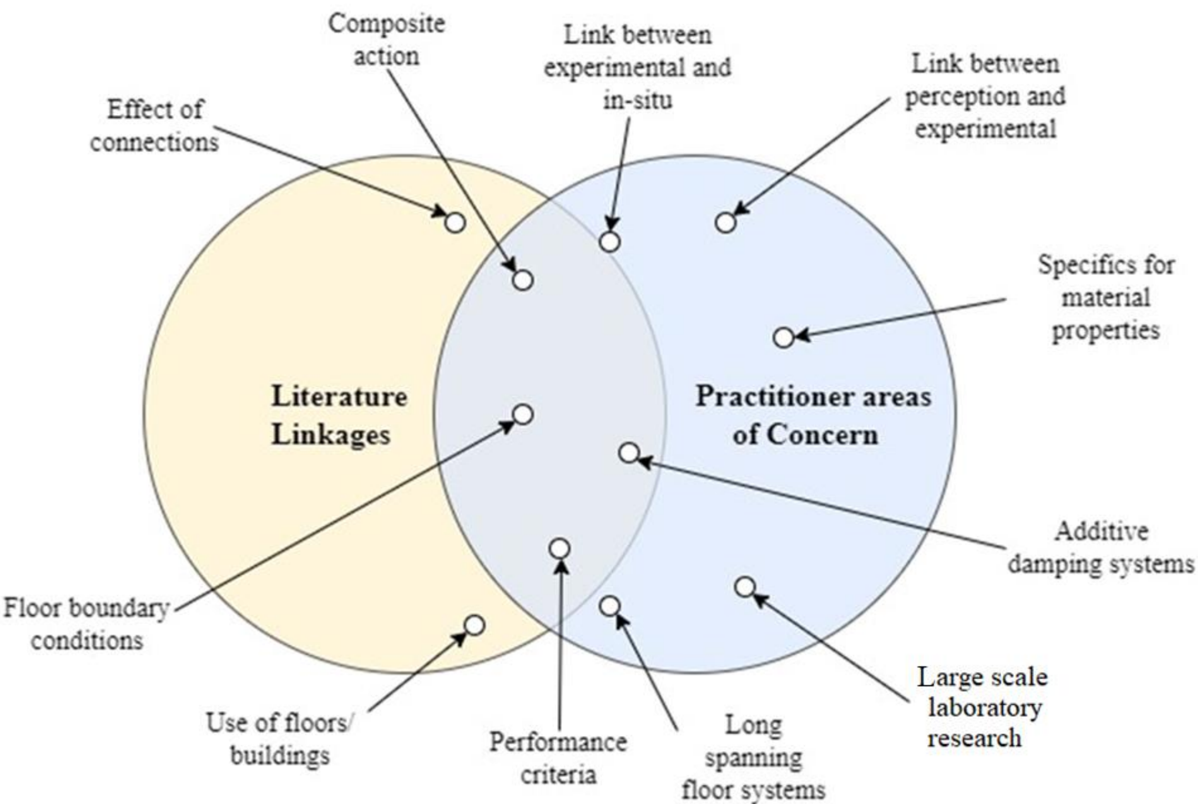


Figure 6: Venn diagram of literature linkages and practitioner focal areas with highlighted key themes [29].

This translates to a sense that there are some instances where research activities are not accurately capturing the demand, desires, and challenges of the broader mass timber industry. Some of these challenges include, but are not limited to:

- ***Observed linkages***: The relationships between laboratory and *in-situ* testing, and the linkage between measured and perceived performance were part of the concern voiced by the industry practitioners that were visited. These relationships (or lack thereof) need to be developed further to allow for research that occurs back in the laboratory to accurately feed into specification activities. While there were some activities progressing in this field, it has not yet been able to yield any significant improvements in industry.
- ***Material understanding***: Taking a step back from the previous point related to the relationships at different stages of implementation, another concern from industry was the lack of robust datasets surrounding mass timber panels and their manufacturable properties. There appeared to be some activities ongoing that anticipate leading to interesting results. However, greater knowledge in this space could lead to a reverse engineering approach to mass timber floor system design where the product design feeds into floor design optimising the manufacturing process.
- ***Exploratory work***: As a result of the barriers noted in Figure 2, these are challenges industry (mostly builders and designers) is focused on overcoming, but these challenges often hinder their appetite to conduct exploratory work. This is noted through the greater areas of concern from the practitioners as "long spanning floor systems" and "large-scale laboratory research" noted below in Figure 6.

5.2 Communication Methods

To ensure the important outcomes of this fellowship are properly communicated and translated to industry during and post the study tours completion, the following communication methods have been employed:

- ***During study tour***:
    - To immediately communicate the status of the travel as well as bring attention and awareness to the issue being investigated through the study tour, social media was used frequently. A total of 7 LinkedIn posts (published weekly) were produced showing some of the breadth and depth of research and scale of industry operations in the visited countries/ regions. Through the posts, interaction was instigated by referencing (tagging) the host institutions and individuals at the organisations fostering further and wider interest. These 7 posts yielded a total of 11 reposts, 37 comments, 348 interactions (likes or other), and 18,253 impressions.
- ***Post study tour***:
    - *Publication Development*: A publication is nearing completion reviewing the current state of knowledge with respect to vibration and acoustics in the mass timber building industry, compiling the observations, discussions, and opinions of the practitioners involved in both the Gottstein Fellowship study tour and the Timber Queensland learning project. This combination of work and publications is expected to form the foundation of Mr Faircloth's PhD thesis. It is expected to be submitted by early 2025 [29].
    - *Wood Solutions Educator Workshop*: As a result of the successful return after the Gottstein Fellowship study tour, Mr Faircloth was nominated internally as the DPI staff person to attend the Wood Solutions Educator Workshop, focusing on the general theme of overcoming barriers to the increased use of mass timber in the built environment. The workshop was held in Launceston, Tasmania in November 2024.

- *RNDBI Conference Attendance*: Mr Faircloth attended the first conference held by the "Research Network for Decarbonising the Building Industry" (RNDBI) organised by the University of Melbourne in November 2024 where he was able to present some of the learning highlights from the study tour. The RNDBI was founded with the purpose of bringing researchers with different material focuses (timber, steel, concrete) together to share knowledge and collaborate towards a roadmap for suggested methods to decarbonize the building industry.

6 Conclusions & Recommendations

This report has highlighted the findings of a comprehensive study tour across 13 countries, involving the insights and expertise of 112 practitioners. The report defines and discusses key factors that shape the challenges involved with refining the design process for mass timber structures to effectively address vibration and acoustic events. It should be noted that it is not the view of the author that there exists a large number of bouncy floors in the world as a result of these challenges. Rather, it is more likely that due to the discrepancies and challenges raised by practitioners, a high proportion of overly conservative floor designs could exist. Through building upon data sets and re-calibration of design guides, these conservative practices (where unnecessary; unlike safety and char factors) could be reduced, leading to more sustainable design practices and an optimisation of the used resource. The findings of the study tour can be segmented and summarised into:

- *Product Design*: Several interesting statistics surfaced through this section such as the increasing demand for design information felt by mass timber panel producers (75%), designers encountering challenges during the design stage for mass timber floor systems (61%), concerns raised by consultants over vibration and/ or acoustics (44%), and complaints raised by occupants over vibration/ acoustic performance (17%).
- *Product Performance*: By diving deeper into the 16 most prominent standards/ design guides, a usefulness ranking system was developed to compare the view of the practitioners visited to a frequency occurrence of each standard in 100+ scientific publications. Several scenarios were identified where the most frequently used standard wasn't ranked as highly useful by the practitioners, and vice versa.
- *Regional Variation*: A large proponent of regional variation appeared to be the design standard detail or lack thereof for some regions. This contributed to the 27% of practitioners noting challenges in standard/ design guide selection and a further 71% of practitioners considering perception measurements are under-represented across most of the available standards/ design guides.
- *Standard & Design Guide Comparison*: The review of some 16 standards and design guides for floor design and evaluation resulted in three key standards surfacing as preferred by both practitioners and through the literature globally. These included the new

revision to the euro code set to be released in 2027 (FprEN 1995-1-1 [36]), the concrete design guide CCIP-016 [38], and the guide to evaluation of human exposure to vibration in buildings BS EN 6472-1 [39]. While the review and discussions highlight the preference towards these standards and design guides, it is the opinion of this reports' author that there is still developmental work to occur in order to effectively match the demands of a changing industry with those of a relatively new building solution.

From this report, a number of outcomes have been captured within newly developed and funded research activities looking at some of the challenges specific to i) novel mass timber floor systems, ii) linkages between measured and perceived performance, and iii) the influence of discrete mass timber panel material properties. It is believed and planned, that through addressing the aforementioned challenges or opportunities, greater confidence will follow in using these sustainable building materials. The outcomes of this report will direct Mr Faircloth through focusing on these three challenge topics through his ongoing PhD research.

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