

Research Analysis

Quantitative Reliability Analysis of Mitigations Against Construction-Stage Wetting of Cross Laminated Timber Roof Structures

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Cross Laminated Timber (CLT) has vulnerability to moisture ingress and damage, with potential to affect architectural and structural performance. The construction-stage presents significant challenges due to exposure to atmospheric and constructional moisture sources. A clear knowledge gap exists for information to allow designers to quantitatively compare the effectiveness of potential construction-stage mitigation methods and make informed design and execution decisions. With a focus on CLT roofs, this research establishes and enacts a methodology that generates and evaluates data to fill this knowledge gap. In a novel application to buildings-design, Cooke's Classical protocol for Expert Elicitation was applied to a panel of 10 leading industry experts who evaluated 19 commonly recommended moisture mitigation strategies. Results show that several widely endorsed measures may in fact perform poorly in practice or impose major design, cost, or time burdens. The findings provide new evidence to improve design guidance and strengthen moisture-risk analysis and decision-making through objective identification of effective mitigation strategies. This will support more reliable outcomes and help ensure the safe expansion of timber construction as part of broader global decarbonisation of the construction industry.

Keywords: Mass Timber Construction, Cross Laminated Timber, CLT, Moisture, Decay, Expert Elicitation, Structured Expert Judgement

Highlights

- Widely recommended risk mitigations are judged to be potentially ineffective
- Novel quantitative data to inform future design and construction guidance for timber structures
- First ever implementation of expert elicitation to support structural timber design

Introduction

Mechanisms and Causes of Moisture Damage to CLT Roofs

Cross Laminated Timber (CLT) is a type of mass timber formed by pressing and gluing, typically 20-40mm thick 80-140mm wide softwood lamellae of timber together side by side in layers with each layer's axis alternating by 90 degrees each time. Prior to lamination, the lamellae are sawn, kiln dried and graded, with defects greater than a defined size removed and the remaining sections finger-jointed end to end for axial

continuity [1]. This structure provides greater consistency of mechanical properties and of in-plane moisture movement. The macro-structure does also introduce small, continuous voids at lamella sides which can act as rapid moisture-transport routes from cut edges, in addition to the natural moisture routes along the grain of the lamellae themselves.

Timber is an organic hygroscopic material which will readily absorb water in liquid form or from atmospheric humidity. Owing to its origin in a tree, water is preferentially absorbed through cut end grain and along the fibre axis, at a rate 10 times that of the radial or circumferential axes [2]. Water is initially stored within the cell walls then, once fibre saturation is reached, it is stored in the pores between cells.

The wood cell structure is composed of cellulose, hemicellulose and lignin, and all three organic materials can be consumed by different forms of biodegradation given sufficient oxygen, water and favourable conditions of temperature. The most significant form of biodegradation for Cross-Laminated Timber (CLT) in temperate climates is fungal decay. The required conditions of oxygen and temperature are invariably met in building structures; the remaining factor of Moisture Content is thus the most controllable parameter. A generally

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accepted safe, though likely conservative, upper bound on timber relative Moisture Content (MC) for prevention of fungal decay is 20% [3-10].

As a result of excessive Moisture Content, despite modern large-scale mass timber construction still being in its infancy, several failures to meet required longevity have already occurred. One of the primary drivers of failure is degradation due to excess moisture originating from the construction stage [11]. Related to this, an important factor in the realisation of large timber building structures is gaining sufficient insurance coverage during construction and the service life of the building [12]. A factor that is emphasised in insurance industry guidance is evidencing positive project-specific design and construction decisions and clear communication of these to the insurer [13].

For a number of reasons, CLT roofs are consistently found to be an area most often affected by moisture damage [14]. They are the area most directly exposed to precipitation during construction and consist of large planar surfaces with many joints and thus potential entry points for water. Unlike floors, roofs typically remain exposed externally while follow-on waterproof, non-vapour-diffusible layers are added, increasing the risk of trapped moisture. A further issue is the prevalent practice of installing CLT roofs with zero fall to the structure, influenced by reinforced concrete slab design. The architectural and constructional advantage of this approach is that supporting beams are level and planar, minimizing upper storey height. Rainwater drainage is then achieved by tapering the finishes above the slab. However, in the temporary condition there is no passive gravity path for shedding of water. Other geometry-related vulnerabilities arise when roof features disrupt passive rainwater shedding. Elements like valleys, invert, upstands, and parapets can cause water to pool, increasing timber moisture uptake due to hydrostatic pressure and prolonged exposure. These vulnerabilities also apply to the in-service condition; if there is a breach of the waterproofing layers and water makes its way through to the structural deck, it will accumulate rather than be drained.

Moisture Control - Existing Research and Guidance

To observe and quantify moisture in timber structures, numerous academic studies have monitored buildings during or after construction [15-27], tested timber in labs [19, 26-32], or run numerical simulations and risk modelling [33-41]. While each offers important localised insights, none present the quantitative comparison of a full range of design and construction mitigations required to directly inform structural or architectural design decision-making.

North America, and in particular the Pacific North West, has seen a number of programmes of moisture monitoring of mass timber buildings during construction including; Peavy Hall building at Oregon State University [42-44], Carbon 12 in Portland, Oregon [15-19], Brock Commons Phase 1 at the University of British Columbia [20-22] and the Wood Innovation and Design Center, Prince George, BC [16-18]. Scandinavian and Nordic countries have also been active in site monitoring studies, including investigations conducted in Estonia [18], western and central Sweden [19-21], and Norway [22, 23], as

well as analyses based on a broader Norwegian damage-investigation database [23]. In all instances moisture intrusion was reported, despite varying degrees of preventative actions. In many, the Moisture Content exceeded the generally accepted 20% safe threshold for avoidance of fungal decay [3-10] and in some, sufficient damage was sustained that remedial actions were required. There are very few instances of construction moisture monitoring in Europe, beyond Scandinavia, though Leyder [24, 25] used monitoring to concurrently investigate moisture effects on losses in pre-tensioned timber elements.

Several researchers have carried out lab testing of CLT with slightly different objectives, methods of wetting, protection measures and acceptability criteria, which have yielded differing results. Kordziel [19] found wetting from above was significantly more onerous than from below. McClung et al. [26] reported acceptable free-drying within a month of submersion with sealed edges, whilst Wang [27] reports unacceptably high Moisture Content six months after wetting from above and application of non-breathable layers above and below. Johns et al.'s [28] comparison of dry-out between impermeable, permeable and freely-ventilated CLT showed integration of a ventilated void above CLT in the roof assembly doubled dry-out rate. Similarly, Lepage et al. [29] observed drying to acceptable levels after six months in non-covered samples, whereas those with cementitious screed still retained significant moisture. Schmidt et al. [31] also reported the strong influence of edge sealing in moisture transport within the CLT. Water spray testing by Schmidt et al. [30] recorded permanent visual, mechanical and integrity defects caused by cyclic wetting and drying. The anisotropic properties of the CLT layout, exposed end grain at panel edges and entrapment at joints were all noted as significant effects. Niklewski et al [32] carried out monitoring of Moisture Content within different geometries of sample glulam column-beam connections over the period of a year, including various basic local protection measures such as sealants and capping. However, it was concluded that only full temporary enclosure was effective in maintaining Moisture Content below safe decay thresholds.

These lab tests primarily focussed on characterising moisture transport mechanisms and timelines to arrive at prediction of moisture content in different scenarios. The implications of elevated Moisture Content can be evaluated through decay risk modelling [33]. The principle of an exposure dose of applicable moisture and temperature was applied to timber decay by Brischke and Rapp [45]. This dose-response principle was subsequently integrated into proposed decay risk models [33-36, 39] and the open-source software ClickDesign [41]. However, use of these tools appears to remain confined to wood science and preservation fields focussed primarily on external timber product applications. For these applications, the number of variables in the decay-risk model can be greatly reduced, relative to those in the construction process of a complete building.

Olsson et al. [37] and Oberg & Wiege [38] undertook studies that assessed CLT assemblies through construction-stage

wetting to provide prediction and measurement of mould growth. Although mould does not affect structural performance, its presence may be considered a failure of the construction methodology and many of the principal findings of the studies are transferrable to prevention of fungal decay.

While individual study results could be collated and applied to inform industry guidance, they often lack sufficient breadth of scope or fail to transition from academia to practice due to limited collaboration and alignment of motivation [46]. There is an existing body of industry guidance on managing construction-stage moisture in timber structures, typically produced by industry organisations [10, 47-50] or product manufacturers [51, 52], and occasionally by commercial consultants [14]. Several published sources identify specific recommended methods to mitigate construction-stage moisture hazards [10, 38, 47-50, 53-65], but rarely cite their origin nor indicate relative effectiveness. Rather, the guidance is qualitative in nature, without comparative measures of the effectiveness of different potential mitigation measures. Thus, it is difficult for designers to use these documents as decision-making tools, especially in the early design stage of projects, when the most influential decisions are made.

Research Gap and Focus of Study

It is evident from the research and guidance discussed above that there is currently no consistent, quantitative, and decision-oriented framework that allows designers to compare the effectiveness of construction-stage moisture mitigation strategies for CLT at the design stage. In order to address this challenge, research must critically examine and assess the design decisions and construction methods used to mitigate moisture risks in mass timber during the construction process. In particular, robust quantitative measures of the relative effectiveness of different mitigations are required for designers to make informed project specific decisions within real-world constraints. At present, decision-making is largely based on anecdotal or qualitative information and, while knowledge and experience does exist across the industry, it is fragmented, mostly confined to individuals or organisations and, in some cases, restricted by commercial or legal barriers.

Improved access to reliable and comparable data will support more rigorous risk assessment and evidence-based decision-making by designers and constructors. This will eliminate or significantly reduce the incidence of construction-stage moisture damage, removing a barrier to the wider adoption of low-carbon timber construction.

This study focuses specifically on CLT roof systems. Roofs are typically considered among the most moisture exposed and performance-critical building components during construction and require the most stringent criteria. They share enough common factors with other timber elements to allow the findings to be extended or extrapolated more broadly.

The aim of this research is to establish a quantitative basis for decision-making regarding construction-stage moisture risk

mitigation in CLT roof systems. Specifically, it evaluates and compares a range of mitigation strategies by quantifying both their effectiveness in reducing moisture damage and the disruption impacts associated with their implementation. The resulting dataset will provide designers and contractors with objective evidence to assess trade-offs between alternative mitigation measures and make informed, project-specific decisions. This will address the current reliance on fragmented qualitative knowledge and contribute towards a more rigorous, evidence-based approach to moisture risk management in mass timber construction.

Methodology

Research Design

Measurement Framework

The objective of the study is to quantitatively compare the effectiveness of different construction-stage moisture mitigations to prevent the timber roof slab suffering onset of fungal decay in the CLT roof slab. The key measurement sought by the study is the effectiveness in avoiding onset of fungal decay. To make it more directly applicable this is defined more specifically in this instance as preventing of any part of the CLT roof slab exceeding 20% Moisture Content for more than 14 consecutive days.

The methodology used for this study is Expert Elicitation, or Structured Expert Judgement. This is an established method of gathering data on complex problems from a body of collective knowledge. It has been applied to some fields within the built environment, such as seismic vulnerability, maintenance regimes and live load evaluation [66-68], but not previously applied to structural timber design and execution. An advantage of expert elicitation compared to a more conventional survey, is that it requires only a small number of targeted experts to generate reliable, quantifiable data. The basic principles of expert elicitation are summarised by one of the founding practitioners, Roger Cooke, as; "Reproducibility, Accountability, Empirical Control, Neutrality and Fairness" [69]. By these means, the process remains rigorous and scientifically sound and represents a significant enhancement over a simple survey. Cooke's Classical Model protocol follows a mathematical process for aggregation of experts' data [70]. It therefore allows non-concurrent gathering of the data from different experts. It uses performance in Seed Questions, to which the answers are known to the questioner, to weight different experts in their performance in the Target Questions, which are the actual data of interest. For this study, six Seed questions and 19 Target questions were used.

To inform the Target questions, current research and guidance literature was reviewed to identify relevant mitigation strategies and these were then categorised according to the fundamental mechanism by which they work, as summarised in Table 1.

Table 1 Occurrence of moisture mitigations in research and guidance literature

Mitigation	References																Mechanism
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	
Seasonal timing				Y	Y	Y							Y	Y		Y	Control of probability or magnitude of initiating event
Monitoring of rainfall	Y			Y		Y								Y	Y	Y	Control of probability or magnitude of initiating event
Just-in-time delivery	Y	Y				Y							Y	Y		Y	Control of probability or magnitude of initiating event
Speed of construction	Y	Y		Y	Y	Y							Y	Y	Y	Y	Control of probability or magnitude of initiating event
Temporary enclosure	Y	Y		Y	Y	Y			Y	Y			Y	Y	Y	Y	Interception of precipitation at a distance
Temporary membranes & tapes	Y	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y	Interception of precipitation at surface
Water-repellent coating				Y	Y	Y		Y			Y	Y	Y	Y	Y	Y	Interception of precipitation at surface
Falls to structural deck					Y	Y		Y			Y	Y		Y			Facilitation of rapid water removal and avoidance of hydrostatic pressure
Remove inverts & valleys								Y						Y			Facilitation of rapid water removal and avoidance of hydrostatic pressure
Remove upstands & parapets								Y						Y			Facilitation of rapid water removal and avoidance of hydrostatic pressure
Remove internal downpipes						Y								Y			Facilitation of rapid water removal and avoidance of hydrostatic pressure
Temporary piped drainage				Y		Y		Y		Y				Y	Y	Y	Facilitation of rapid water removal and avoidance of hydrostatic pressure
Active site water management		Y		Y	Y	Y			Y	Y	Y		Y	Y	Y	Y	Facilitation of rapid water removal and avoidance of hydrostatic pressure
Cavity ventilated to inside					Y	Y		Y			Y	Y		Y			~Detection of moisture ingress Facilitation of passive drying
Drying periods in programme	Y					Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	~Detection of moisture ingress Facilitation of passive drying
Moisture measurement protocol				Y		Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Early identification of potential decay conditions (facilitating corrective action)
Embedded electronic moisture monitoring														Y		Y	Early identification of potential decay conditions (facilitating corrective action)
Embedded electronic leak detection					Y	Y		Y						Y		Y	Early identification of potential decay conditions (facilitating corrective action)
Active drying		Y			Y	Y					Y		Y	Y	Y		Corrective action under failure of preventative measures

Reference key: R1: Thivierge, 2011 [53]; R2: Wang, 2016a, b [54, 55]; R3: Wang et al., 2018 [56]; R4: Öberg and Wiege, 2018 [38]; R5: Canadian CLT Handbook, 2019 [47]; R6: RDH Building Science, 2021 [57]; R7: BM TRADA, 2017, 2020 [48, 58]; R8: Riggio, Alhariri and Hansen, 2020 [59]; R9: Structural Timber Association, 2022 [60]; R10: Swedish Wood, 2022b, a [61, 62]; R11: BM TRADA, 2022 [10]; R12: NHBC, 2022 [63]; R13: Tall Wood Buildings in Canada [64]; R14: Timber Development UK, 2024 [49]; R15: Ingenieur Holzbau, 2025 [65]; R16: Danish Technological Institute 2025 [50]

The Form of the Questionnaire

Data was collected via a questionnaire which was devised to meet the requirements of Cooke's Classic Model (CM) of expert

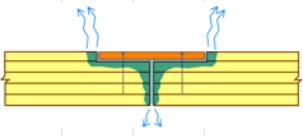
elicitation [69]. The format of the document and the wording of the questions were carefully designed to be unambiguous and arranged and worded to avoid issues of known heuristics and bias [71-73].

The questionnaire, created using Microsoft Excel, starts with tabs for ethics statements, background to the research and participant consent. Next, it gathers data on the background of the participant. Specifically, the nature of their experience, in this case; Academic research, Design consultancy, Material/product provider, Contractor/installer or Other. Finally,

the page queries how many years of relevant experience the expert's knowledge is drawing upon; 0-5, 5-10, 10-15, 15-20 or 20+. Each subsequent tab contains one mitigation question. The first tab is an example question with example answers provided for illustration, Figure 1, and all other question tabs follow the same general format.

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Question number	1 of 28	EXAMPLE QUESTION - Moisture in a ply spline connection in CLT	
<i>Question reference</i> E 1 EXAMPLE QUESTION: If a plywood spline connection between two CLT panels received heavy rain before it was sealed and the first 50mm of the two CLT slabs increased from 12 to 22 % moisture content. Approximately how many days do you think it would take for the joint area to passively dry back to 12% if the building facade was completed straight away and it was left un-encapsulated at 20°C 65%RH?			
			
Drying wouldn't take less than	5 days	5th Percentile	Lower plausible limit
Drying would take at most	30 days	95th Percentile	Upper plausible limit
Drying would probably take	14 days	50th percentile	Best guess
How confident are you in your estimates?	3	Medium level of confidence	(0 = No confidence - 5 = Very high confidence)
Please enter any other information you would like to add to this question or your answers EXAMPLE ANSWER: My answers are based on personal experience of similar though not identical situations			

Participant Information Sheet | Background & Context | Consent Form | Participant Details | **Q1 - Example** | Q2

Figure 1. Extract from questionnaire showing example question page

For each Seed question (Table 2), five potential data points were elicited: 5th percentile (lower plausible limit), 95th percentile (upper plausible limit), 50th percentile (best guess),

self-assessed level of confidence in the answer and a free-text field for explanation or caveating of the answer given, as shown in the example in Figure 1.

Table 2 Seed question wording, answer and reference

No.	Question	Answer	Reference/Source
2	Moisture content of manufactured CLT What % Moisture Content (MC) would you expect Cross Laminated Timber to be at when leaving the manufacturer	12 % (+/- 2%)	CLT by Stora Enso – Technical Brochure [75] Swedish Wood [61]
3	General accepted safe Moisture Content What % Moisture Content (MC) would you expect to be the safe upper limit for a mass timber structural component to avoid fungal decay (as defined in a construction stage moisture control plan)	20 %	BM Trada WIS 4-14 [5] BM Trada Research Summary [10]
4	Wetting in a CLT slab from standing water on top Approximately what % Moisture Content (MC) would you expect at 40mm depth in a CLT slab that had started at 11%MC but had 10mm of standing water on it for one week (For general context, assume a temperate climate in winter & the top lamination is 40mm thick so penetration does not pass through a glue line)	25 %	Olsson, L., Lång, L., Bok, G. and Mjörnell, K., 2023. Development of laboratory experiments to determine critical moisture condition of CLT constructions.[37]
5	Wetting in the base of a CLT wall standing in water Approximately what % Moisture Content (MC) would you expect near the centre of a CLT wall panel 30mm up from its base that had started at 12%MC after it had had its bottom edge placed in 2mm of standing water for one week (For general context, assume a temperate climate in winter and a 100mm thick CLT wall panel)	30 %	Kalbe, K., Annuk, A., Ruus, A. and Kalamees, T., 2021. Experimental analysis of moisture uptake and dry-out in CLT end-grain exposed to free water. [76]

Table 2 Seed question wording, answer and reference (continued)

No.	Question	Answer	Reference/Source
6	Expected rainfall days in winter If you were constructing a timber structure and it was going to be exposed for the whole of November-December-January in a northern-hemisphere temperate maritime climate (eg London, UK). How many days would you expect for the timber to be exposed to rainfall? (more than 1mm)	31 days	UK Meteorological Office Average climate tables 1991-2020 – Station Greenwich Observatory. [77]
7	Expected rainfall days in summer If you were constructing a timber structure and it was going to be exposed for the whole of June-July-August in London, UK. How many days would you expect for the timber to be exposed to rainfall? (more than 1mm)	23 days	UK Meteorological Office Average climate tables 1991-2020 – Station Greenwich Observatory. [77]

Each Target question sheet elicited six potential data points as it also required an assessment of the level of disruption associated with each mitigation (Figure 2). Depending on the

mitigation type, the level of disruption was either assessed in relation to cost/time of construction or to architectural constraints.

13

Question number

13

of

28

Self Adhesive Membrane

Question reference

T 6

If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was

Apply a self-adhesive breathable membrane to the CLT panels in the factory, joints taped on site using matching product and both stay in place until the permanent roof membranes are installed. (eg Siga Wetguard, Rothoblaas Defence, Isocell TimberProtect etc)

How successful do you think it would be?

Would be successful at least	5	times out of 20	5th Percentile	Lower plausible limit
Would be successful at most	15	times out of 20	95th Percentile	Upper plausible limit
Would probably be successful	10	times out of 20	50th percentile	Best guess

How confident are you in your estimates?

(0 = No confidence - 5 = Very high confidence)

How disruptive do you think taking this action would be to the **costs and build-programme** of the project

(0 = No disruption - 5 = Very high level of disruption)

Please enter any other information you would like to add to this question or your answers

CLICK TO GO TO NEXT PAGE >

Figure 2. Extract from questionnaire showing Target question layout

The final spreadsheet tab summarises all the participant's answers to the percentile reliabilities with hyperlinks back to the

relevant tabs for each question, Figure 3, providing the opportunity to review the relative magnitude of answers in one place and amend them if required.

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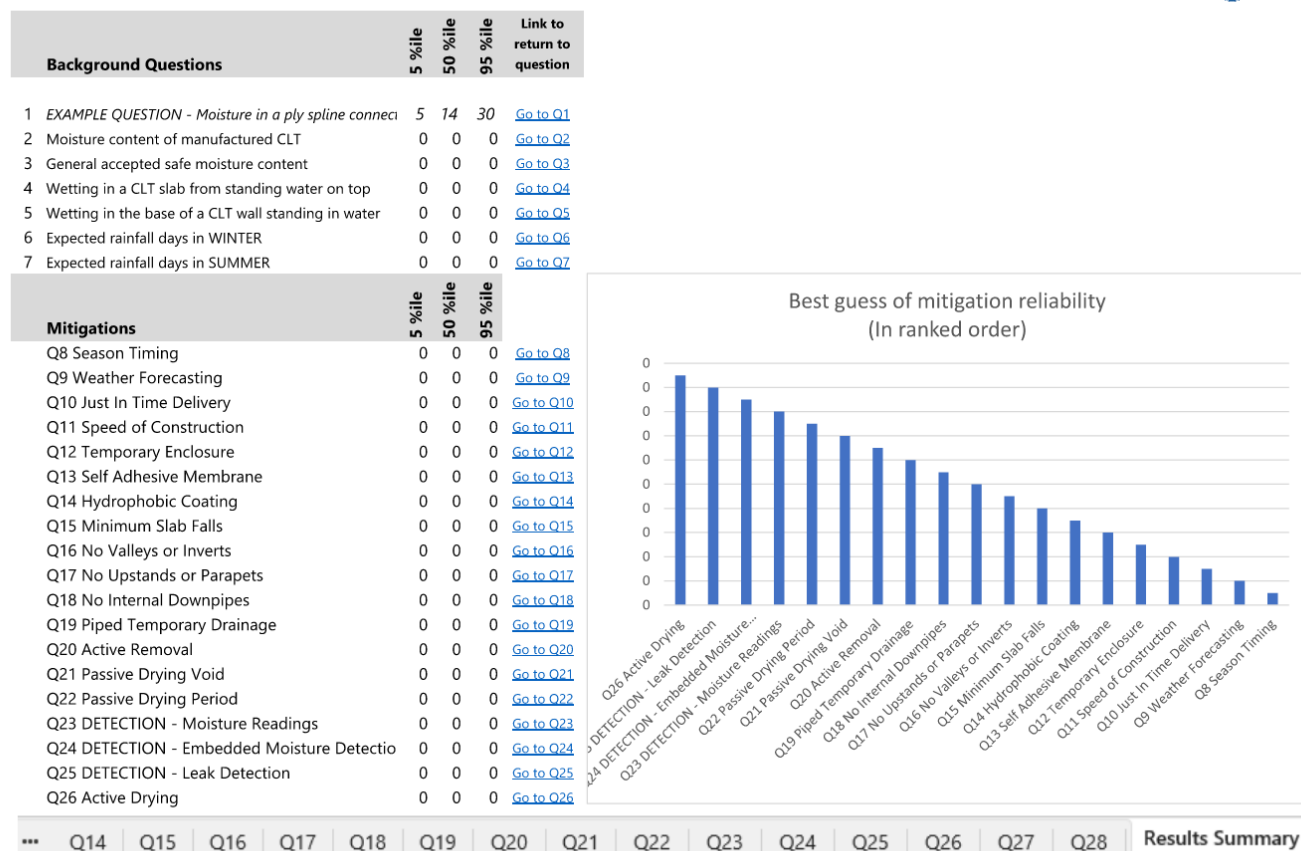


Figure 3. Extract from the questionnaire showing final summary page

Wording of Questions

The Seed questions used are summarised in Table 2. Valid Seed questions should have referenceable answers, be directly relevant to the subject matter, and be such that knowledge of them would influence participant's answers to the Target questions. Devising questions that meet all of these requirements is recognised by practitioners of Expert Elicitation as being challenging [74]. In this instance they include questions related to Moisture Content limits at manufacture, safe fungal decay threshold and response to wetting. Two further questions relate to the main meteorological driver of wetting; rainfall. Sufficient clarifying data is given in the question to minimise ambiguity or misinterpretation. The questions span different subjects, though all are parameters that would directly inform a rigorous risk analysis of construction-stage wetting of a CLT roof and which have specific answers referenceable in peer reviewed literature or published records.

The reliability of expert elicitation is influenced by linguistic framing, heuristics, and cognitive biases [69, 78, 79]. To mitigate these effects, the survey design was aligned with best practices from the literature. Quantitative measures were used instead of descriptive responses to reduce ambiguity and linguistic uncertainty [72, 80, 81]. Tasks were kept small and

self-contained to minimize cognitive load [82], with a final summary page enabling review of percentile estimates in tabular and graphical formats. The three-point percentile plus confidence—was employed to reduce overconfidence and symmetric anchoring around the median estimate [74, 83-85]. Numerical denominators were grounded in realistic ranges; a base of 20 was selected to reflect the typical number of projects informing expert judgment, avoiding anchoring around common percentage divisors like 25%, 50%, or 75% [86]. Each question included a concise summary followed by detailed context to ensure clarity and completeness, reducing the risk of satisficing [87]. Questionnaire layout was optimized for clarity and visual appeal, with mitigation methods illustrated diagrammatically to enhance engagement and response rates [69, 87] (visual examples are shown in Figures 1 and 2). The final proposed methodology was reviewed and approved by the University of Bath Research Ethics Committee.

Prior to the elicitation from the ten expert participants, the draft questionnaire was trialled on a pool of six pseudo-experts as recommended by Cooke [69]. This included practicing timber engineers and academic staff working in related fields. As a result of their feedback, several additional changes were made to question wording, to reduce ambiguity, and to the presentation format to aid navigation. The final wording of the

Target questions within the questionnaire is presented in Table 3.

Table 3 Target Question Wording – Refer to Table 1 for background in literature

No.	Question
8	Season Timing If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Timing the start of construction for the most favourable time of the year in terms of rainfall. (For the 5-storey, 15x40m building described in the 'Background & Context'). How successful do you think it would be?
9	Weather Forecasting If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Monitoring the 5-day weather forecast and timing installation of the roof elements for a predicted dry period. Bearing in mind how long the dry period might last in relation to how long it would take to get the permanent roof coverings in place. How successful do you think it would be?
10	Just in Time Delivery If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Adopting just-in-time delivery so that timber is not stored on site for more than 48 hours before installation. How successful do you think it would be?
11	Speed of Construction If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Ensuring that design of elements, connections and envelope detailing maximises the speed of construction and enclosure of the timber frame. How successful do you think it would be?
12	Temporary Enclosure If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Erection of a temporary weathertight roof plane over the timber structure as soon as it is complete and staying in place until permanent roof membranes are in place. How successful do you think it would be?
13	Self-Adhesive Membrane If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Application of self-adhesive breathable membranes to the CLT panels in the factory, joints taped on site using matching product and both stay in place until the permanent roof membranes are installed. (eg Siga Wetguard/ Isocell Protect SK/ Rothoblaas Defence etc) How successful do you think it would be?
14	Hydrophobic Coating If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Application of a temporary sprayed/painted water repellent coating to the surfaces of CLT panels in the factory (Remmers Induline SW-910 / Arxada LotusPro) How successful do you think it would be?
15	Minimum Slab Falls If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Ensure that all CLT structural slabs are inclined on a minimum 1:40 fall. (As opposed to zero-fall CLT and only the finishes laid to a fall) How successful do you think it would be?
16	No Valleys or Inverts If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Ensure that there are no valleys or inverters in the CLT slabs which cause a designed net longitudinal fall of less than 1:80. How successful do you think it would be?
17	No Upstands or Parapets If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Ensure that there are no upstands or parapets which interrupt a direct gravity-driven path for water off the roof. How successful do you think it would be?
18	No Internal Downpipes If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Ensure that there are no surface-water downpipes present internal to the footprint of the roof. ie all downpipes run down outside the building perimeter. How successful do you think it would be?
19	Piped Temporary Drainage If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Provide temporary water-disposal routes within closed, sealed, piped drainage runs. How successful do you think it would be?

Table 3 Target Question Wording – Refer to Table 1 for background in literature (continued)

No.	Question
20	Active Removal If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Provide site attendance for removal of standing water on CLT surfaces within one hour of rainfall ceasing. Inside working hours, approx. 08:00-17:00 Monday to Friday. How successful do you think it would be?
21	Passive Drying Void If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Adoption of a sheathed non-structural deck, supported on battens off the structural CLT in order to form an air cavity ventilated to the space inside the building. How successful do you think it would be?
22	Passive Drying Period If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Planning the construction programme such that a period is available for the underside of the CLT roof deck to remain un-encapsulated to allow passive drying through to the inside of the building. How successful do you think it would be?
23	DETECTION – Moisture Readings If you employed the following method to ALERT YOU to there being any areas of CLT at high Moisture Content anywhere in the roof A strict protocol being in place to take, record and communicate Moisture Content measurements at pre-defined locations in the CLT slab using hand held moisture meters. Locations are chosen to be representative of general high-risk areas for wetting. How successful do you think it would be?
24	DETECTION – Embedded Moisture Detection If you employed the following method to ALERT YOU to there being any areas of CLT at high Moisture Content anywhere in the roof Embedded electronic moisture monitoring devices in place to measure, record and communicate moisture readings in the CLT. Locations are chosen to be representative of general and high-risk areas for wetting, (eg Wiiste/ WoodSense/ Tector) How successful do you think it would be?
25	DETECTION – Leak Detection If you employed the following method to ALERT YOU to there being any areas of CLT at high Moisture Content anywhere in the roof Embedded leak detection sensors in place below the primary waterproofing membrane and above the CLT though not embedded in it. (eg AquaTrace, ProGeo etc). How successful do you think it would be?
26	Active Drying If the only thing you did to try and prevent the timber roof slab suffering onset of fungal decay was; Active drying of the CLT through provision of relevant temporary enclosure and active drying through application of controlled temperature and humidity airflow. How successful do you think it would be?
27	Optimum Set of Mitigations In your opinion, what is the optimum set of mitigations that a project can employ. In consideration of balancing effectiveness with constraints on the architectural form and the cost and efficiency of construction execution? How successful do you think it would be?
28	Other Potential Mitigations Are there any other beneficial mitigations or actions that you would recommend, which have not been mentioned in this survey?

Measurement Execution Process

Subject-matter experts invited to participate in elicitation need to have the required knowledge and expertise. Furthermore, this expertise must have been obtained through direct engagement and involvement in the subject, as opposed to purely through passive inheritance of received knowledge, from guidance literature for example.

Participants were therefore selected from a pool of the most active timber construction subcontractors, mass timber

investigation specialists and academic researchers in this specific field, see Figure 4. These were primarily UK-based but with others from mainland Europe. All had a minimum of 5 years timber-specific experience, with most having over 10 years' experience. Two were specialist timber-defect investigators, five worked within specialist timber design consultancy, six currently or previously worked for timber contractors, three were involved in timber academic research and two currently or previously worked for mass timber product suppliers.

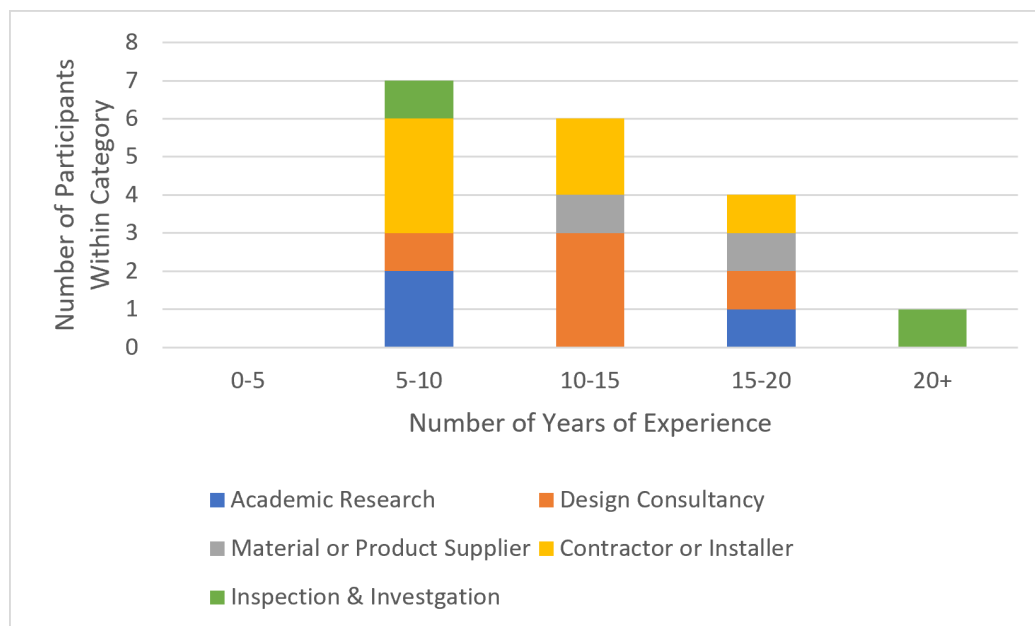


Figure 4. Participant Expertise. Note that some participants appear in multiple categories.

A short introductory video explaining the project, process and to run through the questionnaire was presented to each participant during a video call at the time of them completing the questionnaire. Thus, all participants were provided the same background information and briefing on the context, data collection method and way to navigate the questionnaire. While a total of thirteen experts were initially contacted, ten data sets were finally returned by experts from academia and industry. Experts were notified of the considerations of anonymity and made aware that formalised research ethics approval had been granted and they each completed the participation statement declaration.

The participants took between 20 and 40 minutes to complete the six Seed questions and 19 Target questions. Several experts provided additional qualitative information as well as answering the final questions on optimum sets of mitigations and additional mitigations that had not been listed.

Data Analysis

Weighting of results from each expert was carried out according to both Cooke's Classical Model (CM) [69] and the Expected Relative Frequency scheme (ERF) [88]. The un-weighted (Equal Weights (EW) scheme) data was also examined.

In this research an open source Python software, Elicipy (version 1.2.0) [89], is used to perform the complex statistical operations associated with Cooke's Classical Method protocol. This was built upon the foundation of the Excalibur application created at TU Delft in the 1990s [90]. Elicipy has previously been tested and verified by re-running the statistical processes on a dataset originally analysed using a previous set of analysis tools for two peer-reviewed research papers [91, 92].

The principal output is the Global Weight Decision Maker (GWDM), which is the term used within the protocol to describe the ultimate weighted and aggregated mitigation effectiveness measures. The Elicipy software also generates statistical plots for visual representation of the data. Statistical input parameters were retained in line with recommendations by Hanea and Nane [93].

All expert responses were administered remotely via video conference. The facilitator was available throughout to provide clarification of any ambiguity in the questions, but not any guidance on the answer. The expert was also encouraged to review the relative scores assigned between questions at the end, via the summary tab, and to adjust scores as required to accurately represent their judgement on their comparative effectiveness and disruptiveness.

Results and Discussion

The aim of the study is to develop and apply a structured, quantitative method that enables comparative, decision-oriented evaluation of construction-stage moisture mitigation strategies for CLT roofs.

The study successfully employed Cooke's Classical Method for Expert Elicitation to yield a rich quantitative data set which not only assessed the relative effectiveness of a wide set of mitigations but also provided a measure of the relative disruptiveness of applying them. This is a key parameter for decision making in real projects, where constraints on aesthetics, time, cost and other factors must be balanced against system performance.

Weighted Mitigation Effectiveness

Table 4 shows the mitigations ranked by effectiveness according to Cooke's Method (CM) Global Weight Decision Maker (GWDM). Their performance relative to the group mean is also indicated.

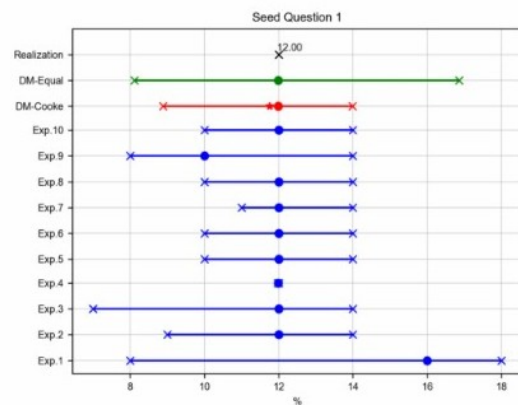
Table 4 Mitigations listed in descending order of assessed effectiveness

No	Mitigation Type	GWDM Qmean (CM % effectiveness)	Performance relative to group mean (% points)
Q12	Temporary Enclosure	73	+17
Q15	Minimum Slab Falls	71	+15
Q23	DETECTION - Moisture Readings	70	+14
Q24	DETECTION - Embedded Moisture Detection	70	+14
Q13	Self-Adhesive Membrane	69	+13
Q17	No Upstands or Parapets	67	+11
Q26	Active Drying	66	+10
Q20	Active Removal	65	+10
Q19	Piped Temporary Drainage	61	+5
Q8	Season Timing	59	+3
Q14	Hydrophobic Coating	58	+2
Q18	No Internal Downpipes	57	+1
Q21	Passive Drying Void	51	-5
Q16	No Valleys or Inverts	48	-8
Q25	DETECTION - Leak Detection	42	-14
Q9	Weather Forecasting	41	-15
Q11	Speed of Construction	38	-18
Q10	Just in Time Delivery	36	-20
Q22	Passive Drying Period	20	-36

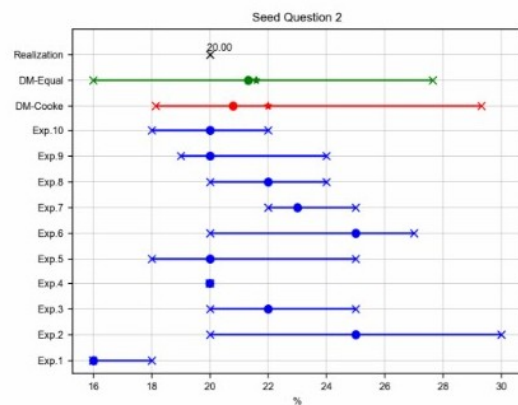
The most effective design measure was providing Minimum Slab Falls and the most effective construction-stage method was providing Temporary Enclosure, closely followed by a Self-Adhesive Membrane. It is noteworthy that mitigations; Passive Drying period, Just in Time Delivery, Speed of Construction and Weather Forecasting are all routinely mentioned as effective strategies in guidance literature [10, 38, 47-50, 53-58, 61, 63, 65, 94], but here are assessed as performing poorly, at less than 50% effectiveness.

Seed Question Performance

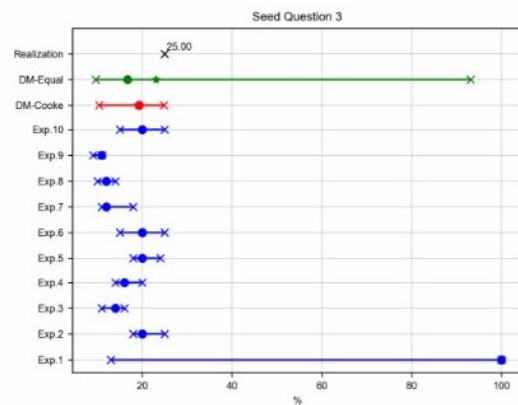
Figure 5 illustrates the answers given by each expert to the Seed questions. For each Seed question the Calibration of the answer can be visually assessed from the proximity of the 50th percentile (Blue dot) to the true answer (Black X) and the Informativeness can be visually assessed by the relative width of the 5th to 95th percentiles (Blue bar). The aggregated Decision Maker can be seen for Equal Weights (green) and according to the Cooke's Classical Method (red).



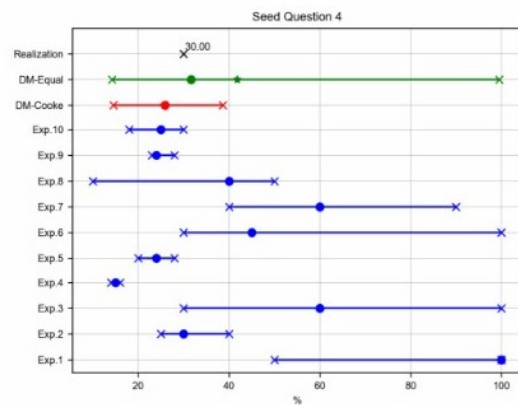
Q2- Moisture content of manufactured CLT



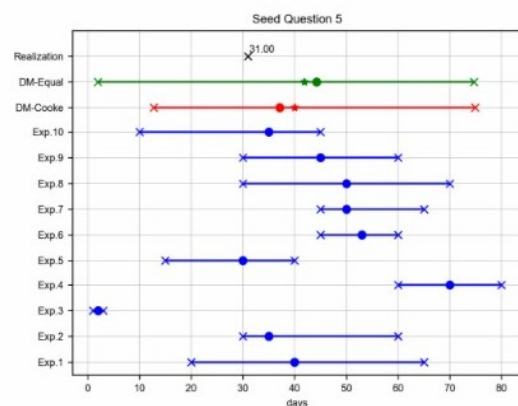
Q3- Generally accepted safe moisture content



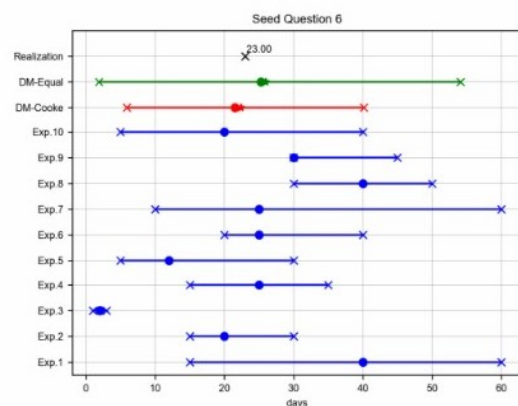
Q4- Wetting in a CLT slab from standing water on top



Q5- Wetting in the base of a CLT wall standing in water



Q6- Expected rainfall days in winter



Q7- Expected rainfall days in summer

Figure 5. Plots of Seed question answers by each expert, and corresponding CM Weighted & Equal Weight Decision-Makers

Q2 was generally answered well in terms of accuracy and informativeness. Q3 showed a surprisingly large scatter considering that the 20% MC threshold is very widely reported in the literature. Q4 is well clustered but generally an underestimate of the true experimentally determined value. Expert 1's answer to Q5 shows a possible misinterpretation of the question or error in entering the answer. Other answers to Q5 also show a large scatter with few experts capturing actual answer with their 5-95%ile ranges. In Q4 Expert 1 again returns a significant outlier, potentially for the same reasons as before.

Q6 gives a relatively large scatter with only around half the experts capturing the actual answer with their 5-95%ile ranges. Q7 has a relatively large scatter but more than half the experts capture actual answer with their 5-95%ile range. The answers to Q6 and Q7 raise the question of whether weather prediction is a good measure of relevant expertise. Rainfall frequency is certainly an essential part of the hazard analysis, but in a real-world project the data could in principle be accessed from weather records to inform a rigorous risk-assessment.

Reliability of Expert Data

Performance in the Seed questions was variable with some responses showing considerable deviation from the actual answer. The Seed questions all related to the risk assessment of construction stage moisture damage but represented

different parts of a holistic picture. The results may therefore indicate that there are very few members of even the expert community, who have detailed knowledge which combines climatic conditions, wood science, buildings design and on-site construction. This conclusion is further indicated by the spread of self-reported confidence in certain Seed questions (Table 5).

Table 5 Self-reported confidence values for questions with mean values per question and per expert

Confidence (5 = max., 0 = min.)													
No	Type	Subject	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Mean
Q2	Seed	Moisture Content of manufactured CLT	5	5	4	4	5	5	5	4	5	3	4.5
Q3	Seed	General accepted safe Moisture Content	5	4	5	4	5	5	5	4	4	5	4.6
Q4	Seed	Wetting in a CLT slab from standing water on top	3	3	3	2	3	4	4	3	3	2	3
Q5	Seed	Wetting in the base of a CLT wall standing in water	3	2	4	3	4	4	3	4	3	4	3.4
Q6	Seed	Expected rainfall days in WINTER	3	3	3	2	3	4	3	3	3	3	3
Q7	Seed	Expected rainfall days in SUMMER	3	4	3	2	3	3	3	3	4	3	3.1
Mean confidence for expert across all seed questions			3.7	3.5	3.7	2.8	3.8	4.2	3.8	3.5	3.7	3.3	3.6
No	Type	Subject	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Mean
Q8	Target	Season Timing	2	4	2	3	3	4	3	2	4	2	2.9
Q9	Target	Weather Forecasting	2	4	2	3	3	4	3	4	3	3	3.1
Q10	Target	Just in Time Delivery	2	4	2	3	3	4	4	3	4	3	3.2
Q11	Target	Speed of Construction	2	4	2	3	4	4	3	4	4	3	3.3
Q12	Target	Temporary Enclosure	4	5	3	4	5	5	5	4	3	4	4.2
Q13	Target	Self-Adhesive Membrane	3	5	2	4	4	5	4	4	5	4	4
Q14	Target	Hydrophobic Coating	3	3	2	4	4	3	3	4	3	4	3.3
Q15	Target	Minimum Slab Falls	4	5	3	3	5	5	5	3	4	3	4
Q16	Target	No Valleys or Inverts	2	4	2	4	5	3	5	3	2	2	3.2
Q17	Target	No Upstands or Parapets	2	4	2	4	5	4	5	3	3	3	3.5
Q18	Target	No Internal Downpipes	3	3	2	4	5	4	3	3	3	3	3.3
Q19	Target	Piped Temporary Drainage	3	0	3	3	4	4	4	0	2	2	2.5

Table 5 Self-reported confidence values for questions with mean values per question and per expert (continued)

Confidence (5 = max., 0 = min.)													
No	Type	Subject	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Mean
Q20	Target	Active Removal	3	5	3	3	3	5	5	3	5	4	3.9
Q21	Target	Passive Drying Void	2	5	2	4	5	4	3	3	1	3	3.2
Q22	Target	Passive Drying Period	3	5	4	4	5	4	1	3	5	4	3.8
Q23	Target	DETECTION - Moisture Readings	2	5	3	4	5	5	5	4	5	5	4.3
Q24	Target	DETECTION - Embedded Moisture Detection	2	3	2	4	5	4	3	4	5	5	3.7
Q25	Target	DETECTION - Leak Detection	2	4	2	3	5	4	3	4	5	5	3.7
Q26	Target	Active Drying	4	3	4	4	5	5	3	4	2	4	3.8
Mean confidence for expert across all target questions			2.6	3.9	2.5	3.6	4.4	4.2	3.7	3.3	3.6	3.5	3.5

Confidence scale: 5 = max., 0 = min.

It is noted that data is based on a relatively small sample of ten expert participants. However, this is not uncommon within the field of expert elicitation, where the nature of a specialist subject is such that there is frequently only a small pool of sufficiently qualified people available. None of the experts were risk analysts specifically, only by proxy through their industry or research roles. The process of expert elicitation through Cooke's Classical Model is however specifically designed to account for a variance in performance between experts and to weight them accordingly.

However, distinct trends were evident in the data, between different experts and across the range of their backgrounds. It

is therefore concluded that the data is reliable and indicative of the current state of knowledge and experience across the timber construction industry.

Effect of Expert Weighting

Figure 6 illustrates the experts' mitigation effectiveness measures aggregated using both the Equal weights (EW) and Cooke's Classical Model (CM) methods along with how much this is shifted by the expert weightings ($\delta Q_{\text{mean}}(\text{EW}-\text{CM})$). A larger shift between EW (black dashed) and CM (blue solid) indicates that experts' performance in the Seed questions had a more significant effect on the weighting.

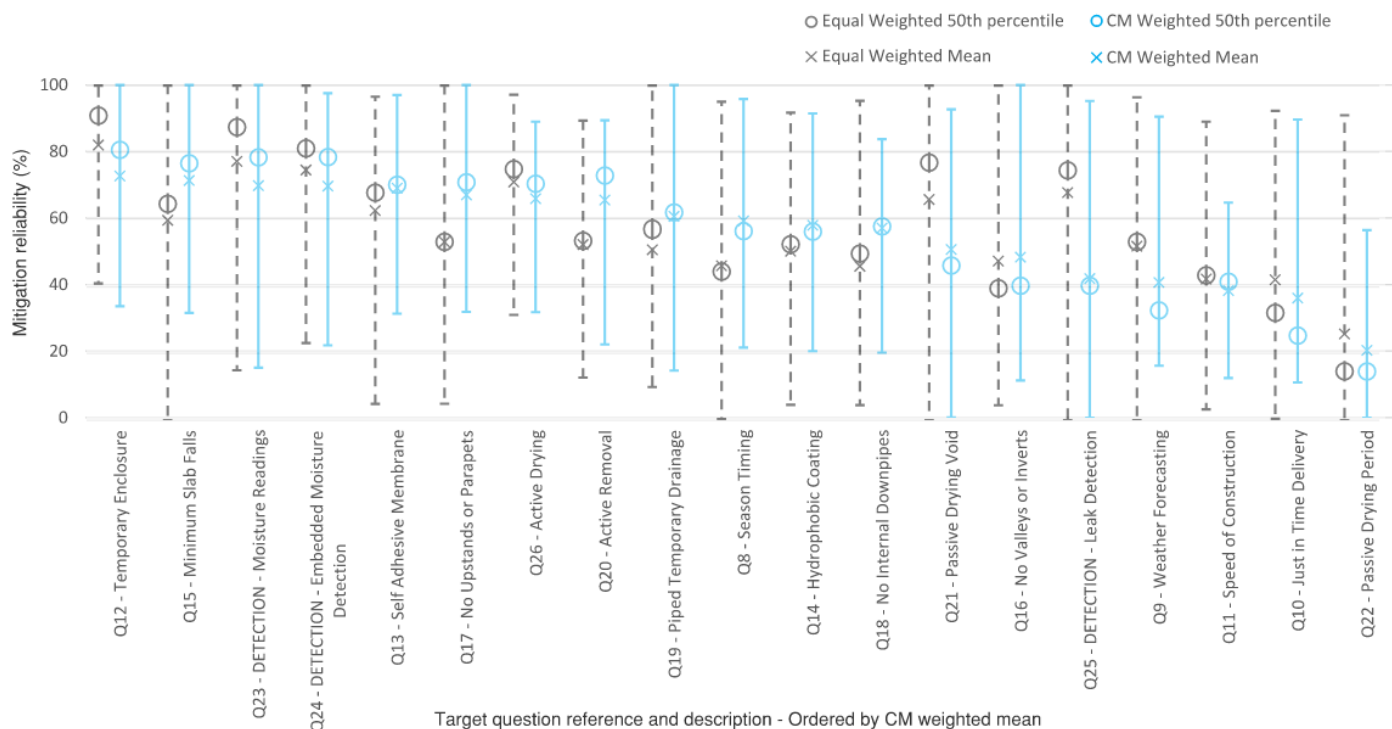


Figure 6. Aggregated 5th 50th 95th percentile and mean values for mitigation reliabilities based on Equal Weights (EW) and weighted according to Cooke's Classical Model (CM)

Mean effectiveness according to CM weighting is mostly in the 50% to 80% interval, but with many having a 95th percentile in the 90-100% interval and therefore assessed to plausibly be very effective. However, the range down to the 5th percentile often extends below 25% effectiveness and thus suggests that the mitigation could plausibly be effective only a quarter of the time. This is a large spread of effectiveness and could be due to uncertainty on the part of the expert or the variability of the projects which their experience draws upon. The largest percentage-point change is a reduction of 38% on the effectiveness of leak detection. There are a number with increases or decreases in the interval of 20 to 30%, which is a relatively significant modification and certainly one that could influence design decision making. With each of these larger

shifts it is informative to consider how closely the Seed questions correspond with the relevant Target question. For example, does knowledge of timber moisture transport correspond to experience or knowledge of leak detection systems?

Effect of CM Weighting on Effectiveness Distributions

Figure 7 illustrates the probability density functions, for each of the Target questions, based on both the CM and EW weightings. Most show similar shapes for the CM and EW plots, which indicates a level of robustness in the data and suggests that the overall trend is not excessively sensitive to the weighting scheme [91] and that it is not artificially introducing nor omitting a reported pattern in the experts' answers.

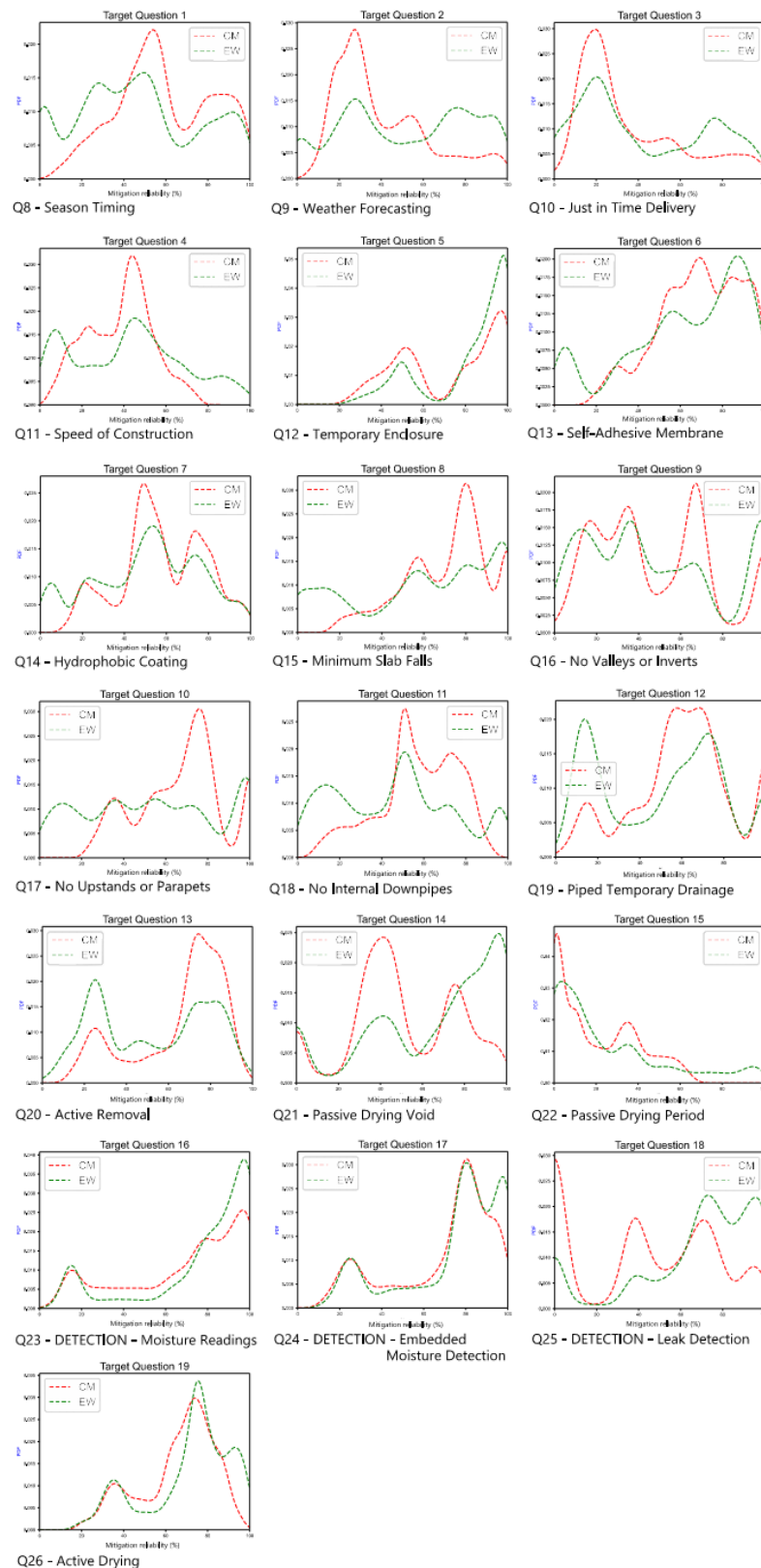


Figure 7. Probability Density Functions for each Target question, showing the Equal Weights (EW, in green) and Cooke's Classical Method (CM, in red) results. In each case the horizontal axis in each case is the mitigation effectiveness in the interval 0-100%.

Self-Reported Confidence

Table 5 illustrates the self-reported confidence of experts for each seed and Target question, scored between 0 (0% confidence) and 5 (100% confidence). This is as distinct from

the accuracy and informativeness score provided by the CM protocol.

The results in Table 5 show a spread of confidence between experts and between questions. Most experts showed a high

level of confidence on Seed questions 2 and 3 and less so on Seed questions 4-7 although rarely scoring below 3 out of 5. Experts 1 and 3 consistently reported low confidence through most Target questions, with mean confidences of only around 50 %. All other experts reported a mean of above 65 % confidence. General confidence was high, which helps reinforce that the experts were suitably qualified. The more specific areas of lower confidence may indicate a lack of direct experience with some mitigations.

Disruptiveness

In addition to mitigation reliabilities, a measure of the disruption that each may have on the design or construction was also elicited. Table 6 shows individual expert's assessed disruptiveness as well as the group mean. Figure 8 plots disruptiveness against CM-weighted effectiveness indicating regions where a positive combination of highly effective but low disruptiveness is achieved (green) as well as where mitigations are assessed as low effectiveness and high disruptiveness (red).

Table 6 Assessed disruptiveness of each mitigation

No.	Subject	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Mean
Q12	Temporary Enclosure	100	80	80	80	100	80	100	80	100	40	84
Q15	Minimum Slab Falls	80	100	60	60	100	100	100	60	80	60	80
Q26	Active Drying	100	40	60	80	100	80	100	80	80	40	76
Q8	Season Timing	80	100	100	20	0	100	80	60	60	80	68
Q14	Hydrophobic Coating	60	60	40	80	80	60	60	80	60	80	66
Q25	DETECTION - Leak Detection	80	60	60	60	40	40	100	80	60	80	66
Q9	Weather Forecasting	80	100	80	20	40	60	60	60	100	40	64
Q16	No Valleys or Inverts	40	80	40	80	100	60	100	60	40	40	64
Q22	Passive Drying Period	0	0	80	20	100	80	100	60	100	20	56
Q24	DETECTION - Embedded Moisture Detection	80	40	40	40	40	40	100	80	40	60	56
Q18	No Internal Downpipes	80	80	80	40	20	40	60	60	40	20	52
Q21	Passive Drying Void	80	20	40	60	0	60	0	80	100	80	52
Q10	Just in Time Delivery	80	20	80	20	0	0	80	60	100	60	50
Q11	Speed of Construction	80	40	40	20	20	20	60	80	80	60	50
Q17	No Upstands or Parapets	80	60	60	60	20	60	0	60	60	20	48
Q23	DETECTION - Moisture Readings	60	40	60	40	0	0	20	80	20	80	40
Q13	Self-Adhesive Membrane	60	0	20	40	20	20	60	60	60	20	36
Q19	Piped Temporary Drainage	60	0	60	20	20	0	80	0	40	40	32
Q20	Active Removal	60	0	40	20	0	0	40	40	20	60	28

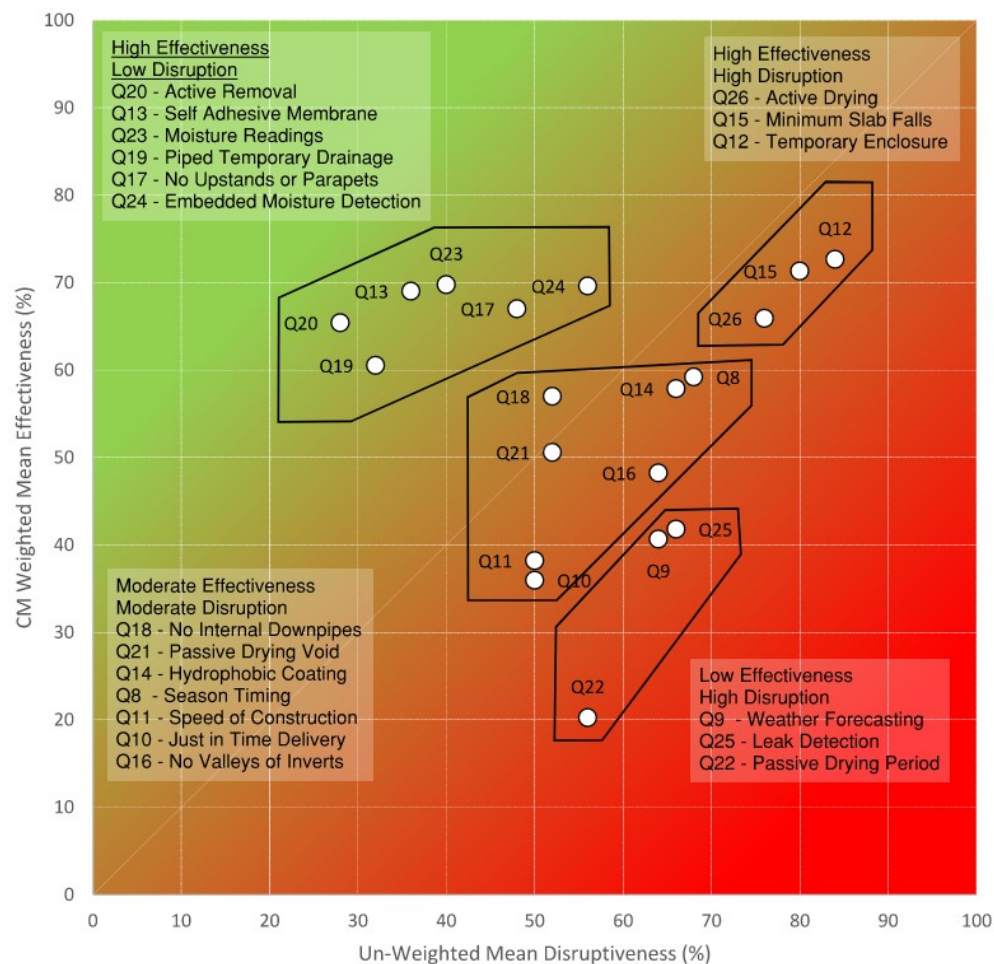


Figure 8. Plot of Effectiveness against Disruptiveness for each mitigation. Mitigations are grouped according to outline performance. Mitigations are listed in order according to their proximity to the ideal of max effectiveness & min disruptiveness (top left corner).

Optimum Set of Mitigations

Table 7 illustrates the frequency by which different mitigations were selected by participants to be part of their 'optimum set of mitigations' in answer to question 27. It illustrates patterns in which mitigations are chosen to be implemented as part of a

combined approach. The trend only partly reflects the assessment of the most effective mitigations when judged individually. In reality, the individual mitigations interact with each other, although the main set of questions could not capture this without the permutations becoming unmanageable.

Table 7 Frequency of each mitigation's inclusion in question 27 'optimum combination'

Mitigation	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Frequency (%)
Q8 Season Timing	Y				Y					Y	30
Q9 Weather Forecasting			Y							Y	20
Q10 Just in Time Delivery											0
Q11 Speed of Construction	Y									Y	20
Q12 Temporary Enclosure			Y					Y			20
Q13 Self Adhesive Membrane	Y	Y		Y	Y	Y			Y	Y	70

Table 7 Frequency of each mitigation's inclusion in question 27 'optimum combination' (continued)

Mitigation	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Frequency (%)
Q14 Hydrophobic Coating				Y							10
Q15 Minimum Slab Falls	Y	Y		Y	Y	Y	Y	Y	Y		80
Q16 No Valleys or Inverts	Y			Y	Y		Y		Y		50
Q17 No Upstands or Parapets				Y	Y		Y		Y		40
Q18 No Internal Downpipes						Y					10
Q19 Piped Temporary Drainage	Y					Y		Y	Y		40
Q20 Active Removal								Y	Y	Y	30
Q21 Passive Drying Void											0
Q22 Passive Drying Period											0
Q23 DETECTION - Moisture Readings		Y	Y		Y			Y	Y		50
Q24 DETECTION - Embedded Moisture Detection								Y		Y	20
Q25 DETECTION - Leak Detection						Y					10
Q26 Active Drying											0
50th %ile (Most likely) effectiveness of combination	85	80	100	60	75	100	100	100	100	100	
Disruption cost/time (%)	80	40	60	60	20	20	0	60	60	40	

Exp1–Exp10 identify Experts 1–10.

This question was designed to check on experts' opinion in a more direct way, where review of the full set may have meant that clear 'favourites' were not as evident. It also supplements the disruptiveness assessment by asking for a balance of effectiveness against cost, logistics and design constraint.

Mitigations Q13 Self-adhesive Membranes and Q15 Minimum Slab Falls were selected most frequently at 70 % and 80 % respectively. Q16 No Valleys or Inverts was selected 50 % of the time. All four of Q13, 15, 16 and 17 are complimentary in geometrically facilitating passive drainage; a combination of two or more of these was selected in 7 out of 10 combinations. Q23 Moisture Readings on site also scored highly at 50 %.

Of note are mitigations where the individual effectiveness was judged highly but not frequently selected in the optimum combination. Examples include Q10 Just in Time Delivery, Q12 Temporary Enclosure, Q14 Hydrophobic Coating, Q21 Passive Drying Void, Q22 Passive Drying Period and Q26 Active Drying. A number of these were assessed as having high disruptiveness, which could explain their omission from optimum combinations. Table 8 illustrates a correlation between low frequency of adoption in optimum combination with high disruptiveness

Table 8 Mitigations with low frequency of adoption in optimum combination and high disruptiveness

Description	Question Ref	Effectiveness (50th %-ile "Most likely")	Disruptiveness	Frequency of adoption in optimum combination
Temporary Enclosure	12	73 %	84 %	20 %
Just in Time Delivery	10	36 %	50 %	0 %
Active Drying	26	66 %	76 %	0 %

It is notable that Q16 No valleys or inverts rates relatively low overall (Table 4) despite being commonly chosen as part of the optimum combination (Table 7), perhaps because it is considered not to be very effective when used in isolation. It is closely analogous to Q15 Minimum slab falls and Q17 No upstands or parapets which both rate within the top six when rated individually. Three out of the top 4, as scored in the optimum combination, are found in the top 5 rankings in this table also, namely, Q13 Self-adhesive membranes, Q15 Minimum slab falls and Q23 Taking moisture readings on site.

The popularity of groups of complementary low-disruptiveness mitigations indicates that an approach of 'defence-in-depth' [95], as found in fire safety engineering and other risk analysis sectors, may be favoured. A key element of this was also adoption of a method of measuring the timber Moisture Content, although this was not paired with passive or active drying as part of the optimum combination. This indicates that it is adopted as a monitoring and warning system, rather than as a substitute for pro-active mitigations.

Strengths and Limitations of the Study

The study employs a rigorous methodology, Expert Elicitation via Cooke's Classical Method, which greatly improves the accuracy and transparency of the questionnaire process and richness of the data. It directly addresses heuristics and bias in the questioning technique and weights the data according to a well-tested methodology. This is in contrast with the standard practice of basic questionnaires used within the construction industry, yet in line with other disciplines where safety and reliability risk analysis of complex systems is regularly undertaken. Although the process is more complex and the method of application more stringent, the data is more readily interrogatable and the methodology reproducible.

The sample size was limited to 10 successfully returned data sets, from experts based mainly in the UK and not further than western and central Europe. Therefore, results are inherently based on the experiences of this group in terms of the scale and architectural form of projects in this geographical region and on the prevailing atmospheric and meteorological conditions. Expert Elicitation is used as a short-cut to complex data, but it is possible that even the most qualified experts do not have the right combination of expertise and that their answers are misleading or biased. Ideally the sample size would be increased, though not at the expense of relaxing the specificity of expertise required. To keep the questions as simple and unambiguous as possible they were framed as the

individual effectiveness of each mitigation in isolation. Only question 27 aimed to elicit judgement on interactions between, and combinations of, mitigations. The real-world application of mitigations is almost always as a set, with the decision to employ one influenced by the presence of another.

Practical Outcomes

The key recommendations for design and execution teams include the following.

Design decisions are important; Measures such as ensuring minimum fall gradients to roof slabs and avoidance of parapets and upstands are highly effective. They are inherent and passive fail-to-safe measures which are less reliant on immediate actions by personnel.

Don't rely on avoiding the rain; Measures such as seasonal timing, weather forecasting, just in time delivery or speed of construction are all judged to be only moderate or low effectiveness. Most project execution programmes will not be adaptable nor short enough to allow this. Equally, don't rely on passive drying through open voids or hold-periods in the programme. The building design and plan for the execution process should therefore assume that rain will occur and will fall onto the timber, except in the instance that full temporary enclosure is provided. This enclosure is highly effective but also introduces cost and logistical issues.

Actively remove water and monitor moisture content; Using self-adhesive breather membranes, active water removal and use of piped temporary drainage are all highly effective with low disruption, as well as working well together. This should be coupled with a well planned and executed programme of monitoring the Moisture Content of the timber, via hand-held moisture meters or live sensors.

There are certain barriers to implementing the most effective measures. Adapting aspects of the building design to improve execution-stage moisture control may initially be considered disproportionately disruptive architecturally. However, it is likely that the same measures will also facilitate better moisture performance and resilience throughout the building's life. In situations where positive design actions are not taken, more stringent and disruptive measures will be required during execution to balance the risks, an example could be full temporary enclosure of the building until completion of the permanent waterproofing.

Conclusions

This study addresses the lack of rigorous quantitative guidance on managing moisture risks in timber structures

during construction, an issue with broad implications for safety, cost, disruption, longevity, and sustainability. The study aimed to develop and apply a structured, quantitative method that enables comparative, decision-oriented evaluation of construction-stage moisture mitigation strategies for CLT roofs. A literature review identified 19 potential mitigation measures for controlling CLT roof moisture, which were evaluated by subject-matter experts using a detailed questionnaire. Responses were analysed via the well-established Cooke's Classical Method for Expert Elicitation, a novel application in structural timber design that enhances data rigor, richness, and transparency. The findings, grounded in UK and north-west European practice, are most applicable to similar climates and construction methods but potentially applicable world-wide.

The results enable quantitative, comparative evaluation of individual and combined mitigations, supporting systematic risk assessment and construction planning. Effectiveness varied widely; several commonly recommended measures, such as weather forecasting, rapid construction, just-in-time delivery, and passive drying, were rated in this study as below 50% effectiveness. In contrast, temporary enclosure, sloped slabs, moisture detection, and self-adhesive breathable membranes were rated highest in effectiveness. Disruptiveness was also assessed, with design-related mitigations evaluated for design impact and construction-related ones for cost, time, and logistics. Temporary enclosure emerged as the most effective but also most disruptive mitigation. High-effectiveness, low-disruption options included active water removal, self-adhesive breathable membranes, moisture readings, and piped drainage. These mitigations can therefore be considered as a baseline for good practice.

These findings support the use of holistic decision-making for construction planning and risk management for timber construction, addressing an urgent need identified by industry, insurers, and legal bodies. Advancing moisture resilience in timber buildings enhances safety, economic performance, and environmental sustainability, contributing to broader climate resilience. This study marks a novel and significant development in this advancement.

Declarations

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Ethics

This study was reviewed and approved by the University of Bath Research Ethics Committee under reference number 1139-1211.

Author contributions

Matt Caldwell: Conceptualisation, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation,

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Competing Interests

None

Data Availability

An appendix of additional information and data is available at <https://researchportal.bath.ac.uk/en/datasets/>

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