Monitoring building climate and timber moisture gradient in large-span timber structures

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Abstract

The evaluation of damages in large-span timber structures indicates that the predominantly observed damage pattern is pronounced cracking in the lamellas of glued-laminated timber elements. A significant proportion of these cracks is attributed to the seasonal and use-related variations of the internal climate within large buildings and the associated inhomogeneous shrinkage and swelling processes in the timber elements. To evaluate the significance of these phenomena, long-term measurements of climatic conditions and timber moisture content were taken within large-span timber structures in buildings of typical construction type and use. These measurements were then used to draw conclusions on the magnitude and time necessary for adjustment of the moisture distribution to changing climatic conditions. A comparison of the results for different types of building use confirms the expected large range of possible climatic conditions in buildings with timber structures. Ranges of equilibrium moisture content representative of the type and use of building were obtained. These ranges can be used in design to condition the timber to the right value of moisture content, in this way reducing the crack formation due to moisture variations. The results of this research also support the development of suitable monitoring systems which could be applied in form of early warning systems on the basis of climate measurements. Based on the results obtained, proposals for the practical implementation of the results are given.

Keywords: indoor climate; temperature; relative humidity; monitoring; wood; glued laminated timber; moisture; timber moisture content; moisture gradients; shrinkage; swelling; tension perpendicular to the grain stresses; shrinkage cracks

1 Background

The evaluation of damages in large-span timber structures ([1] - [3]) shows that a prevalent type of damage is pronounced cracking in the glue lines and lamellas of glulam timber elements. Figures 1 and 2 show the types and causes of damage deduced from the dataset of 245 assessments of large-span timber structures [4]. In almost half of the cases, damage can be attributed to low or high moisture content (MC) or significant variations of this quantity over time. The resulting moisture gradient and the associated shrinkage or swelling will lead to internal stresses in the cross-section. If these stresses locally exceed the very low tension perpendicular to grain strength of wood, the result will be a stress relief in form of cracks.

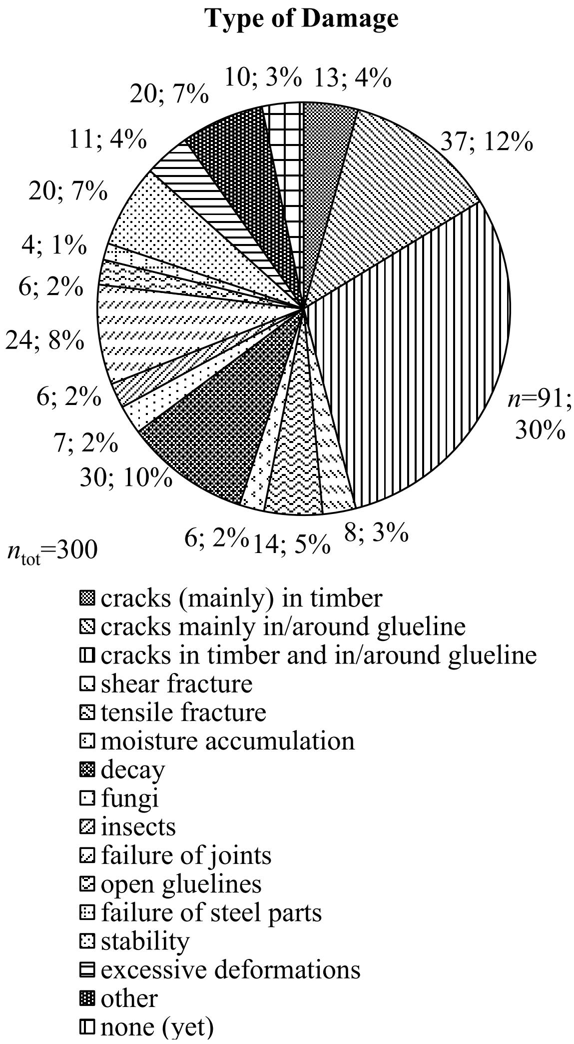

Figure 1: Type of damage from an evaluation of 245 assessments of large-span timber structures [4]

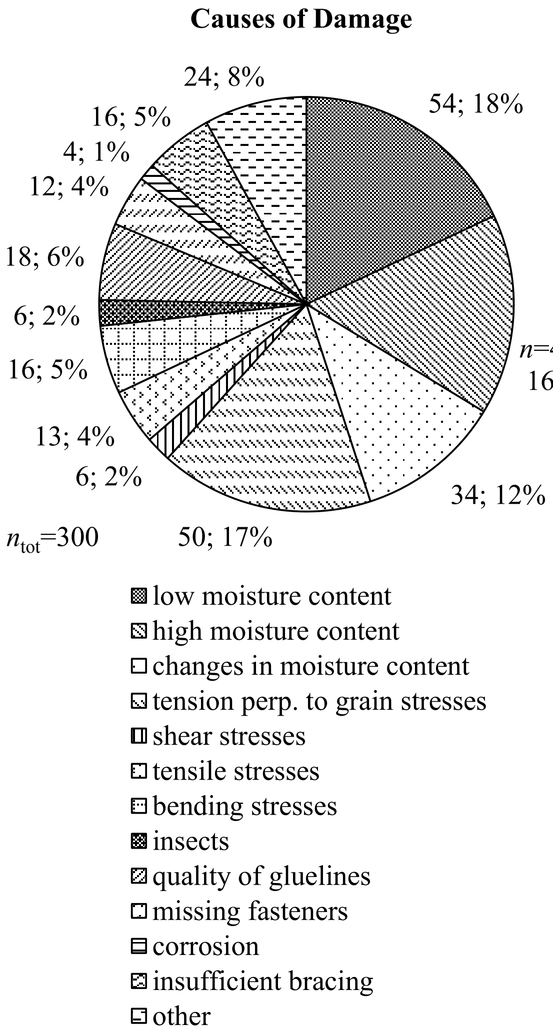

Figure 2: Causes of damage from an evaluation of 245 assessments of large-span timber structures [4]

Low or high moisture contents or severe changes of this quantity over time could sometimes be attributed to local conditions (e.g. roof leakage) but in the majority of cases, they could be explained by the climatic conditions, depending on the construction type and use of the building, and seasonal variations of the building climate. Figure 3 contains timber MC and climatic conditions for all structures for which such information was obtained during the assessment of the building. If multiple measurements of MC were taken, the given value represents the mean value of these measurements. If measurements were taken at different depths, the mean value of the near-surface measurements (mostly at 15 mm depth) is given. All evaluated measurements represent snap-shots of the situation on the day of assessment. They do neither give indication on the timber MC at the opening of the building (beginning of operation) nor on seasonal variations of the timber moisture content. The measured timber moisture contents for buildings in Service Class 1 (SC 1) [8] (see Chapter 2.1 for description) show pronounced variations around a mean value of u = 10.7 %. The corresponding measurements of temperature and relative humidity feature a pronounced variation as well. Structural elements in Service Class 2 (SC 2) show smaller variations ($u_{mean} = 14.9$ %). Structural elements in Service Class 3 (SC 3) unsurprisingly feature large variations of timber MC ($u_{mean} = 22.4$ %) and building climate. The mean values of timber MC in dependence of the Service Class correspond well with the values listed in [1].

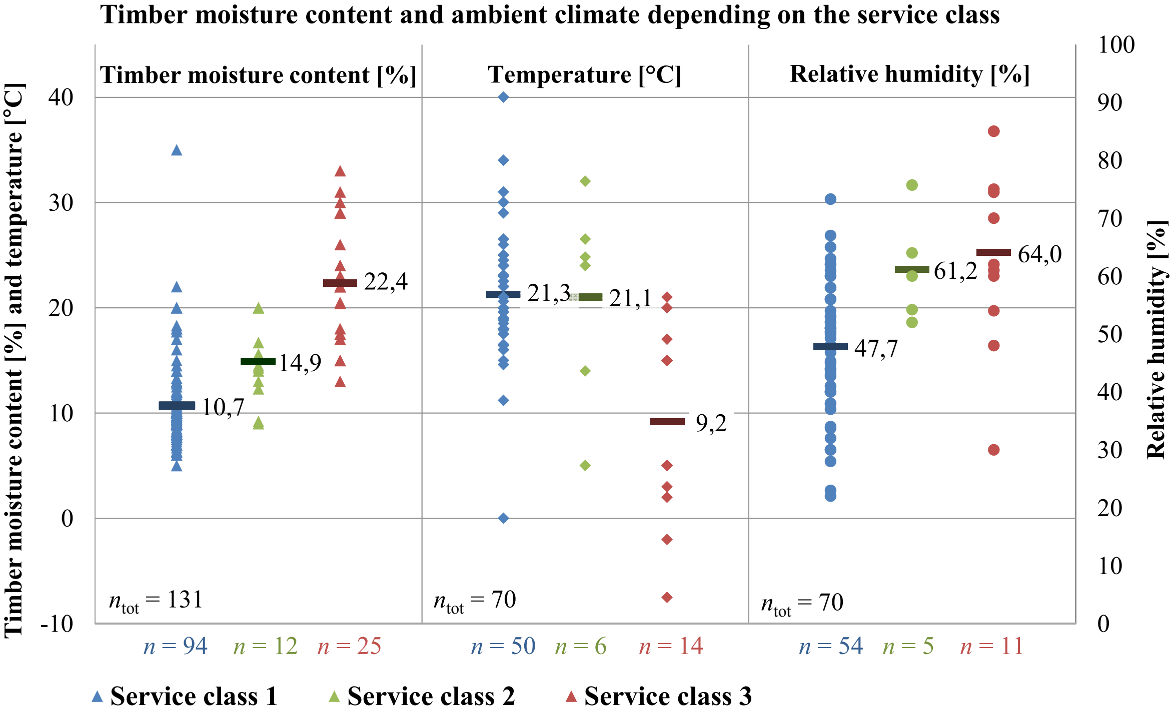

Figure 3: Timber moisture content and ambient climate depending on the Service Class, from the evaluation of 245 assessments of large-span timber structures [4]

The large variations in timber moisture content, temperature and relative humidity for buildings in SC 1 can partly be traced back to the diversity of types of use of these buildings. A differentiation of timber MC depending on the building use is given in Figure 4. This comparison only contains types of use for which at least three buildings could be evaluated. The timber moisture contents in closed and heated buildings are often noticeably low. If structural elements, featuring high timber MCs due to deficient roof structures were excluded, the mean values of timber MC in closed and heated buildings would all fall below $u = 10$ %. 47 % of the evaluated structures featured timber elements with MCs below 10 %. The mean values determined for riding rinks ($u_{mean} = 18.2$ %) and ice-skating rinks ($u_{mean} = 21.6$ %) support their categorization in SC 2 and SC 3, respectively [9].

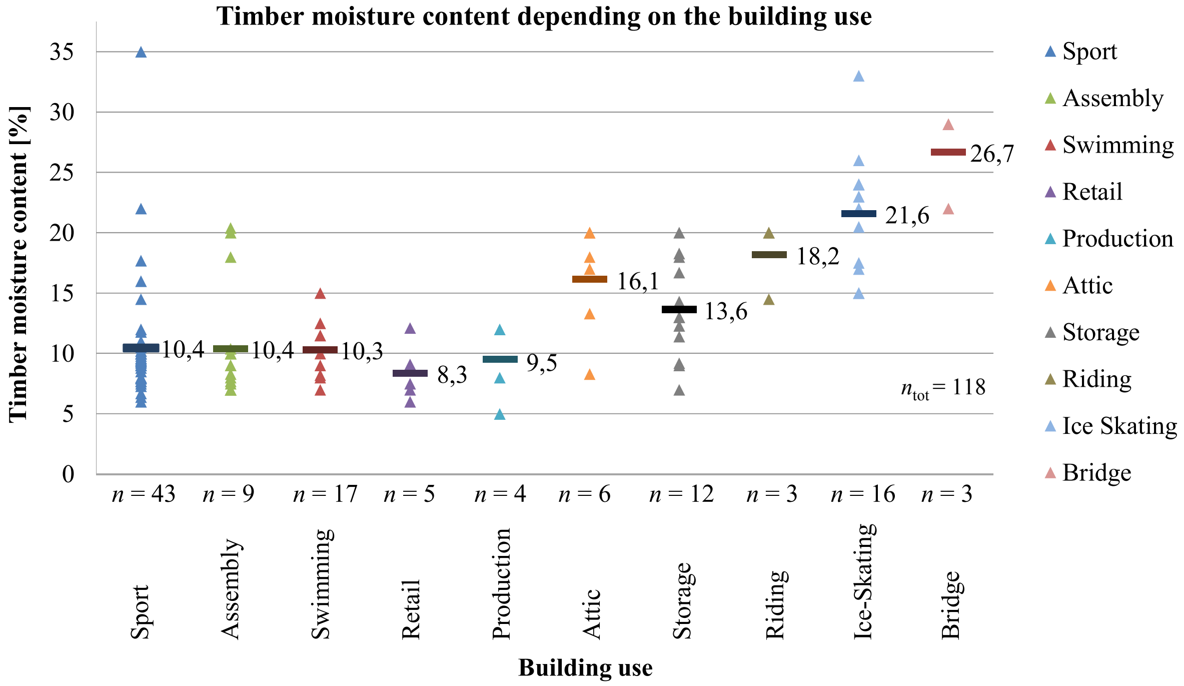

Figure 4: Timber moisture content depending on the type of building use, from an evaluation of 245 assessments of large-span timber structures [4]

Information on the sequence and magnitude of seasonal variations can only be obtained through long-term measurements of climate data (temperature, relative humidity) and timber moisture content. In the case of (large-span) timber structures, the measurement of moisture at different depths of the cross-section is of particular interest to draw conclusions on the magnitude and rate of adjustment of the moisture distribution to changing climatic conditions. Although past research projects covered the long-term measurement of timber MC and/or temperature and relative humidity [10] – [17], none of them was carried out under the objective to enable a comparison between timber structures in large buildings of different types of use. The same is valid for the long-term measurement of moisture content at different depths on structural timber elements in-situ (phase “operation” in Figure 1). Both objectives have been covered within the research project presented herein. Data received through such measurements can additionally be used to validate computational models, see e.g. [18], [19].

2 Description of the research project

2.1 Introduction

The reaction of wood to moisture forms an integral part of any task in connection with this natural and renewable building material. This also applies to the planning, execution and maintenance of buildings built with wood or wood-based products. From logging the tree to its anticipated use, e.g. as a structural element, wood will go through various phases of processing and shape during which it is subjected to varying environmental conditions. Their influence on the wood moisture content (MC) can be illustrated by the “moisture chain” (development of wood MC), sketched in Figure 1. The values given therein are indicative, more information can be found in [5] (growth), [6] (production) and [7] (operation).

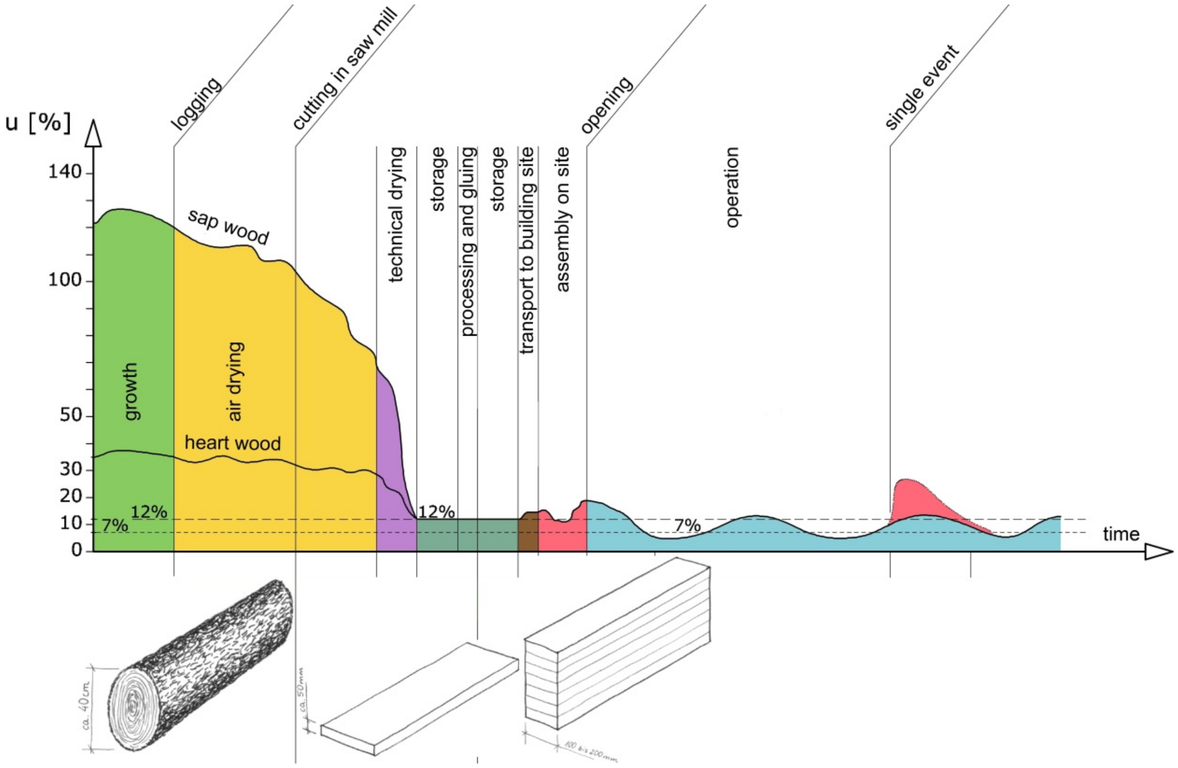

Figure 5: Sketch of a possible „moisture chain“, i.e. development of wood moisture content from the tree to glued-laminated timber elements in the building (the values given in this schematic are indicative)

Changes in wood MC lead to changes of virtually all physical and mechanical properties (e.g. strength and stiffness properties) of wood. In EN 1995-1-1 [8], this is accounted for by classifying the timber elements into one of three possible Service Classes according to the climatic conditions during the design service life. According to [8], "Service Class (SC) 1 is characterised by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65 % for a few weeks per year. In Service Class 1 the average moisture content in most softwoods will not exceed 12 %. Service Class 2 is characterised by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85 % for a few weeks per year. In Service Class 2 the average moisture content in most softwoods will not exceed 20 %. Service Class 3 is characterised by climatic conditions leading to higher moisture contents than in Service Class 2" [8].

An additional effect of wood MC variations is the associated shrinkage or swelling of the material. Since the outermost fibres of the wood cross-sections adapt faster to the climatic conditions, the resulting moisture gradient and the associated shrinkage or swelling will lead to internal stresses in the cross-section. If these stresses locally exceed the very low tension perpendicular to grain strength of wood, the result will be a stress relief in the form of cracks which can reduce the load-carrying capacity of structural timber elements in e.g. shear or tension perpendicular to the grain.

2.2 Chosen types of use and types of buildings

Within this research project, long-term measurements of timber moisture content (MC), temperature and relative humidity in a total of 21 buildings (halls with large-span timber roof structures) with seven different types of use (destinations) were carried out (see Table 1). All buildings are located within 120 km around the City of Munich. While all buildings used as “indoor swimming pool”, “gymnasium (sports facility)” and “production and sales” were heated and featured closed building envelopes, all buildings used as “riding rink”, “agriculture” and warehouse” were unheated and featured partly open building envelopes. In the case of ice-skating rinks, only closed buildings (climatized and non-climatized) were chosen since results for open or partly open ice-rinks are already available [14], [17]. When selecting the buildings, attention was given to cover the typical types of structural systems for large-span timber roofs. Only structures featuring softwood glulam with at least 140 mm width were investigated. In each building, the data was collected at two different locations of measurement in order to capture possible varying climatic conditions, e.g. due to solar radiation or due to the influence of heating systems. All necessary information for each building (e.g. building envelope, environmental conditions, climatization, structural system, element dimensions, surface treatment and locations of instrumentation) was prepared in separate building information sheets, including plan view, sectional view and photo documentation.

Table 1: Chosen types of use and number of buildings in each use

	Use	Number		Use	Number
A	Indoor swimming pool	3	E	Production and Sales	2
B	Ice rink	4	F	Agriculture (livestock)	3
C	Riding rink	3	G	Warehouse	3
D	Gymnasium (sports facility)	3		Total	21

2.3 Method of measurement and verification of measured data

The electrical resistance measurement method was chosen for the measurements of the timber moisture content. This method is reliable and widely applied, and allows for the non-destructive measurement of moisture gradients across the cross-section at one specific location (see e.g. [20]). For MC $6\ \% \leq u \leq 30\ \%$, commercially available moisture meters feature variance tolerances of ± 1.0 % or lower. For an in-depth explanation of the electrical resistance measurement method and an overview and comparison of alternative methods for a continuous measurement of timber MC, the reader can refer to [21].

The measurement system had to be able to cover MCs in the low range which implies the measurement of high electrical resistances (e.g. 6 % MC in Norway spruce $\approx 10^{11}\ \Omega$). To validate the chosen measurement system, this system, was installed on test specimens of glued-laminated timber from Norway spruce (Picea abies) and exposed to very dry, very humid and varying climate in the climate chambers of the materials testing laboratory at the Technische Universität München. The MCs were continuously measured with the adopted measurement equipment and compared to the results obtained using a calibrated reference moisture meter (GANN Hydromette RTU 600). There was neither a significant difference in the results of the two measurement systems, nor when using different types of electrodes, demonstrating the accuracy of the chosen electrical resistance measurement method. For further verification, two independent series of 4 x 6 test specimens from Norway spruce (Picea abies) (L x B x H = 85 x 60 x 30 mm) were produced and stored under four different controlled climatic conditions (20° C / 45 % RH; 20° C / 65 % RH; 20° C / 85% RH and 20° C / 100 % RH) which were realized by saturated saline solutions.

After the specimens had reached constant weight, their MC was measured with the chosen moisture meter (Scanntronik Gigamodule) and two reference meters (GANN Hydromette RTU 600 and Greisinger GMH 3850). By subsequent kiln-drying, the actual MC was determined. Within the range of timber MC measured during this research project ($u_{\max}$ = 19 %), good agreement was obtained for MCs between 12 % and 18 %, see Figure 6. Maximum absolute deviations in MC of 1.3 % were measured for the dry specimen, whereby the chosen moisture meter as well as the reference moisture meters tend to underestimate the actual MC at low ranges.

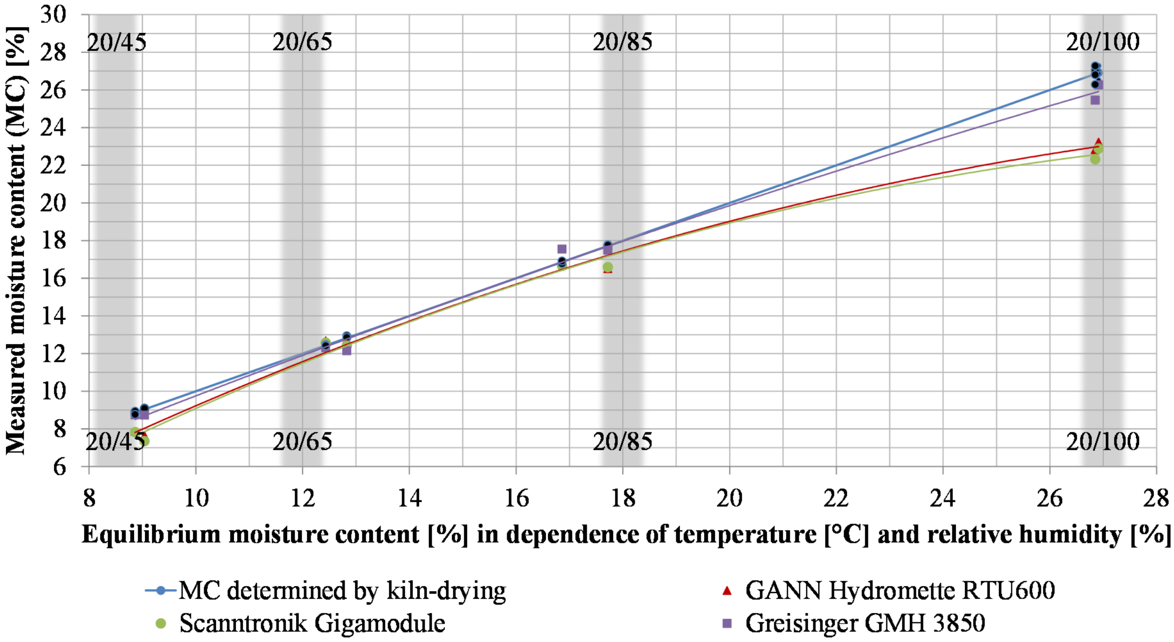

Figure 6: Results of the laboratory tests to verify the results obtained by the chosen method for long-term measurements (resistance method – Scanntronic Gigamodule)

2.4 Installation of measuring equipment, readout and processing of data

At each location of measurement, four pairs of teflon-isolated electrodes (GANN) with varying length were installed to enable the measurement of moisture content (MC) at clearly defined depths of the cross-section. To prevent erroneous measurements in the case of surface condensation, the heads of the electrodes were also partly teflon-isolated, see Figure 7. For exact positioning of the electrodes in one lamella, ideally perpendicular to the grain, a drill guide featuring two diameters for each depth was used in connection with a drilling template. The ram-in electrodes were connected to the moisture meter by custom-built, shielded coaxial cables. The moisture meter developed in cooperation with the project partner enables the determination of MC at up to eight channels. The measurements were taken every hour. Each channel was actuated separately to prevent mutual interference. Subsequently, the measurements were transmitted to a data logger. The climate data was recorded via a second data logger in combination with a sensor unit for relative humidity and air temperature. In addition, the surface temperatures at the two points of measurement were recorded to allow for the temperature compensation of the MC, see Figure 7.

After installation of the measuring equipment at two locations of the roof structure in each of the 21 buildings, the data stored in the data loggers was read out three times over the measurement period. A manual readout was preferred to remote transmission since it could be combined with a reference measurement taken with another moisture meter, a function control as well as a control of the point of measurement itself. During these controls and the subsequent data analysis, a few noteable issues were observed. In the indoor swimming pools, the chlorous climate resulted in accelerated corrosion and temporary malfunction of the climate sensors. This could be eliminated by exchanging them for digital, dew resistant sensors, see also [21].

In ice-skating rink "B2", a power line, although attached to the opposite side of the beam, led to an occasional shifting of the measurements for the duration of a few hours. Condensation around the point of measurement in buildings "C3" and "G1" caused a short-circuit between the non-isolated plug-connections of the electrodes, resulting in a temporary deviation of the measurements for the duration of a maximum of three days. In all cases, the corresponding data was ignored and linear interpolation was applied between the last and first set of correct measurements.

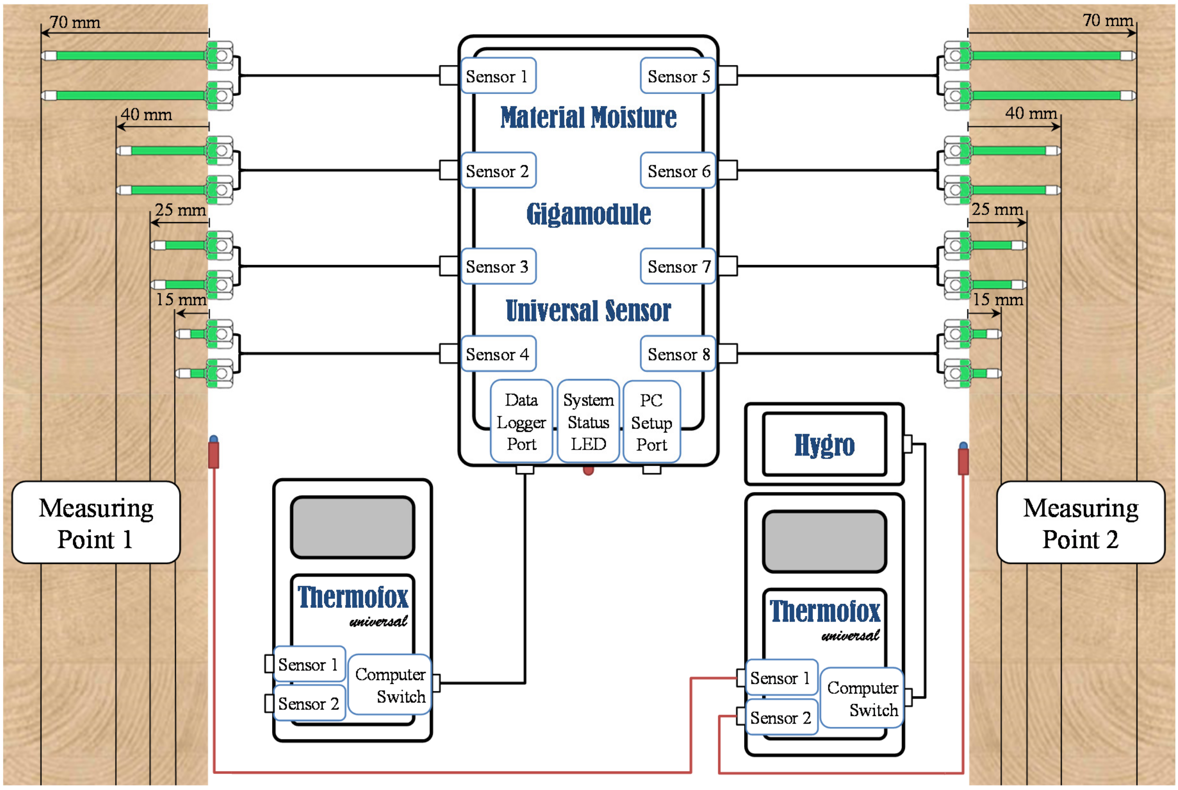

Figure 7: Schematic of the measuring equipment

To analyze the data, an Excel program was developed which made it possible to read the large amounts of data at the end of the planned duration of measurement and to further process and graphically illustrate the data in different charts. When converting the raw data, i.e. measurements of electrical resistance into timber MCs, a compensation of the effect of temperature was considered. To this aim, the actual material temperatures at the different depths were calculated from the measured surface temperatures, using the explicit Euler method [22] in combination with values for thermal conductivity given in e.g. [23] (see also [24], [25]). A modification of the measured timber MCs with respect to the differences to the values determined by kiln-drying observed during the laboratory tests (max. $\Delta u = 1.3$ %), was not undertaken since all measured timber MCs were in the range of the accepted variance tolerance ($u \leq 20$ %, see Figure 6).

For comparative reasons, the measurements of relative humidity and temperature were used to determine the equilibrium MC prevailing in the cross-section near the surface as a moving average over ten days. This was done by applying the theoretical model of Hailwood & Horrobin [26] in combination with the coefficients determined by [27] (see also [24]). The influence of surface treatments which were present on the timber roof structure of ice-skating rinks “B1” and “B4” was not considered since the type of treatment could not be determined unambiguously.

3 Results

3.1 Processing and representation of results

Within the evaluation period from 1 October 2010 to 30 September 2011, a total of over 2.2 million records were collected and analyzed by means of a specially developed Excel program. The data read from the data loggers was prepared as curves (time series) of relative and absolute humidity and temperature at the location of measurement over time, see Figure 8. The same type of representation was chosen for the measurements of timber moisture content (MC) at the four depths of the cross-section, see Figure 9. This figure also contains the calculated equilibrium MC.

In addition, graphical representations over the cross-section were derived for the timber MC. This type of representation allows to create envelope curves of minimum and maximum timber MCs, see Figure 10, as well as envelope curves of minimum and maximum timber moisture gradient $\mathrm{grad}(u) = du / dx$, see Figure 11. The graphical representations confirm the damped and delayed trends of timber MC with increasing depth.

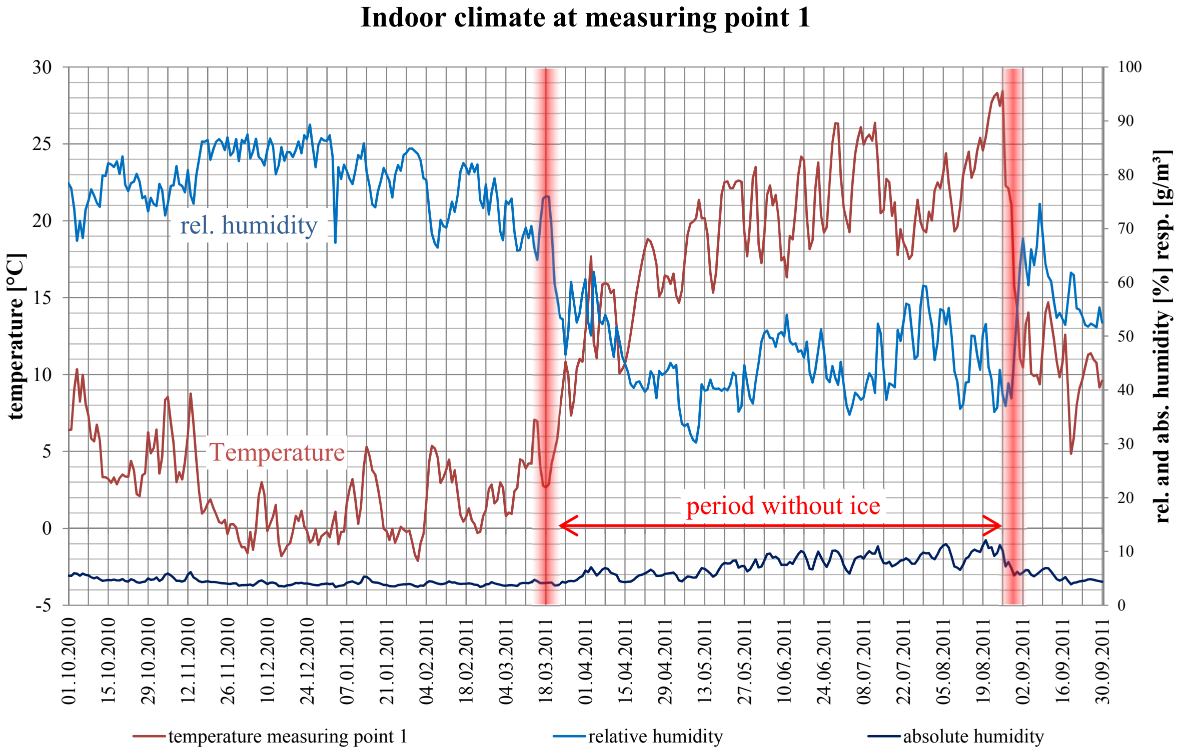

Figure 8: Variation of the relative and absolute humidity and the reference temperature over the measurement period, for the ice rink B2

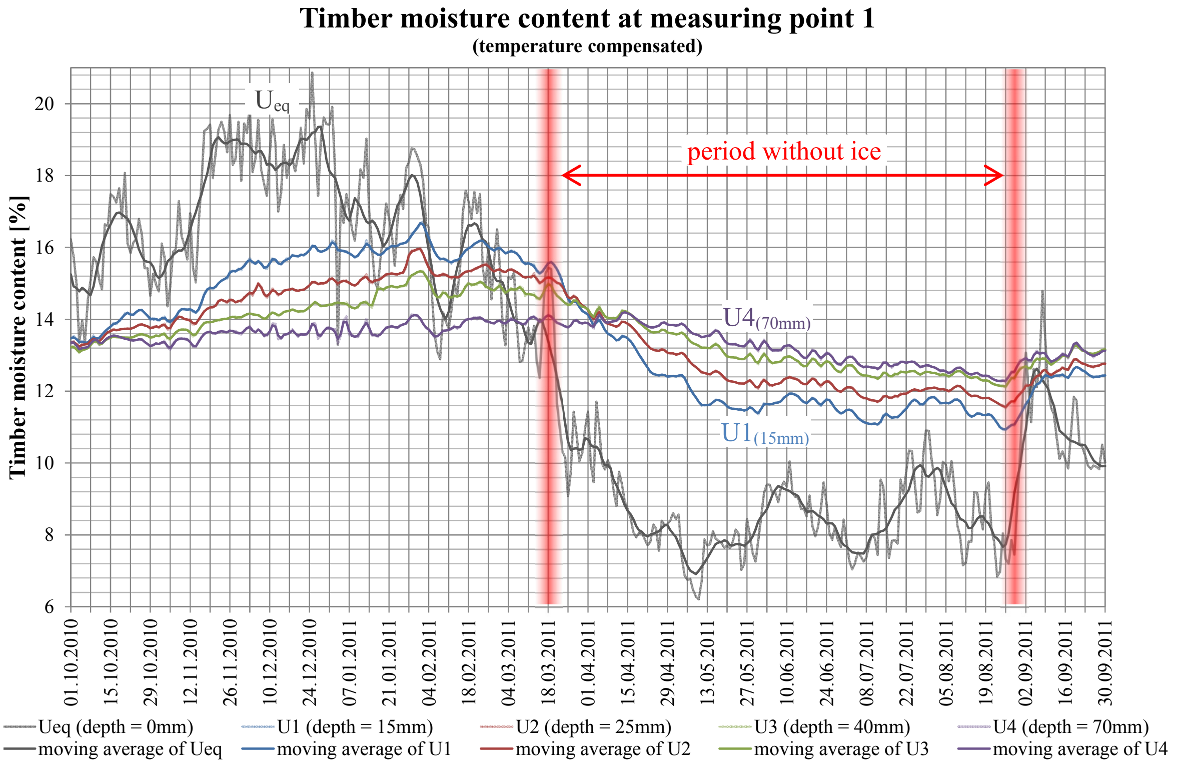

Figure 9: Variation of timber moisture content at different depths of the cross-section over the measurement period, for the ice rink B2

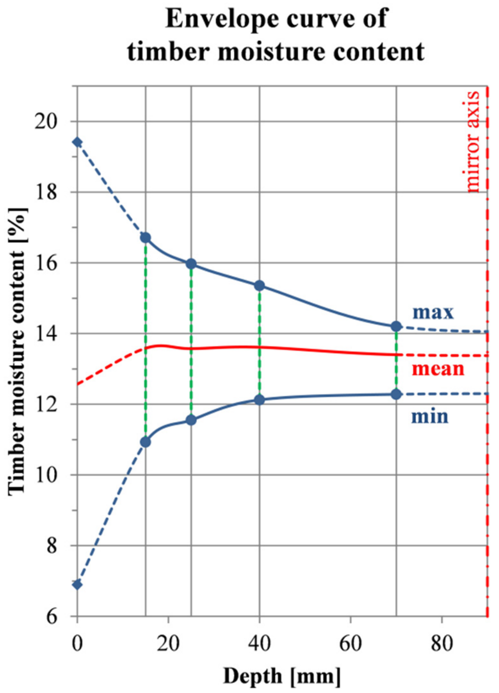

Figure 10: Envelope curve of the timber moisture content at different depths of the cross-section, for the ice rink B2

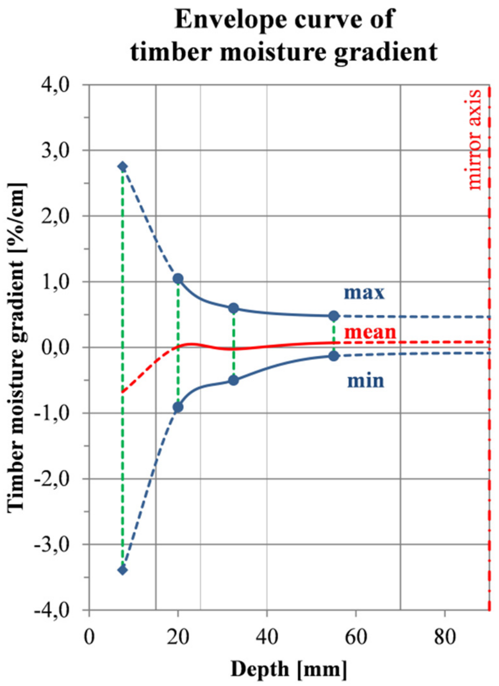

Figure 11: Envelope curve of the timber moisture gradient at different depths of the cross-section, for the ice rink B2

3.2. Results and remarks with regard to the different types of use

3.2.1 General results

In the following, a summary of the results of all buildings is provided in tabular format, see Table 2. This type of representation was chosen since a graphical representation does not allow for a quick and concise overview of the results of all buildings. For the graphical representations, the interested reader is kindly referred to the final report [7] of the research project. The table contains the mean values of relative humidity and temperature (both based on daily mean values) as well as the mean value of timber moisture content (MC), averaged across all depths. In addition, the maximum amplitude, i.e. the difference between maximum and minimum value measured during the evaluation period, is given for all parameters. For the timber MC, the maximum gradient between two depths as well as the maximum difference in timber MC between the outermost (15 mm) and the innermost point of measurement (70 mm) is given. Figure 12 contains a graphical explanation of all data given in Table 2.

A comparison of the results of the individual types of building use confirms the expected large range of possible climatic conditions in buildings with timber structures. Evaluated for all types of use, the average timber MCs ranged between 4.4 % and 17.1 %, whereby the lower threshold should be regarded as a special case. As expected, the moisture gradients are lower in insulated and heated buildings than in non-insulated, partly open buildings with stronger influence of the naturally varying outdoor climate. If not explicitly stated, the numerical values of timber MC (*u*), temperature (*T*) and relative humidity (*RH*) given in the following, represent mean values.

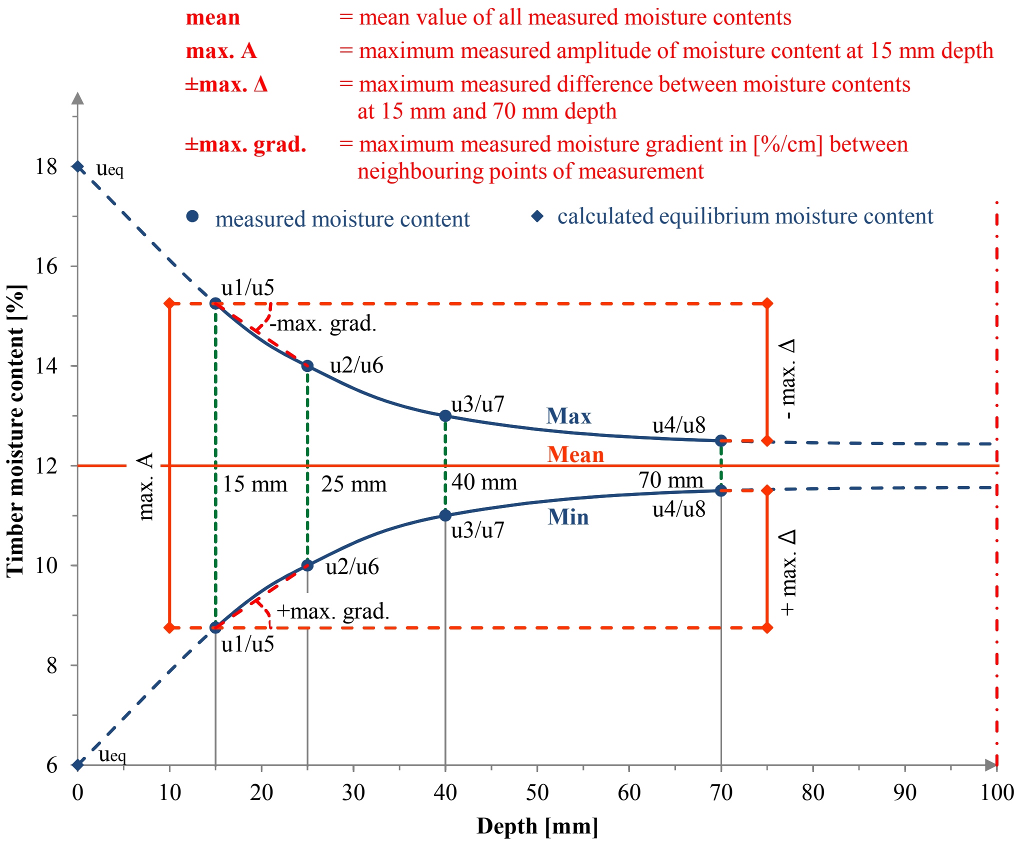

Figure 12: Schematic of envelope curve of moisture contents in the timber cross-section including notation of analyzed parameters

Table 2: Numerical summary of measurement results

Building	**Moisture content at measuring point 1**						**Moisture content at measuring point 2**						**Temperature**		**rel. Humidity**	
	mean	max. A	±max. Δ		±max. Grad.		mean	max. A	±max. Δ		±max. Grad.		mean	max. A	mean	max. A
	[% MC]		[% MC]		[%/cm]		[% MC]		[% MC]		[%/cm]		[°C]		[% rh]	
A	Indoor swimming pool															
A1	8,7	1,4	1,0	0,0	0,1	-0,2	9,3	1,2	0,4	-0,2	0,5	0,0	29,7	6,7	48,3*	6,8*
A2	16,1	1,8	0,6	-0,5	0,6	-0,4	15,0	2,6	1,6	-0,6	1,3	-0,3	28,7	6,0	88,6*	19,4*
A3	8,7	1,6	4,8	2,3	1,4	0,7	7,7	1,8	1,7	0,2	1,0	0,3	30,5	19,5	45,6*	29,0*
*In these buildings, a temporary malfunctioning of the climate sensors was encountered. The values given represent the periods of regular measurement.																
B	Ice rink															
B1	15,5	3,3	1,7	-1,0	0,9	-0,5	14,2	2,5	0,4	-1,9	0,7	-0,3	9,4	26,2	69,0	44,0
B2	13,5	5,8	1,9	-2,8	0,9	-1,0	15,2	6,6	1,9	-3,9	1,2	-0,8	9,9	29,9	62,2	59,1
B3	10,8	5,1	3,8	-1,6	1,5	-1,0	9,6	4,0	2,1	-1,7	1,3	-0,4	19,9	14,1	40,2	57,0
B4	13,3	1,9	0,9	-0,6	0,7	0,2	14,9	2,8	-0,3	-2,1	0,0	-0,7	9,2	18,8	68,3	44,7
C	Riding rink															
C1	17,1	3,3	1,3	-1,0	0,6	-0,5	16,4	3,4	0,0	-2,8	-0,2	-1,2	13,3	22,5	79,7	52,6
C2	15,5	5,1	0,1	-3,5	-0,1	-2,8	15,8	3,8	1,2	-1,4	0,8	-0,7	10,5	28,6	77,8	48,6
C3	14,4	4,9	2,7	-1,5	0,7	-1,1	15,5	4,5	1,8	-1,6	0,8	-0,5	9,8	30,5	77,9	52,3
D	Gymnasium (sports facility)															
D1	4,4	2,1	0,6	-0,3	0,3	-0,2	5,9	1,2	1,1	0,0	0,7	0,2	27,4	26,7	27,7	29,6
D2	8,0	2,0	0,7	-0,9	0,2	-0,3	8,1	2,1	1,1	-0,6	0,6	-0,2	20,6	16,7	42,8	42,0
D3	10,2	2,2	1,3	-0,5	0,8	-0,1	10,0	2,1	1,7	-0,2	0,7	-0,1	20,8	7,9	51,2	34,0
E	Production and Sales															
E1	7,7	1,8	0,6	-1,2	0,5	-0,1	7,8	1,6	0,3	-1,3	0,5	-0,1	18,4	17,5	40,9	38,6
E2	4,8	1,9	0,5	-0,7	0,7	-0,3	4,7	2,2	0,9	-1,1	0,5	-0,9	27,1	21,3	25,8	49,9
F	Agriculture (livestock)															
F1	16,4	3,7	-0,9	-3,7	-0,3	-1,2	15,6	3,0	-0,9	-2,7	-0,5	-1,9	11,6	21,6	74,7	45,6
F2	14,9	5,6	-0,1	-2,8	-0,7	-2,1	15,1	3,7	0,2	-2,1	-0,1	-1,4	14,2	22,4	68,4	48,1
F3	14,4	4,7	-1,3	-5,5	-0,9	-2,8	15,2	4,5	-1,2	-5,1	-0,7	-2,6	12,6	28,2	69,2	54,1
G	Warehouse															
G1	10,5	8,7	3,0	-5,2	1,2	-3,2	13,9	5,4	1,4	-2,6	0,7	-2,1	10,1	32,6	74,3	62,5
G2	13,3	6,1	1,2	-4,4	1,2	-1,4	12,7	3,6	0,7	-2,5	0,5	-1,0	9,7	32,5	67,1	54,0
G3	11,5	3,6	1,7	-1,4	1,1	-0,3	12,1	2,9	0,7	-1,7	0,7	-0,7	13,4	25,6	61,3	44,0

3.2.2 Results and remarks with regard to the different types of use

Very constant climatic conditions (T ≈ 30°C, 50 % RH) were found for indoor swimming pools (buildings "A1" and "A3") during standard operation. The timber moisture content (MC) featured small variations and small gradients. Transition zones to the outside air (building "A2") represent an exception due to the lowering of the temperature which results in higher and more fluctuating relative humidity and timber MC.

In gymnasiums (sports facilities, buildings "D"), constant climate was observed as well. The relative humidity ranged between 40 % and 50 % and since all buildings were heated, the temperatures mostly remained constant at about 20° C. This resulted in constant timber MCs between 8 % and 10 % and very small moisture gradients. Building "D1" represents an exception since the roof structure is situated in a shed roof with skylights. This resulted in high temperatures and low relative humidities (RH = 28 %). The corresponding structural elements were very dry (MC of 4 % - 6 %). It should be noted that the measuring equipment tends to slightly underestimate the MCs at the low range (max. $\Delta u = 1.3$ %), see section 2.2.

The climate in both buildings "E - production and sales facilities" is only partially comparable due to their different type of use. Both halls are non-insulated and partly open but due to the heating system, the influence of the outside climate on temperature and relative humidity are damped. Therefore the timber moisture gradient was relatively constant. In building "E2", the metal processing and ironwork resulted in high temperatures below the roof (temporarily above 30°), combined with very low relative humidities (temporarily below 20 %). The resulting timber MC was about 5 %.

The ambient climate in closed, non-air conditioned ice rinks (buildings "B1" and "B2") was marked by a distinct change between winter (T = 4° C; 75 % RH) and summer months (i.e. ice-free period with T = 15° C; 60 % RH). The timber MC in ice-skating rinks was high and varied noticeably. In air-conditioned buildings (buildings "B3" and "B4"), this effect was significantly dampened. In buildings "B1" and "B4", the film-forming surface treatment showed a damping effect on the moisture gradient. During operation (ice season), the timber MC in structural timber elements above the ice was on average 1.5 % higher than in elements above other areas. It should be noted that the measurements were taken at the side faces of the beams and not at the bottom side facing the ice. Surfaces facing the ice cool down due to radiation exchange. This can lead to condensation, partly resulting in the formation of an ice-layer, and in the case of timber elements to increased MC, see e.g. [14].

The climate in riding rinks (buildings "C") was marked by seasonal variations leading to high amplitudes of temperature and relative humidity, the latter at high level (RH = 78 %). During the winter months, the combination of cold air in the non-insulated and unheated buildings and the humidity introduced by the sprinklers (to capture the dust), frequently resulted in condensation. Like in other types of buildings which are influenced by the outside climate, the timber MCs were higher (MC ≈ 16 %) and featured stronger seasonal variability. Due to the seasonal nature of the variations, these result in noticeable but not in exceptionally high timber moisture gradients.

Similarly strong seasonal variations of climatic condition were found for agricultural buildings with livestock (buildings "F"), the relative humidity being slightly lower (RH = 70 %). In the winter months, the interaction of the cold outside air and increased humidity in the non-insulated, unheated and partly open buildings resulted in high timber MCs and partly in condensation.

Since warehouses (buildings "G") are oftentimes realized as partly open buildings, the climate is highly influenced by the outside climate. The mean values of timber MCs ranged between 10 % and 14 %, their variation was amongst the highest of all evaluated types of use. Building "G1" is used to store plants during winter. The additional humidity introduced by the plants resulted in high relative humidity and occasionally in extensive condensation. The structural elements below skylights (i.e. exposed to direct sunlight) featured the highest amplitude and moisture gradient of all buildings evaluated.

In addition to the previously described, construction and use-dependent climatic conditions, the results of the research project highlight one more important aspect. Temporary interventions (such as renovations) or changes of use (temporary or permanent) can lead to major changes in climatic conditions, which are reflected by distinct changes in timber MC. Within this research project, strong drying of timber elements (renovation of indoor swimming pool "A3" and temporary conversion of ice-skating rink "B3") as well as strong moistening of dry timber elements (conversion of former metal-processing production facility "E2") was measured. Although the evaluation period could sometimes not cover the full effect of the intervention, a noticeable increase of the moisture gradient was observed. Accordingly, care should be taken during such interventions to realize a decelerated change of climatic conditions.

4 Conclusions

4.1 General

Historically the subject of moisture content in structural timber elements tended to be treated from the viewpoint of how to prevent high moisture contents to inhibit decay or growth of fungi. The evaluation of damages in large-span timber structures shows that cracking parallel to the grain due to low or severe changes of moisture content is amongst the prevalent types of damage in such structures. These cracks reduce the capacity of the cross-section to transfer tension perpendicular to grain or shear stresses. Shrinkage related cracking might be less pronounced in structural elements from solid timber if the correct sawing patterns are applied. Structural elements from glued-laminated timber with large cross-sections are more vulnerable in that aspect due to their reduced adaptability to changing ambient climate. Fast and/or significant changes of ambient climate can be due to the type of construction and use of the building. Locally, these changes can be intensified, e.g. around skylights or in the proximity of heating systems.

The conclusions and recommendations linked to this project can be grouped into conclusions that are directly derived from the results given above and guidance on best-practice that is supported by the results of this research project.

4.2 Conlusions from the research project

A comparison of the results for buildings of different type and use confirms the expected wide range of possible climatic conditions (temperature, relative humidity) in buildings with timber structures. Evaluated for all types of use, the average moisture contents range between 4.4 % and 17.1 %. The graphical representations confirm the damped and delayed adaptation of timber moisture content with increasing depth. The moisture gradients are lower in insulated and air-conditioned buildings compared to buildings with stronger influence of the naturally variyng outdoor climate. The closed, insulated and heated buildings (indoor swimming pools, gymnasiums, production and sales) featured rather constant but dry climate. Here, the most severe change of moisture content will mostly occur during the first winter of operation, after assembly and closure of the building. Accordingly, care should be taken to realize a decelerated change of ambient climate. The second group of buildings featured strong but periodic changes of moisture content (e.g. ice-skating rinks), partly caused by an increased influence of the outdoor climate on the indoor climate in unheated and non-insulated buildings (e.g. riding rinks, agriculture, warehouses).

In addition to the previously described, use-dependent climatic conditions and their influence on timber moisture content, the results of the research project identify another important aspect. Temporary interventions (such as renovations) or changes of use (temporary or permanent) can lead to major changes in climatic conditions, which are reflected in distinct changes in timber moisture content. This results in a major increase in potential for damage due to e.g. crack initiation in glued-laminated timber elements. Accordingly, care should be taken during such interventions to realize a decelerated change of ambient climate.

4.3 Recommendations for best-practice

Potential measures to avoid fast decrease or increase of timber moisture content include adjusting the heating system so as not to reduce the relative humidity too fast and too strong. An artificial air humidification, e.g. in the form of evaporation basins is another possibility to damp the speed of drying of the structural timber elements. An alternative is a surface treatment, e.g. in the form of products which damp the moisture absorption and release in the first years of operation of the building (to counteract fast drying of newly installed elements in constant but dry climates). Such interventions should be carried out by expert personnel. The timber moisture content during production, transport and installation should not deviate too much from the expected equilibrium moisture content ($u \leq 12$ %).

In buildings featuring a substantial influence of the outdoor climate on the indoor climate, the application of insulation on the roof could help to dampen the strong changes of indoor climate and correspondingly the timber moisture gradients. Timber structures in areas exposed to direct sunlight (e.g. below skylights) or in the proximity of exhausts of the heating system, should be given attention with respect to potential crack initiation due to rapid drying after a period of increased humidity. Protective, exchangeable covering in the form of panel materials seem to be one feasible measure. This possibility is being investigated and measured in a separate research project carried out by the authors in collaboration with the Studiengemeinschaft Holzleimbau e.V. In ice-rinks, the largest change in the building climate and timber moisture gradient resulted from the ice preparation after the summer break. By air-conditioning the buildings, this effect can be significantly dampened. In riding rinks, the combination of cold air and humidity introduced by the sprinklers, frequently results in condensation. In order to reduce this effect during the cold season the sprinklers should only be used when it is absolutely necessary for the equestrian sport.

The findings presented imply that designers should be given more information and guidance on how to treat the subject of timber moisture content during construction, use, temporary interventions and change of use of their specific building. A potential implementation of the conclusions presented would be to include such information in textbooks or commented versions of codes, highlighting the benefits of using timber elements which feature a moisture content mirroring the expected average moisture content. To increase the awareness towards specific climates it should be considered to include examples of classification of buildings of specific use into Service Classes (e.g. riding rinks, ice-skating halls) in textbooks or commented versions of codes. At the same time it should be stated that the expected average moisture content is to be determined individually for each building. Another important objective is to increase awareness towards dry climates. It would be worthwhile to consider including a note in the code stating that the average moisture content of softwoods in heated and insulated buildings (Service Class 1) will in most cases be below 10 %.

4.4 Outlook

Currently measurements are continued in 10 of the 21 buildings featuring seasonally varying climate. For this, the measurement equipment was upgraded in order to take additional measurements of the temperature within the cross-section. These measurements shall be used to verify the approach to calculate the material temperature in the different depths on the basis of the measured surface temperatures. The continued measurements shall also help to answer the question whether the outside climate during the first year of measurement is representative for the regular climate at the location of the buildings.

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