

Short report for the research project:

Building Climate – Long-term measurements to determine the effect on the moisture gradient in timber structures

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1 Objective of the research project

The natural and renewable material wood is characterized by its pronounced hygroscopic nature. Even after processing, e.g. when used as construction material in buildings, changes in the ambient climatic conditions will result in changes of the timber moisture content (see Figure 1). This in turn leads to changes of virtually all physical and mechanical properties (e.g. strength properties) of wood. In standards for timber construction, this is accounted for by classifying the structural timber elements into one of three possible service classes according to the climatic conditions during the design service life.

An additional effect of changes of the wood moisture content is the associated shrinkage or swelling of the material. This is much more pronounced perpendicular to the grain than in grain direction. Since the absorption and release of moisture is realized through the surfaces, the outermost sections of the wood cross-sections will adapt to the climatic conditions at first. The resulting moisture gradient and the associated shrinkage or swelling will lead to internal stresses in the cross-section. These stresses will partly be reduced by relaxation processes but when the stresses exceed the very low tension perpendicular to grain strength of wood, the result will be a stress relief in form of cracks which can reduce the load-carrying capacity of structural timber elements.

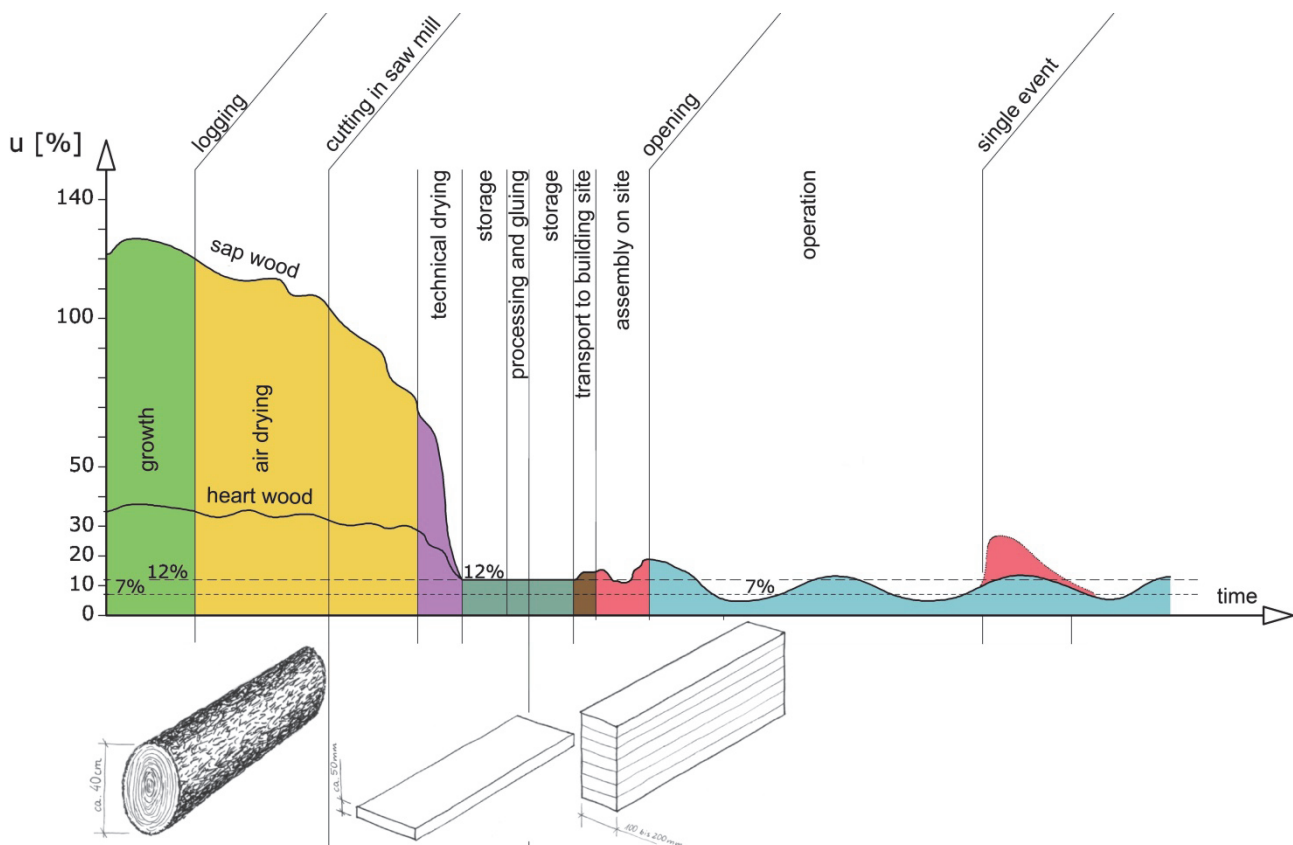


Figure 1: Sketch of a possible “moisture chain”, i.e., development of wood moisture content from the tree to glued-laminated timber elements in the building

The evaluation of damaged large-span timber structures shows that the predominantly observed damage is pronounced cracking in the gluelines and lamellas of glued-laminated (glulam) timber elements. A significant proportion of these cracks is attributed to the seasonal and use-related climatic variations within large-scale buildings and the associated inhomogeneous shrinkage and swelling processes in the timber elements. This leads to the necessity to better determine and describe the climate-related stresses in large-span timber structures. This leads to the necessity to better describe the climatic conditions in large-span buildings featuring timber structures by means of measurements.

Through long-term measurements of climate data (temperature, relative humidity) and timber moisture content on large-span timber structures in buildings of typical construction type and use, data sets were generated which deliver information on the sequence and magnitude of seasonal variations. The measurement of moisture in different depths of the cross-section is of particular interest to draw conclusions on the size and speed of adjustment of the moisture distribution to changing climatic conditions. The moisture gradient has direct influence on the size of the internal stresses and possible damage potential. Similarly, the results provide a review and extension of the previous classification of buildings into use classes. They allow for a more precise indication of range of resulting equilibrium moisture content for the specific use, enabling the installation of timber elements with adjusted moisture content. The results of the research project also support the development of appropriate monitoring systems, which could be used in the form of early warning systems based on climate measurements.

2 Realisation of the research project

2.1 Chosen types of use and types of buildings

Within the research project, long-term measurements in a total of 21 halls with seven different types of use (see Table 1) were realized within two measurement periods of one year each. When selecting the objects, attention was given to cover a wide range of types of timber constructions. In each hall, the data were collected at two different points of measurement in order to capture possibly varying climatic conditions (e.g. solar radiation or the influence of building appliances).

Table 1: Chosen types of use, number of objects in each use and period of measurements

Cat.	Use	Number in measurement period I	Number in measurement period II
A	Indoor swimming pool	3	0
B	Ice rink	4	2
C	Riding rink	3	2
D	Gymnasium (sports facility)	3	0
E	Production and Sales	2	2
F	Agriculture (livestock)	3	2
G	Warehouse	3	2
		21	10

2.2 Applied method of measurement

For the measurements of the timber moisture content the resistance measurement method was chosen, since this method constitutes the generally accepted state of the art. Moreover does this reliable and widely applied method allow for the non-destructive measurement of moisture gradients across the cross-section. The chosen method is based on measuring the electrical resistance or conductivity of wood. Since water has a much higher electrical conductivity than wood, meaning that its electrical resistance decreases with increasing moisture content, it is possible to deduct the present moisture content in one specific location. For the measurement of the distribution of moisture over the cross section, four pairs of teflon-insulated electrodes with varying length were used at each point of measurement to enable the measurement of moisture content in clearly defined depths of the cross-section. 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 moisture content at up to eight channels. The moisture measurements which were generated every hour at both points of measurement are subsequently transmitted to a data logger. The climate data are 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 are recorded to allow for the temperature compensation of the moisture content (see Figure 2). Prior to the second measurement period, the measurement equipment was adapted to the experience gained in the first measurement period. This included isolating the electrode heads to prevent short circuits between the measuring channels. The measurement equipment was placed in an installation box to prevent external influences. The number of climate sensors was doubled to enable measurement of temperature and relative humidity on the beam surfaces in direct vicinity of the measurements of timber moisture content. At both points of measurement the material temperature was determined by two temperature sensors installed in 20 and 40 mm depth. Figure 2 gives a schematic of the measurement technique.

Before installing the measurement technique in the buildings, the system was installed on test specimens of glued-laminated timber from spruce 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 moisture contents were continuously measured with the measurement equipment and compared to the results of cyclic measurements with a calibrated reference moisture meter. There was neither a significant difference in the results of the two measurement systems, nor when using different types of electrodes. For further verification, two independent series of test specimens from spruce were produced and stored under four different controlled climatic conditions (very dry to very humid). After the specimen had reached constant weight, their moisture content was measured with the chosen moisture meter and two reference meters. By subsequent kiln-drying, the actual moisture content was determined. Good agreement was obtained for moisture contents between 12 % and 18 %, maximum absolute deviations of 1.3 % were measured for the dry specimen, whereby the chosen moisture meter as well as the reference moisture meter tend to underestimate the actual moisture content at low ranges.

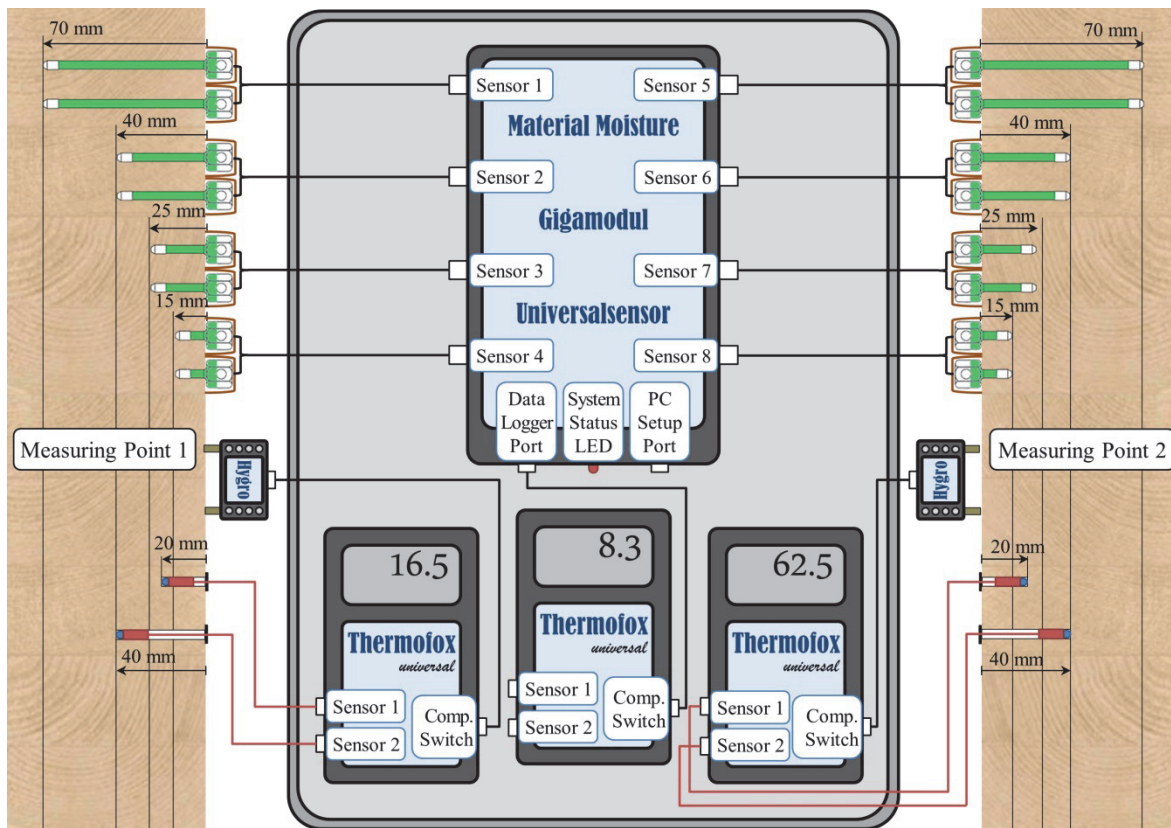


Figure 2: Systematic presentation of the measurement technique.

After installation of the measuring equipment in a total of 21 objects, the data stored in the data loggers were read out three times over the measurement period, whereby a functional check as well as a reference measurement with another moisture meter was carried out at the same time. To analyse the data, a 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 measurements of electrical resistance from the raw data into timber moisture contents, a compensation of the effect of temperature was undertaken. For this, the actual material temperatures in the different depths were calculated from the measured surface temperatures, using the explicit Euler method. For comparative reasons, the equilibrium moisture content prevailing in the cross-section near the surface in dependence of the surrounding climate was determined by the theoretical model of Hailwood & Horrobin and given as moving average over 10 days.

3 Summary of the results and Conclusions

The developed measuring system proved to be suitable to realize long-term measurements of timber moisture content and climatic conditions in buildings with timber structures. The use of teflon-insulated electrodes of different length allowed clear statements about the gradient of moisture in the cross sections. Within the two evaluation periods from 1 October 2010 to 30 September 2011 (Period I) and 1 April 2013 to 30 March 2014 (Period II), a total of over 3.6 million readings were collected and analyzed. The data read from the data loggers were prepared as curves (time series) of relative humidity and temperature at the location of measurement over time, see Figure 3. The same type of representation was chosen for the measurements of timber moisture content in the four depths of the cross-section, see Figure 4.

Indoor climate at measuring point 1

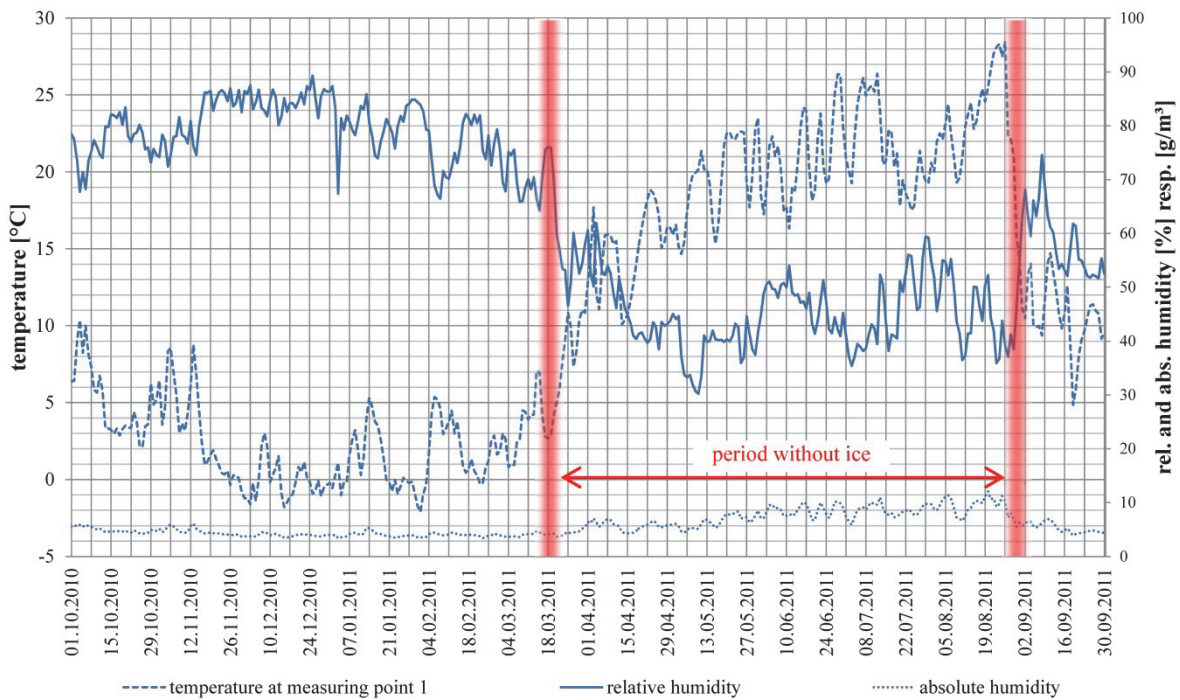


Figure 3: Variation of the relative and absolute humidity and the reference temperature over the measurement period, exemplary given for an ice rink.

Timber moisture content at measuring point 1 (temperature compensated)

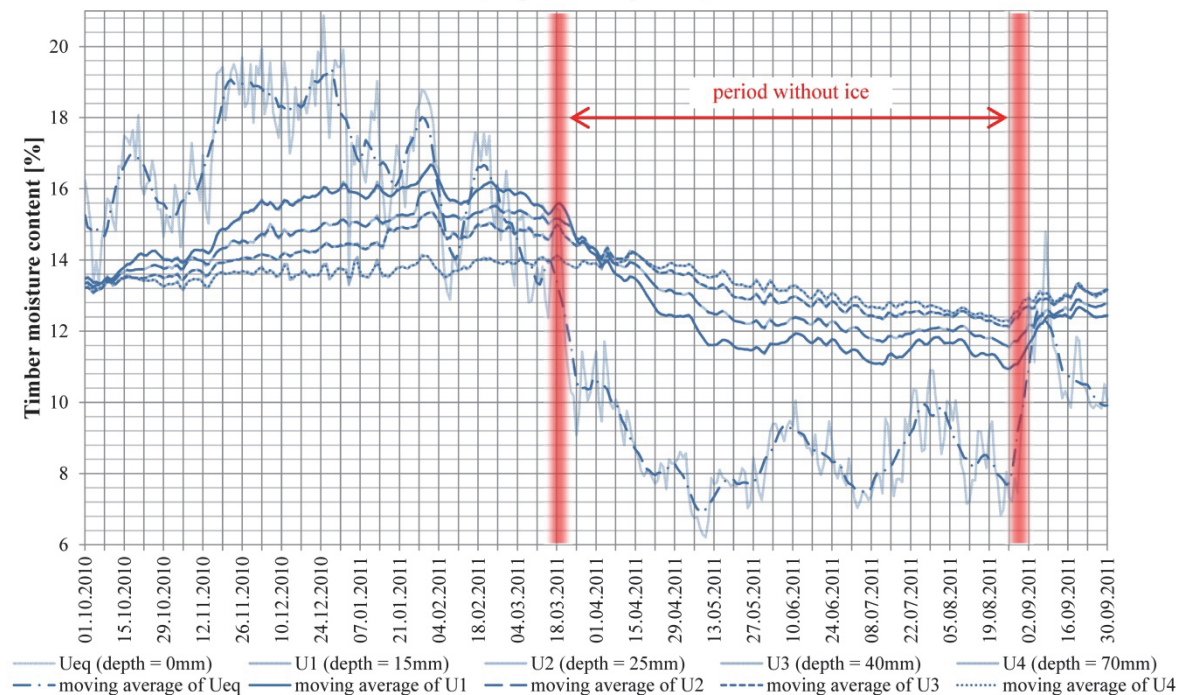


Figure 4: Variation of timber moisture content at different depths of the cross-section over the measurement period, exemplary given for an ice rink.

In addition, graphical representations over the cross section were derived for the timber moisture content. This type of representation allowed to create envelope curves of minimum and maximum timber moisture contents, see Figure 5, as well as envelope curves of minimum and maximum timber moisture gradient $\text{grad}(u) = du/dx$ over the cross-section, see Figure 6. These results form the basis on which to draw conclusions about the magnitude of moisture induced stresses and hence the potential for crack initiation.

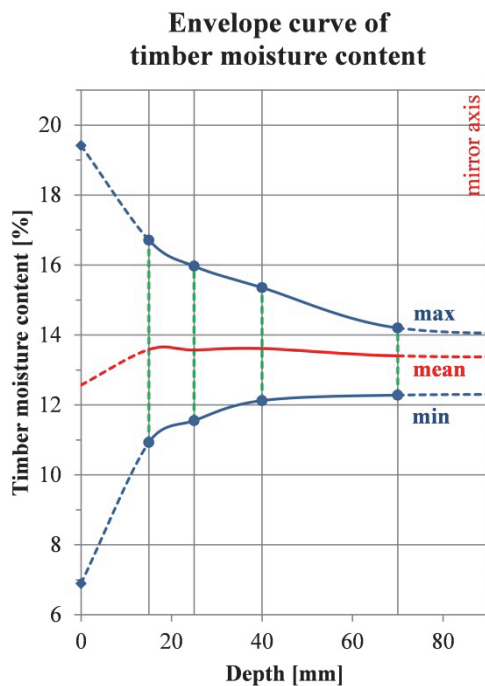


Figure 5: Envelope curve of the timber moisture content at different depths of the cross section, exemplary given for an ice rink.

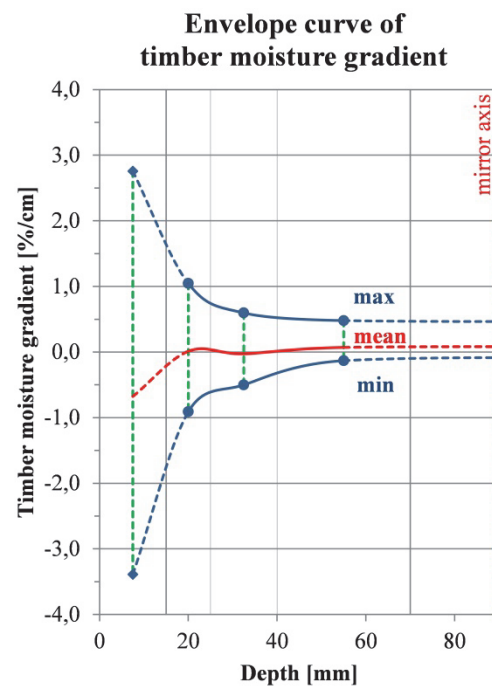


Figure 6: Envelope curve of the timber moisture gradient at different depths of the cross section, exemplary given for an ice rink.

A comparison of the results of the individual types of building use confirms the expected large range of possible climatic conditions (temperature, relative humidity) in buildings with timber structures. Evaluated for all types of use, the average moisture contents lie between 4.4% and 17.1%. From the graphical representations, a damped and delayed adaptation of timber moisture content can be identified with increasing depth. The moisture gradients are lower in insulated and heated buildings than in buildings with stronger influence of the naturally varying outdoor climate.

The average moisture contents in heated and insulated buildings (e.g. swimming pools, gymnasiums, production and sales) were in the range of 6 – 10 % with annual amplitudes of about 2 %. Due to these relatively constant but dry conditions it should be ensured already during production, transport, installation and construction site operation that the moisture content of (especially large-volume) timber elements differs by only a few percent of the expected equilibrium moisture content ($u \leq 10\%$). Possible measures include a coordinated construction regime (e.g. preventing wetting during prolonged storage, reduction of unnecessary construction moisture). In the design of such structures it should be aimed at avoiding a restriction of free shrinkage and swelling of the components (e.g. due to fasteners at large distances perpendicular to the grain, or reinforcement placed at small distances).

The first winter of operation, after assembly and closure of the building, will in most cases be the most critical period with respect to shrinkage cracks. In this period, the heating system should be adjusted such 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 counter fast drying of newly installed elements in constant but dry climates). Currently no concrete specifications of applicable products for this surface treatment can be given.

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). The average moisture contents of these buildings were in the range of 12 – 16 % with annual amplitudes of about 4 %. Here, the application of insulation on the roof could help to dampen the strong changes of indoor climate and correspondingly the timber moisture gradients. In the case of partly open buildings, the effect of such measures is reduced with increasing amount of permanently open areas in the building envelope. Timber structures in areas exposed to direct sunlight (e.g. below skylights) or in the proximity of exhausts of air ventilation, should be given attention with respect to potential crack initiation due to rapid drying after a period of increased humidity. In areas with strong but periodic changes of moisture content, protective covering in the form of panel materials could be another feasible measure. The last-mentioned possibility is momentarily being investigated and measured in a separate research project carried out by the authors in collaboration with the Studiengemeinschaft Holzleimbau e.V. In riding rinks, the combination of cold air and humidity introduced by the sprinklers, frequently results in condensation. To reduce this effect during the cold season the sprinklers should only be used when it is absolutely necessary for the equestrian sport. 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 addition to the previously described, use-dependent climatic conditions and their influence on timber moisture content and the potential for crack initiation, do 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. Within this research project strong drying of timber elements (temporary conversion of an ice rink and renovation of an indoor swimming pool) as well as strong moistening of very dry timber elements (conversion of a former metal-processing production facility) was observed. 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. The use of remedial measures (e.g. in form of evaporation basins or surface treatment) could also be a means to realize a dampened and controlled change of moisture content. Ideally, such interventions should be accompanied by expert personnel.

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 toward 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 toward 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 %.