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QUALITY ASSURANCE OF TIMBER STRUCTURES BY NEW MONITORING METHODS FOR THE MOISTURE CONTENT OF WOOD

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ABSTRACT: Wood is a hygroscopic material and can absorb or release moisture from the surrounding climate. The wood moisture content (MC) influences the material strengths and stiffnesses as well as the long-term load-bearing behaviour. For this reason, the continuous monitoring of wood moisture content is a suitable early warning system to increase the quality of wood structures in a pioneering way and to detect changes in time. The paper presents several suitable measuring methods for the MC and explains their advantages, accuracies, and applications. The explanations are supported by case studies.

KEYWORDS: wood, quality assurance, moisture content, measuring methods, monitoring

1 INTRODUCTION

The continuous monitoring of wood moisture content is a suitable early warning system. The importance of wood moisture in relation to possible damage in timber construction is shown by Frese & Blaß [1], where 50 % of all investigated objects show damages or failures due to wood moisture changes or low and high wood moisture contents. Dietsch & Winter [2] shows that 30% of these objects are damaged due to seasonal or climate-induced wood moisture changes.

Since the distribution of wood moisture is often not constant across the cross-section, internal stresses perpendicular to the grain (moisture-induced stresses, MIS) arise due to the anisotropic moisture-strain behaviour. These stresses can easily exceed the characteristic tensile strength perpendicular to the grain and lead to crack development, [3]. In curved glulam beams, these stresses can also lead directly to the total loss of load-bearing capacity, as shown in [4], [5].

First, the focus must be on the design regarding the load bearing capacity and serviceability. Therefore, the service classes according to the EN 1995-1-1 needs to be considered. For a more detailed assessment of the expected climate, the results from Franke et al. [6] can also be used. Here, continuous monitoring data for one year was evaluated for different uses, such as sports halls, ice rinks and riding arenas, but also storage buildings, bridges, or mountain stations. The curves obtained show the range of variation and the expected wood moisture content per object.

Second, the condition of the structure must be ensured during the whole life cycle - 50 years for buildings and up to 100 years for infrastructural objects. This is usually done by regular visual checks and inspections combined with control measurements. If the control measurements are carried out continuously by means of a monitoring system, trends in the behaviour, damaging events or even damages can be derived from the data and inspections can be planned more time and cost efficiently.

The control of timber structures over ice rinks, riding surfaces, in warehouses and production halls, for facades made of wood, or flat roofs are engineering applications to ensure the quality of timber construction. The variety of monitoring possibilities is e.g., demonstrated at the "House of Natural Resources" at ETH Zurich, [7]. A dense sensor network was installed to measure, among other things, the prestressing force, the deformation, or relative displacements in addition to the wood moisture content to record the behaviour of the building over several years and to quantify the long-term behaviour of this wooden structure.

Monitoring systems can also be used for system controlling. In an apartment building in Büren in Switzerland, four apartments were equipped with sensors to measure air quality, [8]. Air quality has direct effects on the people who spend time indoors. Measurements of air temperature, air quality, CO_2, and volatile organic compounds (VOC) can be used to assess air quality. The air exchange rate can be reduced to the necessary/optimal amount and the control of the air exchange units can be optimized. The result is a constantly very good air quality with simultaneous energy savings due to the reduction of the air exchange rate when no people are in the apartment.

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2 MEASURING METHODS FOR THE WOOD MOISTURE CONTENT

2.1 GENERAL TO THE MEASURING METHODS

For the measurement of wood moisture content, single point and laminar measuring systems can be used, as shown in overview in Figure 1. For the monitoring of small critical areas, the resistance measuring method, the sorption isotherm method and the passive RFID tag method are available. The principal description of the measurement techniques for wood moisture content is given e.g. in [9], [10]. Specifics for monitoring purposes is discussed below.

2.2 ELECTRICAL RESISTANCE METHOD

The electrical resistance method is the most common non-destructive method to monitor moisture content developments. The method allows measurement of moisture content in different depths from the surface and measured resistances can logged over extended periods of time. The principle is to measure the electrical resistance between two installed electrodes, [9]. The electrical resistance depends on the moisture content, temperature, and wood species. The accuracy of the method is about 1 to 2 M% [9]. Factors affecting the accuracy concern the grain orientation, type of electrodes, wood density, and temperature as well as surrounding electrical installations, permanent fitting/bond of electrodes to wood. Resistance between two electrodes roughly ranges between 100 kΩ to 100 GΩ from the fiber saturation point to about 5 M%, respectively. Once resistances are large, electrical currents are extremely small and electrical fields around the monitored structure are considered a possible source of error.

The choice and installation of electrodes should be done carefully, especially for objects subjected to outdoor climate, strong climatic variations, or direct weathering. Due to the shrinkage and swelling of the wood, normal wood screws or nails may have no or poor contact with the wood or the cable. Both lead to distortion of the resistance measurement and mostly indicate lower wood moisture contents than in reality. The use of hanger bolts and a protective box has proved to be successful, see Figure 2. The hanger bolts must be insulated with suitable material except for the tip. The cables are fixed directly to the hanger bolt with nut and locknut. The shrinkage and swelling of wood have almost no influence on the required good electrical contact between wood and electrode. All metallic parts of the electrodes should be made of stainless steel, if possible, [11].

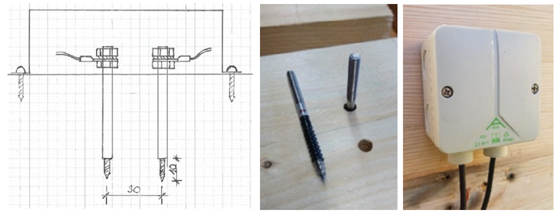

Figure 2: Principal sketch and photos of the installation of the hanger bolt electrodes and protective box, [11]

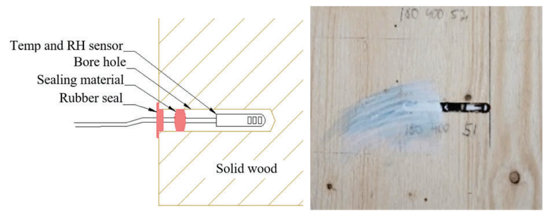

Figure 3: Installation of air temperature and relative humidity sensors in solid wood

2.3 SORPTION ISOTHERMS

2.3.1 General

The equilibrium moisture content in the wood can be derived from the temperature and relative humidity, [12]. The implementation of sensors in small, closed cavities in the wood is called the sorption isotherm method. The sorption isotherm method is most suitable in the presence of glue joints, the influence of salts, the use of protective and impregnating agents, or even in the presence of prolonged temperatures below 5 °C. All these factors do not influence the measurement by means of sorption isotherms. The application and implementation of the measuring probe requires a cavity size of 8 to 10 mm in diameter, whereby the depth of the measuring probe can be controlled as desired, see Figure 3.

2.3.2 Moisture sensor developed at BFH-AHB

To simplify the application of the sorption isotherm method, a special very small sensor was developed at Bern University of Applied Sciences, the Institute for Timber Construction, Structures and Architecture and the Institute for Electrical Engineering and Information Technology. An extra small battery-operated sensor for wood moisture measurement with radio data transmission was developed, see Figure 4. The sensor is located at the tip of the pin shaped extension below the electronic facing

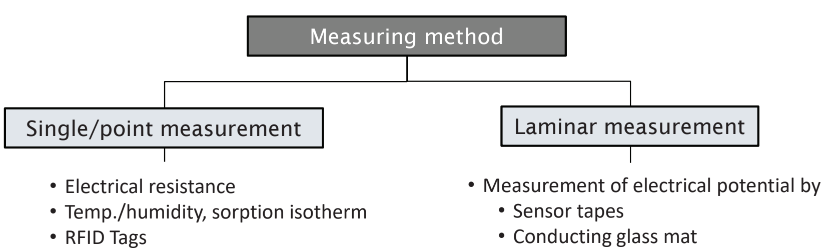

Figure 1: Overview of selected measurement methods for wood moisture content in the monitoring application

outwards. The extension which will be screwed into a drill hole. Different extension lengths could be realized to measure in different depths. The device is inexpensive, easy to apply, and measures, the air humidity, and the temperature in a cavity in any material, and transmits it by radio (LoRa) directly to the cloud or to a gateway (Figure 5). The measurement results can then be processed and visualized.

While every node could work and transmit its data individually, the results of several nodes can be synchronized and collected by using a Gateway. It receives the data by LoRaWAN, saves it and transmits them at once via 4G data net. The gateway also provides a remote access for checking the system conditions. Measurements up to two years can be made with one battery.

2.4 RFID SENSORS

Radio Frequency Identification (RFID) sensors are small devices that use low-power radio waves to receive, store, and transmit data to nearby readers (Figure 6). The basic types of RFID sensors are passive, active, and semi-passive or battery-assisted passive (BAP), [12].

- Passive RFID sensors do not have an internal power source but are powered by electromagnetic energy transmitted from an RFID reader.
- Active RFID sensors have their own transmitter and power source on board the tag.

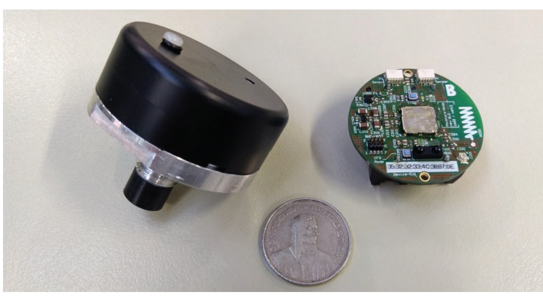

Figure 4: Moisture-Sensor, system with waterproof housing (left), electronic (right).

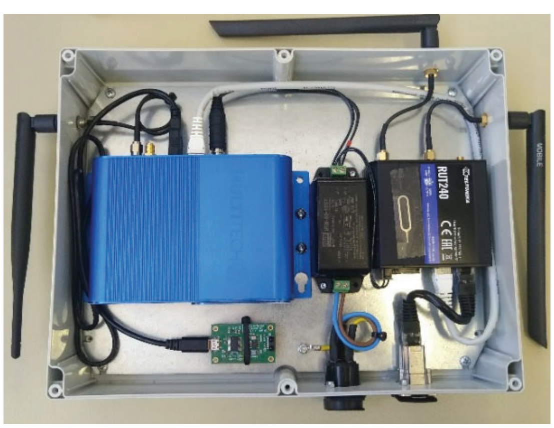

Figure 5: Gateway to use and control several sensor nodes

- Semi-passive or battery-assisted passive (BAP) sensors consist of a power source integrated into a passive tag configuration.

In addition, RFID sensors operate in three frequency ranges:

- Ultra-High Frequency (UHF),
- High Frequency (HF) and
- Low Frequency (LF).

RFID sensors can be attached to a variety of surfaces and are available in different sizes, designs, and shapes (e.g. dogbone or patch, Figure 6). Dimensions vary from a few millimeters to several centimeters. The Smartrac company or RFMicron are already provide passive RFID sensors for capacitive measurement of moisture or humidity. These tags have been successfully applied in the fields of construction, energy, but also healthcare.

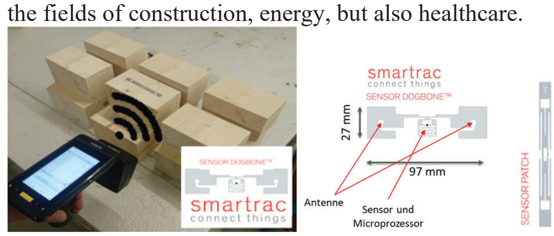

Figure 6: Simultaneous measurement of several RFID sensors installed in the wood specimen (left) and RFID sensor shapes (right)

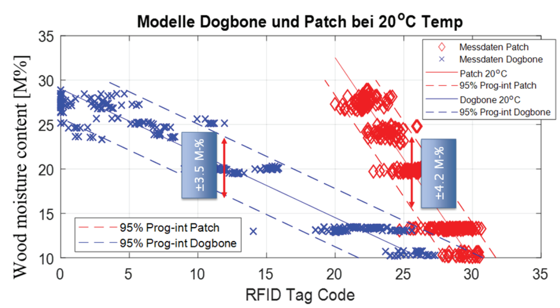

Figure 7: Correlation between RFID sensors code vs. wood moisture at 20 °C for the dogbone and patch sensor

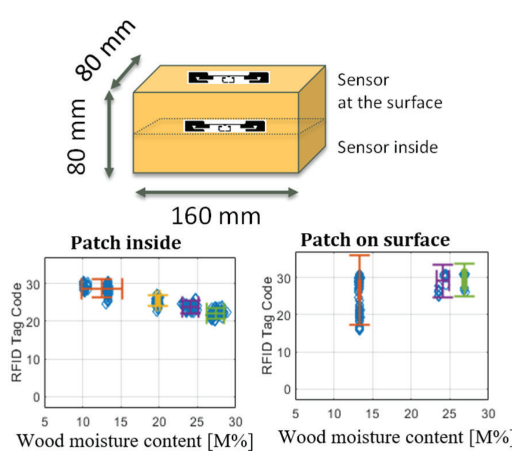

Figure 8: RFID sensor tests at surface and inside, setup (top), correlations (bottom)

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Figure 9: *Bridge Rupperswill, application of sensor band on the wooden panel of a timber bridge (left) and detail of senor band (right)*

The applications of RFID-sensors have shown that the punctual measurement of the wood moisture content is suitable, but with a greater measurement uncertainty than the electrical resistance or sorption isotherm method. The correlation between the read-out sensor code and the wood moisture must currently still be determined on the basis of reference checks. Figure 7 shows an example correlation between sensor code and wood moisture together with the prediction interval. The width of the prediction interval results from the scatter of the measurement data used to derive the correlation. Depending on the application, temperature compensation of the measurement must also be considered. The application range of the model is between 10 M% and 28 M% for the wood moisture. The measurement error of the dogbone shaped sensor and patch sensor is ± 3.5 M% and ± 4.2 M% respectively, derived from the width of the prediction interval. To improve the measuring accuracy, the RFID sensors should be embedded inside the component. The results of a comparative study show lower variations in the measured values, Figure 8.

Due to the very low price of RFID sensors and their small size, several sensors can be installed at each measuring point and an average of the sensor codes could then be calculated. In this way, a higher measurement accuracy can be achieved, and the system is less susceptible to the failure of individual RFID sensors. RFID- sensors make it possible to monitor hard-to-reach and invisible components even without a power supply. The RFID sensors are said to have a service life of 50 years.

2.5 LAMINAR LEACKAGE MONITORING

2.5.1 Sensor tapes

With sensor tapes, it is possible to detect high moisture or wetness in a linear manner, e.g., under a waterproofing layer of flat roofs or road pavements [14]. This measuring method is mainly used in places where water or moisture can spread under the waterproofing. Depending on the spacing and arrangement of the individual tapes, quasi-laminar monitoring can be achieved with the sensor tapes. During monitoring, a potential measurement is made between two wires in the sensor band. The presence of water causes the electrical resistance to drop and can be detected.

For the application in timber bridge structures, a roadway structure with an unbonded waterproofing layer must be used for a two-dimensional leakage detection with linear sensor tapes. Because, depending on the planned transverse and longitudinal slope of the bridge, any water that has penetrated the separating layer between the waterproofing and the deck slab would flow in the direction of the slope and could be detected here, e.g., at a bridge edge or deck transition.

The foot and cycle path bridge between Rupperswil and Auenstein was equipped with sensor tapes, see Figure 9. The monitoring system monitors the possible leakage of the waterproofing and additionally records climate data, material temperature and wood moisture. The on-site measuring unit evaluates the measurement data and sends it to a cloud. The measurements values can be retrieved worldwide at any time using a browser. Warnings and alarms are triggered when critical values are reached.

2.5.2 Conductive fleece

For laminar leakage detection like in flat roofs or landfills, a conductive glass fleece is installed under the waterproofing and above the insulation, [14], [15]. In an intact waterproofing, there is no water flow and therefore no electrical current flow. In case of a leakage in the waterproofing, water penetrates the waterproofing layer and allows the conduction of electric current in the conductive fleece underneath the waterproofing. The presence of water in the case of a leakage changes the electrical properties, respectively the measured value, thus leakages can be detected. After drying out, the original values are restored. Early detection and the detection of hidden water damage are possible.

3 DATA TRANSFER AND SAVING

For the planning, implementation and evaluation of a monitoring system, an exchange with appropriate experts should take place, [16]. At the beginning, the choice of the measured quantity is a first important step next to the definition of the control points and their number. The density of measurement data must be defined individually from object to object or from control point to control point. Specialists in this field can assist and advice in deciding on a suitable system.

The installation of measurement sensors enables the acquisition of measurement data at defined intervals. Data can be transmitted from individual measuring points, e.g., by WLAN, LoRaWan or LPWan to a central module (gateway) and further to a WebPortal, as shown in Figure 10. If the measurement data are stored on a WebPortal, they can be viewed in quasi real time from the workplace and are available worldwide. The server can evaluate the measurement data and trigger warnings or an alarm. Storage and evaluation of the measurement data can also

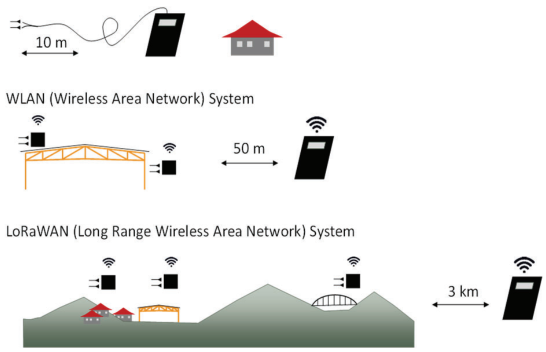

Figure 10: Application of sensor band on the wooden panel of a timber bridge

take place directly on the gateway or other measurement/ storage units and release warnings or alarms (e.g., via SMS). After commissioning, these systems operate autonomously.

The various components (measuring points, measuring device, gateway and user interface) form the monitoring system. Battery-powered systems can operate maintenance-free for up to several years, depending on the system and the number of measuring points.

4 CASE STUDIES

4.1 SOLID WOOD WALL MONITORED BY SORPTION ISOTHERM METHODE

The monitoring results for a solid wood wall show the very good functioning of the sorption isotherm method over different component depths, compare Figure 11. The diagram shows the measured wood moisture content and the calculated equilibrium moisture content (green line) from the room climate over a period of two years. It can be seen very clearly that the sensor near the surface in the wall at a depth of 5 - 10 mm (orange line) reacts very quickly to the room climate with a similar rate of change and amplitude as the calculated compensation moisture. Only in the summer months, when the indoor climate becomes more humid very quickly, there are differences between the orange and green lines. However, these differences quickly equalize. In this construction, for example, plaster-board and abrasion are very diffusion-open materials.

Furthermore, the diagram contains the measured wood moisture contents at depths of 20 - 30 mm, 70 - 80 mm and 95 - 105 mm. Already from a depth of 20 mm (purple line), a "damped" behaviour of the wood moisture with respect to calculated equilibrium moisture can be observed. Here, the wood moisture values are lower in summer and higher in winter than the calculated equilibrium moisture. In this case, the sorption isotherm method allows very precise evaluations of the wood moisture content and the interaction between the room climate and the water content in the solid wood wall.

4.2 TIMBER BRIDGE OBERMATT MONITORED BY ELECTRICAL RESISTANCE METHODE

The bridge Obermatt is monitored over several years within the framework of research projects, by the Institute for Timber Construction, Structures and Architecture at the Bern University of Applied Sciences. Some irregularities could be detected in time, as shown in Figure 13. The measuring points are located at different critical points and in different depths. Figure 12 contains the measurement locations shown on the bridge cross-section.

The wood moisture content was measured near the surface, approx. 20 mm deep, and in the cross-section with a depth of 200 mm. The diagram in Figure 13 shows the change of the air temperatures and relative humidity measured on site together with the calculated equilibrium moisture content on the surface of the wood for the timber bridge Obermatt. The wood moisture content measured in the cross-sections are shown in Figure 14. In addition, the

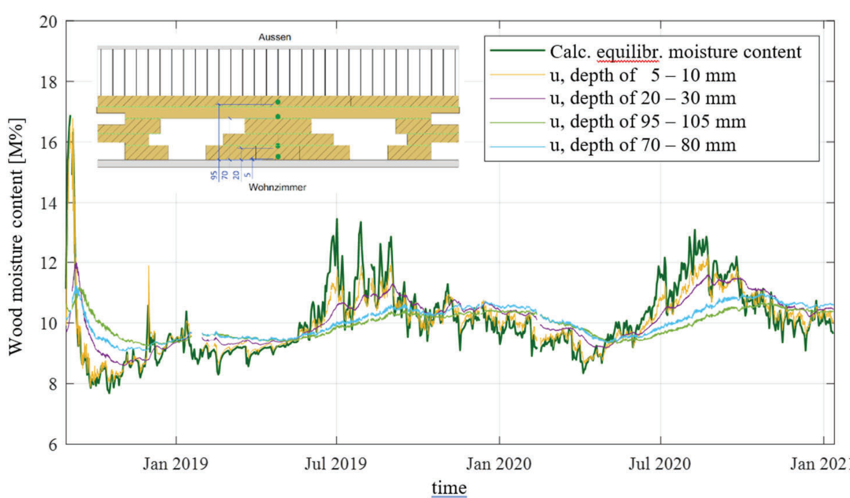

***Figure 11:** Evaluation of the wood moisture content measured with the sorption isotherm method at different depths in a solid wood wall, [8]*

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calculated equilibrium moisture content was determined for each measuring point; a time delay due to the moisture transport in the wood and the duration of exposure to the climate was not considered. The graph of the measured wood moisture content shows a delayed and damped behaviour compared to the calculated equilibrium moisture content.

On the south side, an increase in wood moisture content for one measurement sensor can be observed from August 2013. This is associated with a partial structural leakage, which has since been corrected and the wood is allowed to dry out again. In this case, the installed monitoring system has acted as an early warning system and later serious structural damage could be avoided at an early stage. Further monitoring results and case studies are explained and shown in [17].

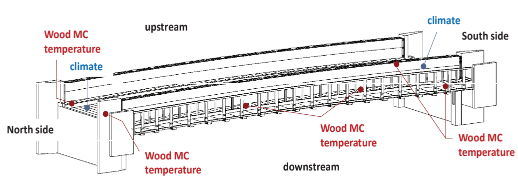

Figure 12: Positioning of the measuring sensors at the Obermatt bridge

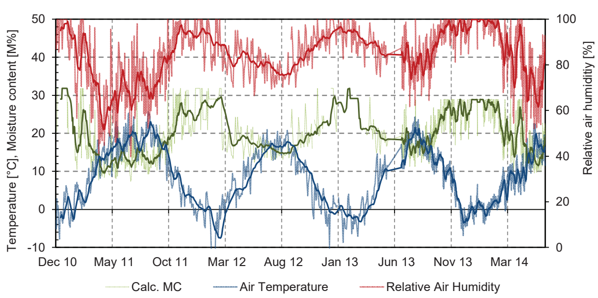

Figure 13: *Climate, wood moisture content and calculated equilibrium moisture content for the Obermatt Bridge*

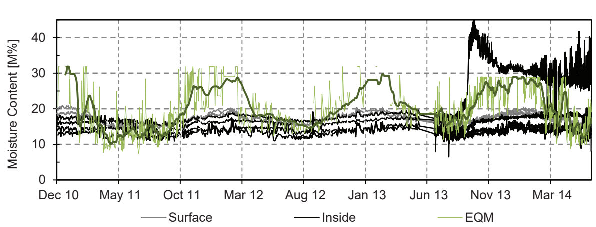

Figure 14: *Wood moisture content and calculated equilibrium moisture Content for the Obermatt Bridge, after August 2013 a leakage is visible in the measuring data*

5 CONCLUSIONS

Wood is a living and recognized construction material. However, wood is also a hygroscopic material and can absorb or release moisture from the surrounding climate. The so-called wood moisture content (MC) influences the material strengths and stiffnesses as well as the long-term load-bearing behaviour. As studies showed, half of the cause of damage to wood structures is due to a change in wood moisture content or seasonal and climate-related changes in wood moisture content. For this reason, continuous monitoring of wood moisture content is a suitable early warning system to increase the quality of wood structures in the future in a pioneering way and to detect changes in time.

The control points in the monitoring should be placed in possible danger zones/hot spots. These can include roadway crossings, support areas, transition areas and penetrations. The various point and area methods presented are suitable for measuring wood moisture content. For the planning, implementation and evaluation of a monitoring system, the number of measuring points, the accuracy and the data storage/transmission should always be defined with a view to the objective. At this stage, an exchange with appropriate subject matter experts can provide positive support.

The electrical resistance measurement method is technically very simple to implement, easy to install and can be replaced from the outside. The sorption isotherm method provides high accuracy by measuring relative humidity and temperature in an insulated cavity. An RFID sensor measures the humidity in the immediate vicinity of the sensor averaged over a certain component depth using the principle of capacitive sensing. The use of RFID sensors is inexpensive and wireless but with less accuracy. Passive RFID sensors even do not require an external power supply or battery and can be used in many applications.

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