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Micro and material climate monitoring in wooden buildings in sub-Alpine environments

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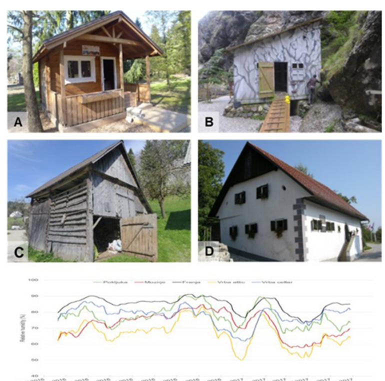
HIGHLIGHTS

- Service life of wood depends on the wood inherent durability and material climate.
- Material climate in real objects was determined in four different objects.
- There was 50.000 moisture measurements performed on 34 locations in four objects.
- The results indicates the correlation between wood moisture and fungal degradation.

GRAPHICAL ABSTRACT



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ABSTRACT

Wood is one of the most important construction materials and its use in building applications has further expanded in recent decades. In order to enable even more extensive and reliable use of wood in outdoor applications, factors affecting wood's service life need to be understood. It is well known that fungal degradation of wood is predominantly affected by temperature (T) and moisture content (MC). In order to elucidate the influence of these two factors, long term monitoring of T, relative humidity (RH) and MC at four locations was carried out: a model house made of thermally modified wood in Mozirje (1), the WWII partisan hospital Franja (2), a hayrack in Pokljuka (3) and a house in the north of Slovenia in Vrba (4). The results clearly showed that fungal degradation of wood is influenced by MC and T. In addition, the influence of micro-climatic conditions on fungal decay was shown.

1. Introduction

Hygrothermal measurements in test houses or real buildings have long been used to address building performance at full-scale in a real environment [17]. These monitoring were performed on various type of buildings, from wooden [22] to buildings made of straw [6]. Field measurements are useful primarily because they expose building components to the whole range of exposure conditions, that cannot be simulated in laboratory conditions. These data are of considerable importance. They can be used to validate the models and to correlate these data with service life data of wood.

The service life of wooden structures is one of the most important pieces of information for the selection of the appropriate construction or façade material. The time during which a particular

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wooden structure will perform its task depends on a variety of factors [8]. However, the service life of wood exposed outdoors is predominantly affected by wood decaying fungi (brown and white rot fungi) [19]. In addition to a material's inherent durability, the moisture conditions and temperature (T) are the most important factors influencing the ability of fungi to degrade wood [18]. These two factors are influenced by the design of the construction, exposure conditions and local climatic conditions (micro-climate). If moisture content (MC) and T are monitored, the severity of a particular location can be evaluated [22]. Based on the severity of the location, additional protection can be applied with design measures. However, if this is not sufficient, a more durable material should be selected. Durable materials can be chosen from the group of naturally durable wood species, wood species treated with biocides or modified wood [11].

One of the issues related to an assessment of micro-climate of a particular location is the question of the moisture limit for fungal decay. There are various data available in the literature. In the first reports authors describes moisture limits are stated to depend predominantly on the fungal species. For example, Schmidt [15] reported that the minimum MC of wood for the growth of *Fibriporia vaillantii* and *Gloeophyllum trabeum* is 30%, while slightly lower (26%) minimum MC are reported for *Coniophora puteana* and *Serpula lacrymans.* Similar values are reported in other references as well [3]. However, recent findings have shown that moisture limits for fungal growth and decay depend on the fungal species in question, and considerably differ among wood species investigated. For example, minimum MC for wood decay varied between 16.3% (*G. trabeum* in Scots pine sapwood) and 52.3% (*Donkioporia expansa* in Douglas fir) [12]. A common question is: how fast will decay occur in various wood based materials, and under what conditions (T and MC) will decay become established and cause structural damage. In buildings where moisture and temperature conditions are not precisely known and often fluctuate, and where the wood is exposed to spores of a wide variety of fungi (mold and decay) of unknown and varying quantities and viability, time for occurrence of decay is hard to be determined [3].

The aim of the present study was to determine the material climate, as defined by Brischke and co-workers [2] and Isaksson and Thelandersson [8], of wooden constructions of four different objects located in the sub-Alpine region at micro-locations with notably different micro-climates.

2. Material and methods

Monitoring was performed on four objects located in different locations with distinctive micro-climates (Fig. 1): a model house made of thermally modified wood in Mozirje (1), WWII partisan hospital Franja (2), a hayrack in Pokljuka (3), and a house in the north of Slovenia in Vrba (4). In Vrba, measurements were performed at two locations: cellar and attic. All of the objects are fairly close together from a geographical perspective. The longest distance between them is less than 100 km.

2.1. Description of the monitored objects

The model house in Mozirje (N 46.334802, E 14.961115) is a log house made of thermally modified (TM) 8 cm thick prefabricated spruce logs (*Picea abies*) (Fig. 1A). The house was constructed in 2009 for exhibition purposes by the company LogHouse (Nazarje, Slovenia). The logs are made of thermally modified wood according to the Silvapro® procedure (Silvaprodukt, Slovenia) at a T around 230 °C. The logs are not surface coated. The dimensions of the cabin are approximately 2 m × 3 m. The cabin is located in a park close to the river Savinja, approximately 340 m above sea level. Some minor parts of the cabin are made of untreated wood, which enabled a comparison between thermally modified wood and reference Norway spruce (*Picea abies*) (Table 1). The second object is a "cabin for the wounded" at the Franja partisan hospital (http://www.muzej-idrija-cerkno.si) (Fig. 1B). This hospital is situated in a remote location in Pasice gorge near Cerkno (N 46.154081, E 14.028197), approximately 600 m above sea level. Since the stream in the gorge is present in all seasons, the RH is always very high. The majority of the huts were completely renovated in 2010 after a disastrous flood in September 2007. The design of the hospital is the same as it was during WWII. It should be noted that the huts were designed as temporary shelters, and subsequently declared a cultural monument of national importance. All the huts are made primarily of Norway spruce wood (*P. abies*). Since the climatic conditions in the gorge are fairly harsh, all the Norway spruce wood was dip-treated with copper-ethanolamine based wood preservative (Cu-EA) (Silvanolin®, Silvaprodukt). The impregnation procedure was not performed correctly, so considerable decay has taken place in the most exposed wood.

The third object, a hayrack on Pokljuka (N 46.304674, E 13.984277), was built approximately 100 years ago and was used in the past for drying and storing hay and other agricultural products (Fig. 1C). The hayrack is made of larch (*Larix decidua*) and Norway spruce (*P. abies*). It is located approximately 1000 m above sea level on an alpine plateau. The last, fourth monitoring was performed in an old farmhouse in the village of Vrba (N 46.387899, E 14.147478) (Fig. 1D). The house has been declared a cultural monument, as an example of old architecture and because it was the birthplace of the Slovenian poet, France Prešeren. The house is located in a sunny exposure, approximately 500 m above sea level (Fig. 1D). In Vrba, measurements were performed in the cellar (humid, not hydro-insulated cellar) and in the attic (dry, ventilated conditions). Use classes of the wood were determined according to EN 335 [25]. All buildings were unheated.

2.2. Monitoring types and equipment

Monitoring of the microclimatic conditions at the various locations did not start at the same time, but they were performed for at least one year and the monitoring equipment and principle was the same at all locations. The durations and micro-locations of the relevant MC measurements are shown in Table 1. In addition, it should be noted that none of the objects are inhabited, although all of them are in use and are maintained. With exception of Vrba, objects are not heated. However, even in Vrba MC was monitored on unheated part of the object.

Three types of continuous monitoring were performed on all of the objects. T sensors Scanntronik (Mugrauer GmbH) were located close to the actual moisture measurement sensors in order to obtain exact values for conversion of electrical conductivity into wood MC [14]. In order to perform this conversion, all relevant wood species and treatments were conditioned at different temperatures and RH to obtain the wood with different MC. Electrical conductivity of the respective wood samples were determined. In parallel MC was determined gravimetrically as well to determine function between wood MC and electrical resistance at given temperature. These calibration curves considered the influence of impregnation applied on respective objects or thermal modification. In general, two T sensors were mounted on each object. T data were collected twice per day, at midnight and noon with Thermofox data loggers (Scanntronik Mugrauer GmbH, Germany). Most of the MC sensors were positioned 20 mm below surface, while temperature was monitored on the surface not to interfere with MC.

In addition, temperature and RH data were recorded hourly with a Thermofox hydrofox. RH and T were determined in the objects, close to the wood MC measurements. The MC was deter-

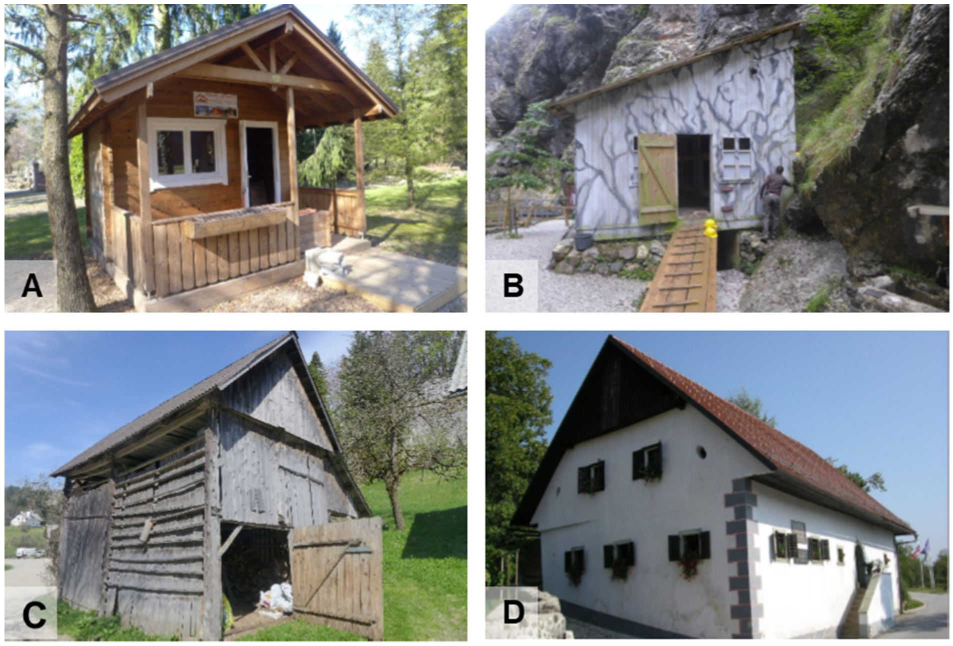

Fig. 1. Model house made of thermally modified wood in Mozirje (A), WWII partisan hospital Franja (B), hayrack on Pokljuka (C), and house in the north of Slovenia in Vrba (D).

Table 1
Descriptions of the moisture content (MC) measurement locations in the objects in which monitoring was performed. Abbreviations underlined indicate the plots displayed in Fig. 4. Use classes are defined according to EN 335 [25].

Location	Beginning	No	Material	Description	Use class
Mozirje	March 2015	M1	TM spruce	Outside wall, close to the ground.	3.1
		M2	TM spruce	Rafter, inside.	1
		M3	TM spruce	Outside wall, 1.5 m above ground.	2
		M4	Spruce	Lath, close to rafter, inside.	1
		M5	TM spruce	Rafter, outside.	2
		M6	TM spruce	Beam inside.	1
		M7	TM spruce	Beam outside.	2
		M8	Spruce	Support beam for flooring.	2
Franja	September 2014	F1	Cu-EA spruce	Cellar. The plank is covered with soil on one side.	4
		F2	Cu-EA spruce	Cellar. Wood plank; part of the ceiling/floor.	4
		F3	Cu-EA spruce	Cellar. Beam; part of the ceiling.	4
		F4	Cu-EA spruce	Cellar. The wood plank can be dried from both sides.	4
		F5	Cu-EA spruce	Pillar on 1st floor. 1.8 m above the floor. Indoor.	1
		F6	Cu-EA spruce	Pillar on 1st floor. 0.5 m above the floor. Indoor.	1
		F7	Cu-EA spruce	Façade, corner, 1.8 m above ground.	3.1
		F8	Cu-EA spruce	Above the door, part of façade.	3.2
Pokljuka	April 2016	P1	Larch	Pillar, close to the ground, 2 cm deep.	3.1
		P2	Larch	Pillar, close to the ground, 6 cm deep.	3.1
		P3	Larch	Pillar, 1.5 m above ground, 2 cm deep.	2
		P4	Larch	Pillar, 1.5 m above ground, 6 cm deep.	2
		P5	Larch	Pillar, 4 m above ground, 2 cm deep.	2
		P6	Larch	Pillar, 4 m above ground, 6 cm deep.	2
		P7	Spruce	Rafter.	2
		P8	Spruce	Beam.	2
Vrba - attic	November 2015	V1	Spruce	Plank, vertical part of the façade.	3.1
		V2	Spruce	Plank, above main entrance.	2
		V3	Spruce	Beam above entrance.	1
		V4	Spruce	Rafter 1.	1
		V5	Spruce	Rafter at the end of the house.	1
		V6	Spruce	Rafter 2.	1
		V7	Spruce	Rafter 3.	1
		V8	Spruce	Rafter 4.	1
Vrba - cellar	November 2015	C1	Spruce	Book shelf close to the floor.	2
		C2	Spruce	Book shelf 1.5 m above ground.	1

mined in parallel. In general, 8 measurements were performed on each object, with the exception of Vrba, where 10 measurements were performed. MC was determined through measurements of electrical resistance (Table 1. Insulated electrodes (stainless steel screws) were applied at various positions and depths and linked to electrical resistance measuring equipment (Gigamodule, Scanntronik Mugrauer GmbH, Germany) [23]. Method was validated with samples that were preconditioned at various RH and temperatures to achieve various target concentrations. This equipment enables accurate wood MC measurements between 6% and 60% (Fig. 3). MC was logged twice per day, at midnight and noon, at the same time as temperature. All the measuring and logging equipment was placed inside a steel box located somewhere in the object, to be protected from wetting and/or vandalism. In order to transfer electrical resistance measured inside the wood, wood species-specific resistance characteristics were developed based on the methodology described by Otten et al. [14]. Use classes of wood were determined according to EN 335 [25]. The results were periodically downloaded to a personal computer and analysed with Scanntronik software SoftFOX and MS Excel. The systems were periodically checked and batteries were replaced on the visits. In total, almost 30,000 MC, 50,000 RH and 60,000 temperature measurements were collected.

3. Results and discussion

3.1. Temperature monitoring

Temperature is one of the most important factors affecting wood's service life. Extreme temperatures can affect fungal vitality. In general, the minimum temperature for fungal growth and degradation is usually close to 0 °C, since there is no liquid water available for fungal metabolism below freezing point. The optimum temperatures for most fungi are between 20 and 30 °C. The maximum for mycelial growth and wood degradation by most wood fungi is generally between 40 and 50 °C, because protein (enzyme) denaturing by heat then takes place [15]. Considerable differences can exist among species and even between different isolates of the same species. However, when interpreting the temperature data in our research, it must be noted that the temperature was measured at one or two locations at most, although the temperature at micro-locations can differ greatly, as indicated by Gobakken et al. [5] in a case study in which wood micro-climate was monitored in Svalbard in Norway. As can be seen from Fig. 2 and Table 2, the temperature at all locations was suitable for fungal growth during most of the year, with the exception of a few winter months that were extraordinarily cold in the winter 2016/2017. The lowest difference between summer and winter temperature was determined in the cellar in Vrba, since the cellar is located underground (1,5 m bellow surface), providing fairly uniform conditions. The highest maximum summer temperature was determined in Vrba in the attic (34.8 °C) and the lowest maximum on Pokljuka (28.5 °C). Since all measuring devices were located in the attic, it can be presumed that the difference is predominantly the result of micro-location and altitude. Pokljuka is almost 600 m above the village of Vrba. In addition, this difference is predominantly the result of the sunny exposure of the house in Vrba, while the house in Mozirje is located in the shade of trees, and Franja is located in a gorge, with one hour of direct sunlight at most. The lowest minimum winter temperature was determined in Mozirje (−15.5 °C), and the highest minimum temperature was, as expected, measured in the cellar of the house in Vrba (−4.7 °C) (Table 2, Fig. 2). If temperature data are compared to other observations from the literature, it can be seen that the temperature in a building depends on the heating, ventilation etc. For example, the average temperature in a heated pool was 31.3 °C, and the average temperature of 19.4 °C was determined in the service part [10]. However, the average temperatures in the buildings, even unheated ones, was higher than outside. For example, the average outside temperature in Vrba was 10.1 °C [1], while an average temperature of 12.5 °C was determined in the attic in Vrba. In addition to extremes, optimal temperatures for fungal growth id of great interest. Table 2 shows the differences in the number/percentage of days with optimal conditions for fungal decay at the different locations. The lowest percentage of optimal temperatures was in the Cellar in Vrba, with only 2% of the measured temperatures being between 20 °C and 30 °C. The highest percentage of optimal temperatures was measured in Mozirje (18%) and in Vrba attic (20%).

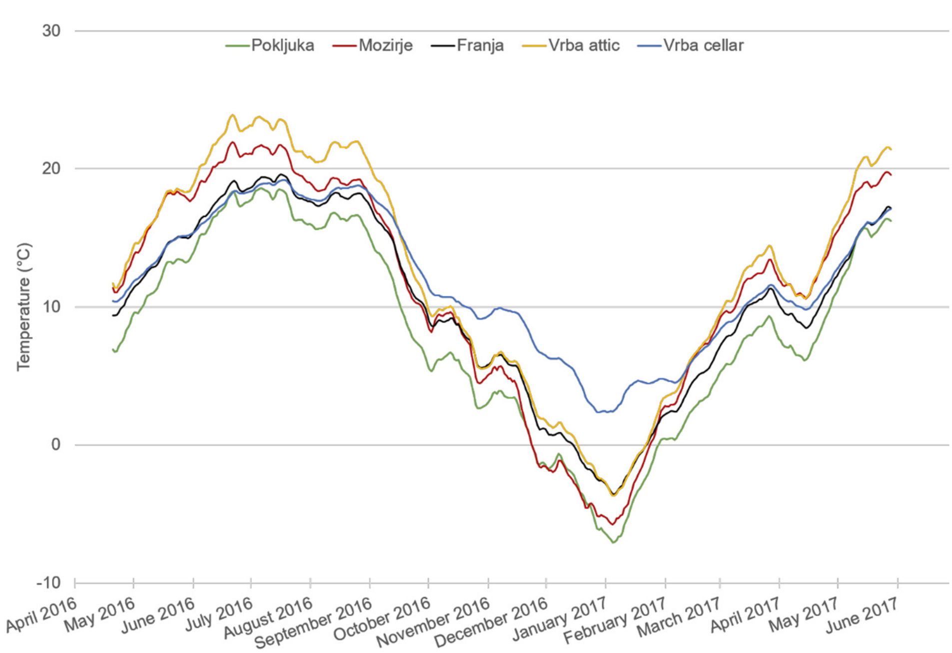

Fig. 2. Average temperature at the various objects. Curves are displayed as moving averages of 20 values. Only overlap exposure period is displayed.

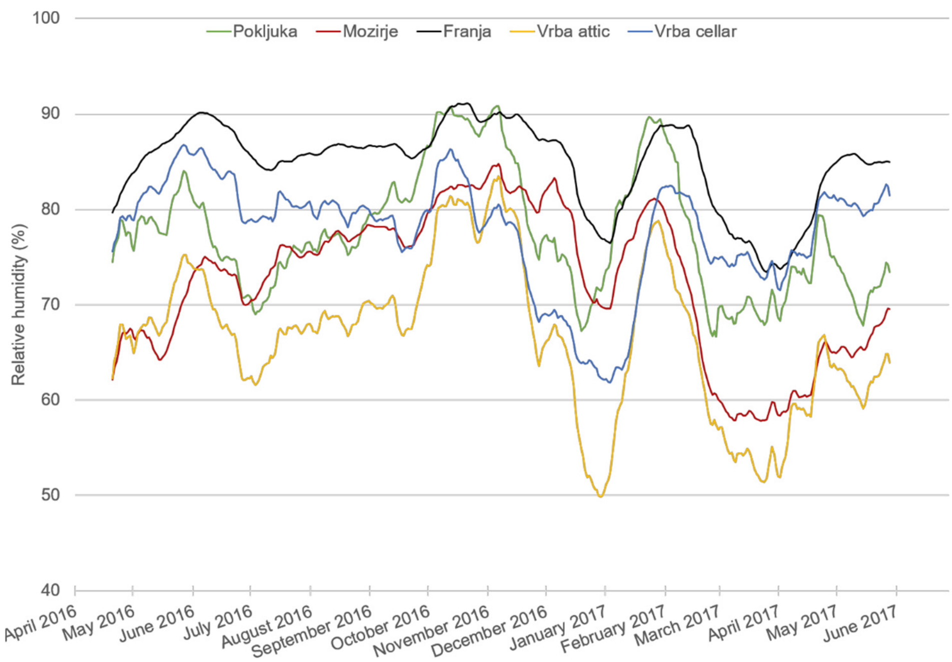

Fig. 3. Average relative humidity at the objects. Curves are displayed as moving averages of 20 values. Only overlap exposure period is displayed.

Table 2
Summarized micro-climatic conditions in the objects in which monitoring was performed for the whole period of monitoring.

	Location									
	Mozirje		Franja		Pokljuka		Vrba - attic		Vrba - cellar	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
Average	11.2	72.1	10.2	84.7	8.2	77.4	12.5	66.4	11.8	77.7
Median	12.1	74.1	10.9	86.0	8.6	81.8	12.8	68.0	11.7	80.3
Min	−15.5	32.6	−8.9	44.3	−15.4	10.0	−11.9	8.9	−4.7	39.4
Max	34.7	95.7	23.2	96.5	28.5	98.5	34.8	98.5	22.7	96.8
Percentage of days with T above 20 °C	18%		5%		8%		22%		2%	
Percentage of days with T between 20 °C and 30 °C	18%		5%		8%		20%		2%	
Percentage of days with the RH above 80%		24%		84%		55%		16%		51%

3.2. Monitoring relative humidity (RH)

RH has a considerable influence on the performance of wood. If the wood is dry, fungi cannot degrade it, in spite of optimum temperature. On wood located in conditions with high RH, the first staining fungi will occur at a RH above 80%, and degradation can also occur at even higher values of RH, above 90%. However, for severe degradation, water leakage and/or a condensing environment is required [26]. As expected, the most humid location was in Franja partisan hospital (Table 3, Fig. 4). This hospital is located in a gorge through which a stream runs. In addition, there are plenty of smaller streams nearby, and there is almost no air circulation and almost no direct sunlight. The average RH in the attic of the cabin in Franja was 84.7% (Table 2). We measured the RH in the cellar of the same cabin for a limited period. The average RH in the cellar of the cabin in Franja was 96.3% (four-month average). This was one of the factors that caused the fast degradation of the poorly treated wood in Franja. The driest location was the attic in Vrba, with an average RH of 66.4%. The low RH is a result of the high temperatures in the attic, prevention of leakage and good ventilation. On the other hand, the average RH in the cellar of Vrba was more than ten percentage points higher (77.7%) (Table 2). The RH in most residential buildings is usually lower, around 50%, predominantly because of air conditioning and a low RH in the winter months. However, Jorge and Dias [10] reported fairly high average RH in a gym hall (64.8%) and public shower-rooms (86.6%). In subtropical regions, the average RH in a house can easily exceed 80%, as described by Du et al. [4] for a house in Chongqing in central China. High RH values are usually associated with moulding and staining problems, and degradation can also subsequently occur [20,7].

3.3. Monitoring the moisture content in wood (MC)

In order to compare the MC of the wood in the monitored objects, typical curves of Norway spruce wood in use class 1 conditions are plotted in Fig. 4. None of the elements was exposed to rainfall or a condensing environment. As expected, the MC of the wood reflects the micro-climate in the particular location. The highest MC of the wood in use class 1 conditions was determined at Franja partisan hospital (average MC 18.6%), followed by that in the cellar in Vrba (average MC 18.3%). Measurements in Franja were not performed for the whole year, since the batteries did not withstand the cold and humid conditions (the area is closed to the public in the winter months). The lowest MC was determined in wood on Pokljuka. This is one of the reasons why an alpine climate enables a fairly long service life of wood in outdoor applications. The average MC of spruce wood on Pokljuka was only 11.6%. The reason for the low MC can be assigned to the sunny and well-ventilated location of the hayrack. However there are the

Table 3
Wood moisture content data in the objects in which monitoring was performed. Abbreviations are the same as for Table 1. Abbreviations in bold indicate locations at which decay was detected.

Location	No	Moisture content (%)				Percentage of measurements above threshold MC		
		Average	Median	Min	Max	20%	25%	30%
Mozirje	M1	8.9	8.7	2.6	14.7			
	M2	6.1	6.0	2.6	11.4			
	M3	6.2	6.0	2.6	11.7			
	M4	15.0	14.7	11.8	18.1			
	M5	8.9	8.3	2.6	19.5			
	M6	5.9	6.0	2.6	9.8			
	M7	9.6	8.5	2.6	22.6	1.3%		
	M8	14.9	15.0	9.5	21.8	0.4%		
Franja	**F1**	38.4	38.3	33.5	47.0	100%	100%	100%
	F2	26.3	26.8	14.5	50.9	76.1%	59.6%	27.1%
	F3	24.7	23.4	13.9	44.1	72.9%	35.1%	18.2%
	F4	31.5	30.0	19.7	45.1	99.9%	91.9%	50.6%
	F5	17.1	16.9	10.5	19.3			
	F6	18.5	18.5	17.0	20.4	0.1%		
	F7	23.4	21.4	16.9	34.3	69.2%	40.0%	3.1%
	F8	18.7	18.0	14.3	30.3	23.0%	3.5%	0.2%
Pokljuka	P1	12.7	12.2	9.9	32.9	1.4%	0.2%	0.1%
	P2	12.2	12.1	5.4	21.0	0.3%		
	P3	10.9	10.8	9.0	22.8	0.2%		
	P4	12.1	12.0	10.7	20.1	0.1%		
	P5	11.6	11.7	9.7	13.3			
	P6	12.8	12.8	11.1	14.6			
	P7	11.6	11.8	6.9	16.1			
	P8	15.3	15.3	13.6	16.8			
Vrba - attic	**V1**	14.3	13.9	9.1	36.8	5.0%	1.3%	0.4%
	V2	17.4	17.5	13.1	22.4	5.5%	0.0%	
	V3	19.3	19.4	16.2	25.1	25.8%	0.1%	
	V4	16.1	16.3	13.5	18.9			
	V5	16.9	17.0	13.7	20.0			
	V6	16.4	16.6	13.7	19.9			
	V7	16.3	16.4	13.7	19.8			
	V8	17.4	17.5	15.0	20.9	0.7%		
Vrba - cellar	C1	18.3	18.2	16.6	20.4	1.8%		
	C2	21.2	20.7	18.9	31.1	76.7%	7.1%	0.8%

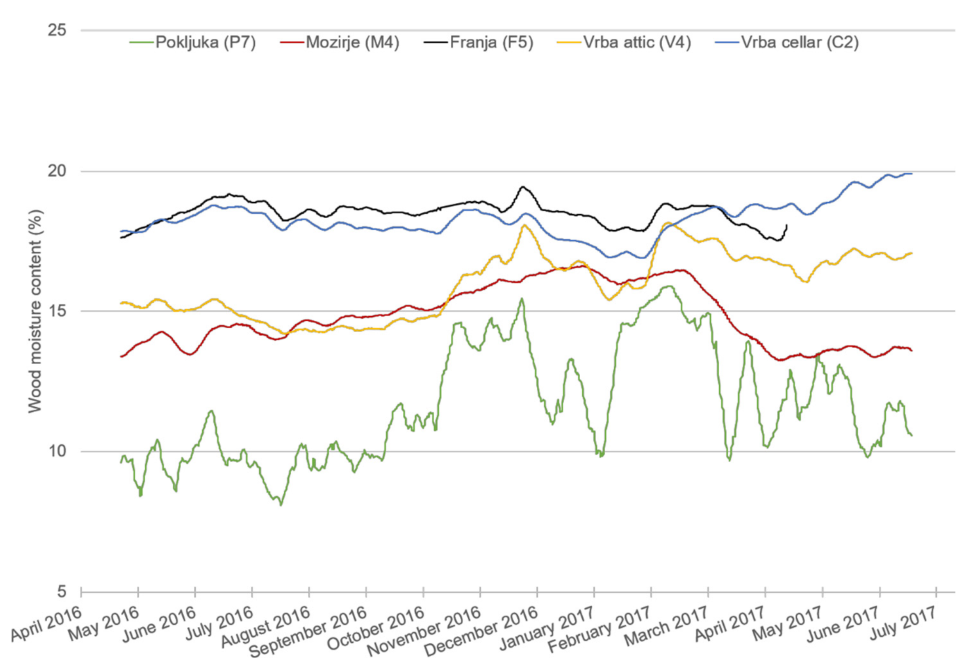

Fig. 4. Average moisture content of spruce wood at the objects. The wood was located in UC1 or UC2 exposure conditions. Curves are displayed as moving averages of 20 values. Only overlap exposure period is displayed.

most prominent MC fluctuations noticed in Pokljuka as well. We presume that there are two predominant reasons for that, assigned to good aeration and microclimate in Pokljuka. It is rather obvious that MC in Pokljuka reflects the RH fluctuations. It should be noted that hayracks were designed for drying, so their position was carefully selected. The MC in Mozirje and Vrba was fairly uniform. The average MC of the wood was 14.8% in Mozirje and 16% in Vrba. However, all reported average MCs are too low for the development of fungal degradation without an additional external source of moisture.

Aggregated data of moisture monitoring are presented in Table 3. In addition to average data, there is the percentage of days that exceeded the particular limit reported. These measurements were performed 2 cm below the surface, so the surface moisture might be even higher. Different thresholds were taken into account. In general, a 25% threshold limit was considered to be the MC required for fungal decay on untreated wood. The days when this threshold was increased are considered to be wet days [2]. However, the threshold limit is not the same for all materials.

For thermally modified wood, in which the sorption characteristics are changed, the threshold MC is positioned much lower [12], usually down to 20%. The cabin in Mozirje was made almost completely of thermally modified wood. It can clearly be seen from the data presented in Table 3 that the MC of thermally modified wood is much lower than that of untreated wood [24,16]. For example, the average MC of the rafter in use class 2 conditions (M5) was 8.9%, while the average MC of untreated spruce wood (M4) in use class 1 application reaches 15.0%. Similar ratios can be observed at other measurement locations. Even the log made of thermally modified wood that was located quite close to the ground (use class 3.1), and was consequently exposed to splash water, had a MC below 15% all of the time (Table 3). This is a clear consequence of the better sorption properties of thermally modified wood [21]. The low MC of the wood in Mozirje is a consequence of thermal modification and the good construction of the cabin. No signs of decay can therefore be determined on the log house after 8 years. Decay was assessed visually with knife picking based on the EN 252 principle [27].

In contrast, severe decay was found in Franja partisan hospital, mainly in the cellar. In addition to the high RH in the cellar, and abundance of water, the main cause of the decay is insufficient preservative treatment. MC measurements were performed at various locations within the hut. As it can be seen from Table 3, the MC of the wood was fairly high. At five out of the eight measurement locations, the MC was above 25% for at least 35% of the monitoring time. It should be noted that, with the exception of sensor F1, the majority of the wood was not in ground contact. The high MCs are the result of the high RH and water condensation. The MC of the planks on the wall (F1 and F4) of the cellar, were higher than 20% all the time. Their MCs were even higher than 25% for 90% of the time. This clearly indicates that the wood must be properly impregnated in order to achieve a sufficient level of protection. Even the MC of the façade was fairly high. It should be considered, although the sensors were mounted from the outer side, the MC measurements takes place in the central part of the planks. Hence we believe, that actual positioning of the sensors do not influence the results. The average MC of the façade (F7) was 23.4%. The façade faces the hillside and is never exposed to sunlight. The wood therefore takes a long time to dry out. In contrast, the wood that acts as a shelter above the door (F8) has most of the surfaces exposed to air, which enables faster drying. Even the wood inside the hut exhibited fairly high MC, considering that this wood is not exposed to rain. The average MC of the indoor wood was 17.1% (F5) and 18.5% (F6). The higher MC was measured in the lower part of the pillar. This MC is too low for fungal development but clearly indicates RH (Table 2). However, it should be noted that this MC is high enough for fungal decay to spread from the cellar to the upper floor [12].

The wood in the hayrack on Pokljuka had the lowest MC among all the monitored objects, with the exception of the cabin in Mozirje, which was made of thermally modified wood. The hayrack was well designed in terms of construction details, so there was no decay on the monitored parts. Particular attention in the MC monitoring was paid to the MC of the pillar. The pillar was made of larch wood and is positioned on a stone foundation. The MC was measured at three levels, close to the ground, in the middle and on the top of the pillar, where the roof overhang completely protects it from rainfall. At every location, MC measurements were taken at two depths, 2 cm beneath the surface (standard) and 6 cm beneath the surface. As expected, the highest MC was determined in the part of the pillar that was in contact with the stone foundation (P1). The highest MC at this location, 2 cm deep (P1) was 32.9%, while a considerably lower MC was determined at a depth of 6 cm (P2, 21.0%). However, the average MC in the pillar was fairly comparable, regardless of the location. The average MC at 6 cm ranged between 12.1% (P4) and 12.8% (P6). These data indicate the good moisture performance of larch wood [13]. The moisture performance of spruce wood is not as good as of larch wood, which is evident from the average MC of the spruce beam (P8, 15.3%) (Table 3). However, the overall MC of the wood in the hayrack on Pokljuka was fairly low, with only a few measurements exceeding the 25% threshold. These data prove the good building practice applied in the past and the mild climate for wood on Pokljuka. The combination of these two factors results in long lasting wooden objects.

In Vrba, moisture measurements were performed at two extreme locations: in the attic and in the cellar. As can be expected from the RH measurements, the average MC in the cellar was much higher than in the attic. The measurements were performed on a wooden cupboard. The part that was closer to the ground (C1) absorbs more water from the wet flooring, which reflected in the higher MC (average MC 21.2%), which was sufficient for the development of the first signs of decay. The upper part of the cupboard (C2) was dryer (average MC 18.3%), as is evident from Table 3. As already stated, the MC in the attic was lower than that in the cellar. However, there was quite a high variation determined in the attic. Two weak points were identified One was the planks on the façade (V1), which are exposed to wind driven rain. This moisturizing source provides enough water to enable decay to develop in water traps. Another weak point was found on the wooden beam (V3, average MC 19.3%) and plank (V2, average MC 17.4%) above the entrance. The MC at these locations was considerably higher than at the other locations in the attic (V4, V5, V6, and V7). Predominantly in the winter months, hot air from the heated interior exits the half-closed doors and then water vapour condenses on the cold wooden elements. Similar observation is reported in the past already [3]. Water in the interior originates from visitors, open fire and insufficient insulation. Fortunately, the MC never increases above the threshold limit of 25%. With the exception of planks on the façade (P1) that were exposed to wind driven rain, the MC never exceeded the threshold values. This indicates that the roofing is well enough designed and maintained. In addition, wind driven rain can cause brown rot degradation during long term exposure if there are water traps present.

The literature data states a critical period of around 325 days with favourable conditions for fungal decay [9]. This means that the first visible signs of decay develop after approximately 325 days during which the MC exceeds 25%, and the temperature enables fungal growth. In the cellar in Vrba, there were only 7% (23 days/year) of measurements that exceeded this limit. However, it must be remembered that the wood in the cellar had been in position for years, so although the percentage of wet days was fairly low, they accumulate in the long term. Our data confirm this theory. In material in which the MC did not exceed the 20% limit, decay was not found.

4. Conclusions

Moisture monitoring is a very useful method for evaluating different microclimatic environment in monitored buildings. There were quite significant variations among the different microclimates and material climates determined over a fairly short distance. However, it should be noted that only one location of moisture monitoring is not sufficient for overall assessment of a building. In order to obtain even more reliable data, monitoring at these objects will be continued.

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