Climate Change Impacts on Heritage Timber Structures

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Foreword

The preservation of our cultural and historical heritage is a responsibility that transcends generations. As I embarked on my doctoral journey, I found myself drawn to a topic of pressing significance: the impact of climate change on our environment. Therefore, the topic of this thesis emerged from a confluence of personal and academic considerations, each reinforcing the urgency and relevance of the subject.

In recent years, climate change has emerged as one of the most significant challenges facing our planet. Its far-reaching consequences extend beyond the realms of the natural environment, affecting various facets of human life, including the integrity of our architectural heritage. Timber structures, with their timeless beauty and historical significance, are particularly vulnerable to the evolving climate patterns that characterize the contemporary era.

Having completed my master's studies, I felt a profound desire to delve deeper into a field where science and heritage preservation intersect. Timber, a material deeply embedded in our architectural history, presented itself as a poignant focal point. My motivation was not only driven by academic curiosity to understand the intricacies of how climate impacts timber structures but also by a sense of duty to contribute meaningful insights to the ongoing discourse on heritage conservation in the face of climate change. I also found that interest and scientific research in wooden elements in the construction and architectural design process is constantly increasing. For example, by searching for the expression "wood in architecture" on the Web of Science, the largest search platform for scientific literature, the number of scientific journal articles has increased from a few tens per year to over eight hundred per year in the past twenty years. The same growth trend is observed when searching for the expression "wood and green architecture": we have gone from a few published publications to more than 150 publications per year.

The scope of this research is both comprehensive and targeted. It seeks to unravel the multifaceted ways in which climate variables, ranging from temperature and relative humidity fluctuations to extreme weather events, interact with timber structures. Through meticulous analysis and experimentation, the study aims to provide a nuanced understanding of the vulnerabilities inherent in these heritage treasures.

The results of this endeavour promise to be far-reaching. By elucidating the climate-induced stresses on timber heritage structures, we not only enhance our theoretical understanding but also lay the groundwork for informed conservation strategies. It is my hope that this research contributes to the development of sustainable practices that can safeguard these cultural artefacts for future generations.

As we navigate an era defined by the imperative of environmental stewardship, this thesis stands as a testament to the interplay between scientific inquiry, cultural preservation, and the imperative of addressing the challenges posed by a changing climate.

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1. Introduction

1.1. Background

Climate change impacts are being felt at an increasing level all over the world. In the last thirty-forty years climate change has become an important problem with severe social and economic impacts. Various research groups are committed to find the causes and alleviate the consequences of the high-impact weather events. The present research joins this challenge and sets as a goal to perform a study in the field of preserving timber heritage structures from climate change impacts.

Climate change leads to significant impacts on heritage wooden structures, posing new challenges to their preservation and management. These impacts are expected to become more severe in the coming decades. The changing climate exposes cultural heritage to diverse pressures and risks that were not previously experienced. The impacts of climate change on wooden structures can lead to deterioration, damage, and degradation.

The vulnerability of heritage wooden structures to climate change is influenced by various factors, including temperature, humidity, precipitation, and extreme weather events. This research addresses the pressing issue of climate change, focusing on its implications for Hungary, and providing a comprehensive analysis of how these changes affect both indoor and outdoor wooden structures. By investigating the complex interplay between environmental factors and wood characteristics, this study offers insights into the intricate relationship between climate shifts and material behaviour, contributing to a deeper understanding of the broader implications of climate change on our built environment. It conducts an in-depth examination of its multifaceted impact on two distinct wooden structures: an indoor construction and an outdoor installation. Furthermore, it examines the alterations observed in the softwood properties when exposed to varying humidity levels within semi-controlled laboratory settings.

1.2. Research questions

During the theoretical study and the research work, the need to answer several specific research questions related to the climate and climate change appeared:

- What are the microclimate peculiarities of Hungary compared to Central-Europe, and how the climate change affects the characteristics of this microclimate?
- How to relate the climatic history of the region to how wood elements interact with climate changes?
- What are the most important climate factors affecting the deterioration of wooden elements?
- What techniques and methods monitor and calculate the value of current climate variables, and how to assess the current state of the structure?
- How does climate change affect the physical and mechanical properties of wood elements?
- How does climate change affect the fracture behaviour of the wooden elements?

- How the continuous monitoring and periodic maintenance, can have a positive impact on the structure?

1.3. Principal objectives and scope

The main objectives of the present research were:

- Investigate the relationship between climate components (e.g., temperature, humidity, precipitation) and their impact on heritage timber structures;
- Analyse historical meteorological data for identifying climate change trends and their potential influence on timber element behaviour and structural integrity;
- Study the reaction of heritage timber structures to various climate components and assess their vulnerability to climate-induced stressors;
- Examine the physical and mechanical properties of wood through laboratory testing under controlled climate conditions, simulating projected climate change scenarios;
- Assess the long-term implications of climate change on the durability, stability, and preservation needs of heritage timber structures.

Thus, the methodology can be summarized in the following points:

Meteorological data analysis:

- Collect and analyse historical meteorological data from different geographical regions;
- Identify the key climate components relevant to the study;
- Compare and evaluate the climate trends over a specific period to discern patterns and variations.

Effect of climate components on timber elements:

- Conduct field investigations of selected heritage timber structures to evaluate their current condition and exposure to climate elements;
- Monitor and measure the reactions of timber elements to varying climatic conditions;
- Identify the factors contributing to timber degradation and damage in different climates.

Laboratory testing:

- Selection of representative wood species commonly used in heritage timber structures;
- Conduct controlled laboratory tests to assess the impact of climate-induced stressors on wood properties (e.g., moisture content (MC), cracks and failures, mechanical strength);
- Analyse the results to determine how wood properties change under different climate scenarios.

Preservation and adaptation strategies:

- Assess existing preservation techniques and study their effectiveness in mitigating climate change impacts on heritage timber structures;
- Develop recommendations for adaptive preservation strategies based on the research findings.

Limitations:

- The study focuses on heritage timber structures in specific geographical regions and may not cover all possible variations in climate conditions;
- In the absence of a climate chamber, standardized laboratory conditions could not be produced directly, however the results were translated to standard conditions. Therefore, the conclusions are not generalized, but valid for the used conditions, described in the Chapters of the Thesis.

2. Literature review

2.1. Timber, as building material

Despite being one of the oldest and most basic building materials available all over the world, its usage decreased because of the advent of modern construction materials and technologies, which offered enhanced structural performance and durability. The decline in the usage of traditional building materials like timber is attributed to the rise of modern construction materials and technologies. Innovations such as high-strength concrete, structural steel, and advanced composites provide enhanced durability, flexibility, and efficiency in construction. In recent years, there has been a resurgence in the usage of timber in construction due to its environmentally friendly properties, as it is a renewable resource with a lower carbon footprint compared to some traditional materials. Additionally, advancements in engineered wood products and construction technologies have enhanced the strength and versatility of timber, making it an attractive and sustainable choice for architects and builders [Chen et al., 2017, Kherais et al., 2020, Mofolasayo et al., 2022]. Construction industry is frequently in the fore-front of helping to solve problems that the world faces today, significant challenges in the future, such as housing shortages, climate change, and personal well-being. Timber can be used in both, light and heavy construction works, in form of columns, trusses, joints, and studs, or roofs, bridges, formwork, or even high-rise buildings [Chen et al., 2017, Kherais et al., 2020, Stepinac et al., 2020]. The use of timber as a construction material has entered a period of renaissance with the development of high-performance engineered wood products, such as cross-laminated timber, which enable the construction of larger and taller buildings [Chen et al., 2017, Stepinac et al., 2020]. Timber structures are generally associated with lower levels of embodied carbon compared to non-wood alternatives, such as concrete and steel [Linkevičius et al., 2023, Said, 2018]. Additionally, timber is a renewable resource that can be recycled and has a lighter carbon footprint than other construction materials [Linkevičius et al., 2023, Said, 2018].

Advancements in engineered wood products and construction technologies [Chen et al., 2017, Kherais et al., 2020, Mofolasayo et al., 2022] have enhanced the strength and versatility of timber, rendering it an appealing and sustainable choice for architects and builders. The construction industry, often at the forefront of addressing contemporary and future challenges like housing shortages, climate change, and personal well-being, finds timber suitable for both light and heavy construction works, encompassing applications from columns, trusses, joints, and studs to roofs, bridges, formwork, and even high-rise buildings [Chen et al., 2017, Kherais et al., 2020, Stepinac et al., 2020].

This renaissance of timber in construction is attributed to the development of high-performance engineered wood products, including cross-laminated timber, facilitating the construction of larger and taller buildings [Chen et al., 2017, Stepinac et al., 2020]. Timber structures, in comparison to non-wood alternatives like concrete and steel, generally entail lower levels of embodied carbon [Linkevičius et al., 2023, Said, 2018]. Furthermore, as a renewable resource that can be recycled, timber boasts a lighter carbon footprint than other construction materials [Linkevičius et al., 2023, Said, 2018]. Timber can also be used as a thermal protection material. Thin walls with great insulation factor values may be achieved by timber frames, thanks to the insulation sandwiched between the studs. Thin, lightweight cladding alternatives allow for increasingly thinner walls to be built while still achieving desired thermal efficiency. Thinner walls and floor spaces are further benefits, as they use less materials, and hence they have lower costs. The timber frame has traditionally provided excellent air tightness as well, thanks to the vapour control layer that is also an air barrier and it is affixed to the inner face of the wall [Rüdisser et al., 2018].

One of the main advantages of timber in seismic zones is its light weight, which attracts smaller seismic loads compared to concrete or steel structures of the same size and complexity. The light weight of timber also results in smaller inertial forces during seismic events [Odikamnoro et al., 2022]. Another advantage of timber in seismic regions is its ductility. Timber structures have the ability to deform and absorb energy during seismic events, which helps to dissipate seismic forces and reduce the risk of collapse. This ductility is crucial for structures in seismic zones as it allows them to withstand the dynamic forces generated by earthquakes [Andreolli et al., 2011, Gohlich et al., 2018]. Timber structures can also be designed with dissipative systems, such as braces or connections that further enhance their seismic performance [Cesare et al., 2020].

2.2. Characteristics of timber, as construction material

Timber possesses inherent qualities that render it a viable and advantageous choice for various applications. The material's historical utilization underscores its enduring significance in the realm of construction. Several important qualities of timber will be discussed in the following paragraphs.

Sustainability

Timber is considered one of the most sustainable and renewable construction materials [Ramage et al., 2017]. It has a lower environmental impact compared to other construction materials [Buka-Vaivade et al., 2022]. The lifespan of timber used in construction typically exceeds the time taken to grow the raw material, making it genuinely sustainable [Ramage et al., 2017]. Timber also has the potential to sequester carbon, contributing to the reduction of greenhouse gas emissions [Seidl et al., 2007]. It is a renewable resource that can store CO_2, making it an important material for sustainable construction [Ramage et al., 2017].

Strength

Timber has high flexural strength combined with low weight, which gives it a significant advantage over other construction materials [Stepinac et al., 2020]. With the development of high-performance engineered wood products, timber can now be used in larger and taller buildings, demonstrating its increasing usefulness as a construction material [Ilgın & Karjalainen, 2023]. Timber buildings are also recognized as robust alternatives to heavyweight constructions, especially in seismic areas [Sandoli et al., 2021].

Lightweight

Timber is a lightweight construction material, which makes it easier to handle and transport during construction [Thomas & Ding, 2018]. Its low weight also contributes to reducing the energy needed for construction, maintenance, and demolition compared to conventional methods and materials [Thomas & Ding, 2018]. However, the inherent lower bulk density of timber can lead to higher impact sound transmission in wooden ceiling constructions [Müller et al., 2021].

Thermal Insulation

Timber has natural thermal insulation properties, which can contribute to energy efficiency in buildings. It helps to regulate indoor temperatures, reducing the need for heating and cooling systems and resulting in reduced energy consumption [Thomas & Ding, 2018]. However, the specific acoustic performance of timber constructions, particularly in terms of impact sound transmission, can be a challenge due to the lower bulk density of the material [Müller et al., 2021].

Aesthetic Appeal

Timber is known for its natural beauty and aesthetic appeal, which can enhance the visual appeal of buildings. It provides warmth and a sense of connection to nature, creating a pleasant and inviting atmosphere [Ernur et al., 2022]. Timber can be used in various architectural typologies, offering a wide range of design possibilities [Svatoš-Ražnjević et al., 2022]. Its use in multi-storey residential buildings has been found to be suitable even in urban contexts [Lattke & Lehmann, 2007].

Workability

Timber is highly workable, allowing for ease of construction and customization [Ernur et al., 2022]. It can be easily cut, shaped, and joined using various techniques, such as mortise-and-tenon joinery. The mechanical analysis of joinery has shown the potential for more sustainable structural connections in timber construction [Fang & Mueller, 2021]. The use of computational tools has further enhanced the workability of timber, enabling non-standard architecture and innovative designs.

Versatility

Timber is a construction material that can be used in various applications, from residential buildings to bridges [Goremikins et al., 2017]. It can be used in different forms, such as solid timber, laminated veneer lumber, and cross-laminated timber [Tulonen et al., 2022]. Timber can also be combined with other materials, such as concrete, to create composite structures [Goremikins et al., 2017]. Its versatility allows for flexibility in design and construction.

Durability

Timber can have excellent durability when properly treated and maintained. It can resist decay, insect infestation, and weathering with the use of preservatives and protective coatings. However, timber's durability can be affected by factors such as moisture content, exposure to extreme conditions, and the presence of fungi or insects. Proper design, construction, and maintenance practices are essential to ensure the long-term durability of timber structures [Ramage et al., 2017].

Fire Resistance

Timber has inherent fire resistance properties due to its charring effect, which forms an insulating layer that protects the inner core of the material. However, the fire resistance of timber can be enhanced through the use of fire-retardant treatments and the incorporation of fire-resistant design features. Fire safety regulations and standards should be followed to ensure the safe use of timber in construction [Ramage et al., 2017].

Cost-Effectiveness

Timber is often considered a cost-effective construction material. It is readily available and can be locally sourced, reducing transportation costs. The lightweight nature of timber also contributes to cost savings in terms of handling and installation. However, the cost-effectiveness of timber can vary depending on factors such as the type of timber used, the complexity of the design, and the availability of skilled labor [Buka-Vaivade et al., 2022].

Local Availability

Timber is a construction material that in most of the cases can be locally sourced, reducing the environmental impact associated with transportation. It promotes the use of local resources and supports local economies. However, the availability of timber can vary depending on geographical location and forest management practices. Sustainable forest management is crucial to ensure the long-term availability of timber resources [Buka-Vaivade et al., 2022].

Reduced Energy Consumption

Timber‘s natural thermal insulation properties help regulating indoor temperatures, reducing the need for heating and cooling systems. The lightweight nature of timber also reduces the energy required for construction, maintenance, and demolition compared to conventional materials. This can result in significant energy savings over the life cycle of a building [Thomas & Ding, 2018].

Carbon Sequestration

Timber has the unique ability to sequester carbon dioxide from the atmosphere, contributing to the reduction of greenhouse gas emissions. Trees absorb carbon dioxide during their growth, and this carbon is stored in the timber used in construction. The use of timber in buildings can therefore help mitigate climate change by acting as a carbon sink. Sustainable forest management practices are essential to ensure the continuous sequestration of carbon in timber resources [Seidl et al., 2007].

2.3. Classification

2.3.1. Classification of trees

Softwood and hardwood are two categories of wood that differ in their botanical origins, physical characteristics, and applications in construction.

Softwood refers to wood that comes from gymnosperm trees, which are typically coniferous trees such as pine, spruce, fir, and cedar. Softwood is characterized by relatively low-density range from 300 to 600 kg/m³, straight grain, and lack of pores or vessels [Notley & Norgren, 2010]. It is generally easier to work with due to its lower density and tendency to have lighter colour. Softwood is also known for its high strength-to-weight ratio, making it suitable for structural applications in construction [Martins et al., 2023]. It is commonly used for framing, decking, and other load-bearing purposes in residential and commercial buildings.

Hardwood comes from angiosperm trees, which are typically deciduous trees such as oak, maple, mahogany, and cherry. Hardwood is characterized by its higher density range from 600 to 800 kg/m³, complex grain patterns, and presence of vessels or pores [Notley & Norgren, 2010]. It is generally harder and more durable than softwood, making it suitable for applications that require strength and resistance to wear and tear. Hardwood is commonly used for flooring, cabinetry, furniture, and decorative elements in construction.

The main difference between softwood and hardwood lies in their cellular structure. Softwood has long, thin cells called tracheids, which provide structural support and transport water and nutrients throughout the tree [Mertens et al., 2017]. Hardwood, on the other hand, has a more complex cellular structure with various types of cells, including vessels that transport water and nutrients [Mertens et al., 2017]. This difference in cellular structure contributes to the physical characteristics and properties of each type of wood.

In terms of availability, softwood is more abundant and widely available compared to hardwoods. Softwood trees grow faster and can be harvested at a younger age, making them a more sustainable and cost-effective choice for construction materials [Ganguly et al., 2020]. Hardwood, on the other hand, takes longer to grow and is often harvested from older trees, which makes them less readily available and more expensive.

In construction, the choice between softwood and hardwood often depends on the specific application. Softwood is commonly used for structural components due to their strength to weight ratio and cost-effectiveness. Hardwoods, with their durability and aesthetic appeal, are preferred for finished products and decorative elements.

2.3.2. Classification of timber

There are various standards by which timber can be classified, like structural grading, and durability.

Structural grading

The timber classification in Europe based on structural grading involves the use of different grading methods and standards. The European strength classes are commonly used for grading structural timber [Ridley-Ellis et al. 2016, Rello et al., 2022, Muñoz et al., 2011]. These strength classes are defined in standards such as EN 338 and EN 1912 [European Committee for Standardization, 2009, European Committee for Standardization, 2012]. The grading methods include visual grading, machine grading, and a combination of both [Kotlarewski et al., 2018, Brunetti et al., 2015, Stapel & Kuilen, 2013]. Visual grading involves assessing the appearance and characteristics of timber, such as knots and defects, to determine its strength grade [Kotlarewski et al., 2018, Brunetti et al., 2015]. Machine grading utilizes non-destructive testing methods, such as ultrasound and induced vibrations, to assess the mechanical properties of timber [Casado et al., 2012]. The combination of visual and machine grading methods can provide more accurate and reliable results [Muñoz et al., 2011].

Durability

EN 350-1 classify timber into different durability classes based on its natural durability against biological decay agents [European Committee for Standardization, 2016].

The durability classes specified in EN 350-1 are as follows:

- Class 1 (Very Durable): Wood with a high natural durability, resistant to decay even under conditions of high risk. Examples include tropical hardwoods like Teak.
- Class 2 (Durable): Wood with a moderate natural durability, resistant to decay under conditions of moderate risk. Many common hardwoods and some softwoods fall into this category.
- Class 3 (Moderately Durable): Wood with low to moderate natural durability, resistant to decay under low-risk conditions. This class includes many softwoods and some hardwoods.
- Class 4 (Not Durable): Wood with minimal natural durability, susceptible to decay under all conditions. This class may require preservative treatment for use in outdoor applications.

The classification is based on the performance of wood without any additional protective measures, such as chemical treatments or coatings. It provides valuable information for selecting appropriate wood species for specific end uses, particularly in outdoor applications where wood is exposed to weather and environmental conditions.

2.4. Environmental impact on timber

Timber is considered a natural material that has a direct interaction with the environment and climate conditions. Thus, climate change induced degradation can have severe impact on the main structure, reduce canopy cover, increase vulnerability to pests and diseases, and altere timber quality [Ghosh et al., 2016, Guo et al., 2010, Mitchell et al., 2017]. These impacts can lead to long-term reductions in timber biomass and overall structure. The main forms of degradation that can be observed on the timber buildings are the biological attacks represented by fungi growth or insect attack (see Figure 1 and Figure 2), splits and cracks, and colour changes [Björngrim et al., 2016, Kherais et al., 2020, Kherais et al., (2022b), Pretzsch et al., 2018, Wang et al., 2018]. The increase in temperature and the amount of precipitation are the principal causative agents of the broad and serious damage, in certain circumstances, to the historically constructed surroundings [Choidis et al., 2021, Kherais et al., 2020, Kherais et al., (2022b), Teodorescu et al., 2017].

Rapid temperature shifts and variations in moisture content (MC) are two common causes of wood damage [Kherais et al., (2022a), Kherais et al., (2022b), Jockwer et al., 2021, Teodorescu et al., 2017]. Local factors might be counted for low or high MC throughout a certain time period, but climate variables and changes have a growing impact. Even before the timber is integrated as a construction element, changes in the moisture content of wood products can induce shrinkage, swelling, and fluctuations in strength and elasticity qualities. For instance, the cross-sectional area, moment of inertia, and structural modulus of a part all decrease due to shrinking [Kherais et al., (2022a), Kherais et al., (2022c), Rhême et al., 2013, Tukiainen et al., 2016].

Figure 1. Fungai decay on timber column [The Constructor, 2021]

Figure 2. Beetles defects in timber [The Constructor, 2021]

Because it strives for a balance with its humid environment, wood is characterized as a hygroscopic substance. When timber is subjected to changes in temperature and humidity, dynamic moisture equilibrium can cause the wood to twist and distort [Kherais et al., (2022a), Kherais et al., (2022c), Kijidani et al., 2019, Shirmohammadi et al., 2021].

The dynamic behaviour of timber's moisture content aims to attain the equivalent moisture content (EMC). EMC, a critical parameter, characterises the moisture content of wood in equilibrium with its surrounding environment, signifyingthe point at which the wood neither gains nor loses moisture, achieving a stable state. This equilibrium is crucial for ensuring the stability and performance of timber in various applications, such as construction and furniture [Forest Products Laboratory, 2010, Quartey et al., 2022].

The EMC is expressed as a percentage and is influenced by factors such as temperature, relative humidity, and the type of wood species. Different wood species show varying equilibrium moisture content levels due to their unique cellular structures and moisture-absorbing characteristics. For accurate measurements, it is essential to consider the specific conditions under which the timber will be used, as well as the local climate.

Wood is classified according to its moisture content, which has a significant impact on the durability of the wood part [CEN, 2006, Shirmohammadi et al., 2021]. Proper design considerations, such as allowing for natural movement and implementing moisture control measures, are crucial to minimize the impact of climate-induced moisture changes on timber structures [Choidis et al., 2021, Zubizarreta-Gerendiain et al., 2017].

Damages of wooden structures due to environmental impact can be categorized into three main categories. Physical damage, chemical damage, and biological damage [Reinprecht, 2016, Ridout, 2019].

Physical damage refers to the structural deterioration of wooden structures caused by environmental factors such as weathering, moisture, temperature fluctuations, and internal stresses. These factors can lead to the degradation of wood fibres, warping, cracking, and decay [Almusaed et al., 2021]. Physical damage can also occur due to natural disasters such as storms, floods, and earthquakes, which can cause severe structural damage to wooden buildings [Ologunorisa et al., 2021].

Chemical damage refers to the degradation of wood caused by exposure to chemicals in the environment. This can include exposure to pollutants, acids, alkalis, and corrosive substances. Chemical damage can lead to the deterioration of wood fibres, discoloration, and loss of strength [Ali et al., 2024].

Biological damage refers to the degradation of wood caused by biological organisms such as fungi, bacteria, insects, and marine borers. These organisms can feed on wood, causing decay, rot, and infestation. Biological damage can significantly reduce the structural integrity and lifespan of wooden structures [Vilčeková et al., 2020].

These classifications categorize damages into exterior and interior damages. **Exterior damages** refer to the deterioration and degradation of wooden structures that occur on the outer surfaces exposed to the environment. This can include weathering, discoloration, and surface decay. **Interior damages**, on the other hand, occur within the internal components of wooden structures and can be caused by factors such as moisture infiltration, condensation, and inadequate ventilation [Reinprecht, 2016, Ridout, 2019].

Also, these classifications can be referred to the time scale of the damage. This classification categorizes damages into immediate and long-term damages. **Immediate damages** refer to the immediate and visible effects of environmental impact on wooden structures, such as physical deterioration or discoloration. **Long-term damages**, on the other hand, refer to the cumulative effects of environmental impact over time, which can lead to structural degradation, loss of strength, and reduced lifespan of wooden structures [Reinprecht, 2016, Ridout, 2019].

2.5. Timber in architectural usage and heritage buildings

Timber in construction has a long and convoluted history. Timber has been used for construction for over 10,000 years, and its flexibility and natural origin makes it one of the most popular building materials for construction of all size levels. The history of the timber stretches back to the Roman era [Woods, 2017]. Ancient Roman and Egyptian civilizations utilized timber in their architecture and buildings. Timber was commonly used in the construction of roofs, columns, floors, and interior elements of buildings [Li et al., 2017]. During the Saxon era, timber cladding was also widely used. In the ninth century, when the remarkable ability was required to create anything out of timber, builders invented timber framing. The medieval ages saw the rise of timber framing, a construction method characterized by timber posts and beams forming the skeleton of buildings. This technique enabled the construction of large halls, churches, and cathedrals across Europe, with prominent examples like Westminster Hall in London and the Notre-Dame Cathedral in Paris [Courtenay et al., 1987, Savolainen et al., 2023]. However, the Neolithic longhouse is the real beginning of wooden construction in Europe, constructed from logs, in circa 6000 B.C. Neolithic longhouse is a remarkable illustration of the extraordinary constructions that can be made from wood (see Figure 3). It is a sturdy and impressive structure, and it was one of the most notable structures of its day. Because of its spaciousness, thirty people could fit inside. Wood hasn't been replaced by anything, not even the discovery of bronze and then steel [Woods, 2017, Bradley, 2001, Pásztor et al., 2015, Savolainen et al., 2023].

Figure 3. Europe's Neolithic timber long house [Bradley, 2001]

Wooden architecture had a special place in the long history of art in Europe and Russia. Today, the vast regions of southern Norway, the Russian Far East, the Czech Republic, Poland, and England where magnificent timber structures still stand are regarded as unique architectural reserves. Some wooden churches, including the Urnes Stave Church and the Wooden Churches of the Slovak part of the Carpathian Mountain Area (see Figure 4 and Figure 5), are listed by UNESCO as world heritage sites [Khodakovsky et al., 2015].

Figure 4. Urnes Stave Church in Sogn, Norway [UNESCO, 2015]

Figure 5. Kizhi Pogost (1694–1874), Republic of Karelia, Russia [UNESCO, 2008]

In modern design engineers and architects use timber to construct roofs, houses, and bridges, because they understood that wood is a cost-efficient, environmentally friendly, appealing, and long-lasting material. During the first decade of the twenty-first century, performance-based building rules have had a freeing effect, reviving interest in the construction of tall wood buildings. At nine stories, London's Murray Grove Tower (see Figure 6) is the world's highest wood structure. Panels of solid cross-laminated wood are being used in its construction. The fire safety design is top-notch because it prevents fire from spreading via hidden spaces in the building's walls and flooring. Anticipate seeing more "brownfield site" (redeveloped urban land) development in the future, as the motivation for employing timber in tall construction is more than just an architectural trend [Smith et al., 2018].

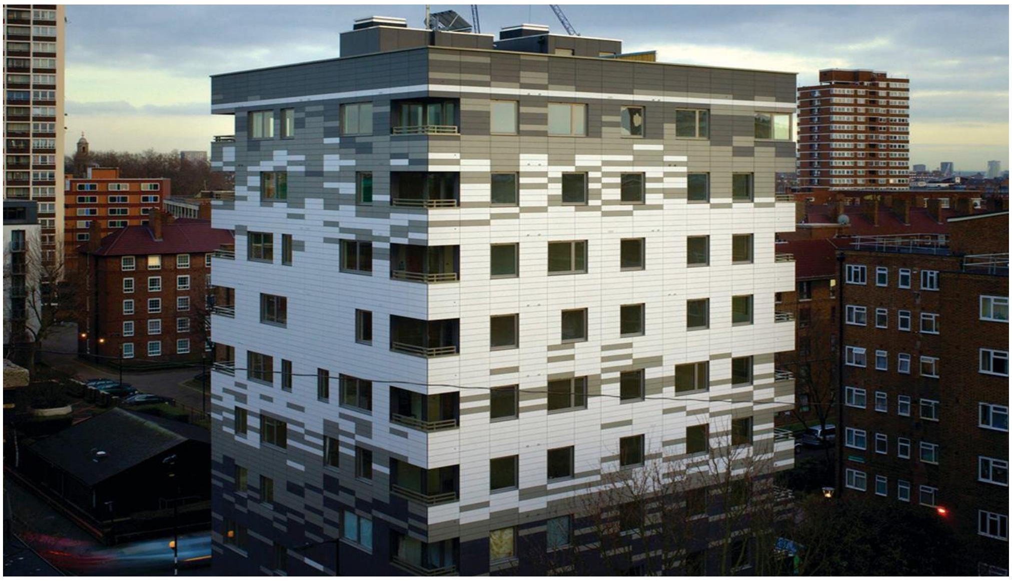


Figure 6. London's Murray Grove Tower [Smith et al., 2018]

2.6. Life cycle assessment in the building sector

Buildings in our society have invariably detrimental effects on the environment. Over the course of their existence, they "use" various kinds of energy resources, occupy space from the natural environment, and after their life-time ends, they might end-up as waste products. Sustainable housing technologies and construction techniques are receiving more attention, and gaining popularity across all sectors of the construction industry. Therefore, regulations like the Energy Performance of Buildings Directive 2002/91/EC (EPBD, 2003) and the updated EPBD 2010/31/EU have been issued by the European Union [Directive, E. U, 2003, Directive, E. U, 2010] with the aim to reduce the energy consumption of homes and subsequently their ecological burdens. In terms of their impact on the environment, buildings are responsible for between 30 and 40 percent of global energy consumption and between 40 and 50 percent of glasshouse gas emissions [Kobayashi et al., 2017]. The residential sector in Hungary accounts for 18 % of CO_2 emissions [Mohammed et al., 2021]. The manufacturing of construction materials accounts for 8 to 12 percent of world CO2 emissions, which has a major effect on the use of natural resources [Larrazábal et al., 2017]. About 40 percent of a building entire energy demand (primary energy) is typically used during construction. Therefore, 60 percent of the total energy is used during the utilization stage, which is mostly attributable to heating/cooling, lighting, and other operating needs [Farooq et al., 2021]. New building concepts, like low-energy and even self-sufficient homes, were encouraged by European regulations [Directive, E. U, 2003, Directive, E. U, 2010].

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to disposal [Buyle et al., 2013, Bendahmane et al., 2022, Cabeza et al., 2014, Cheng et al., 2020, Quintana-Gallardo et al., 2020]. In the building sector, LCA is commonly used to assess the environmental performance of buildings and building materials [Buyle et al., 2013, Cabeza et al., 2014, Quintana-Gallardo et al., 2020]. It provides a comprehensive analysis of the environmental impacts associated with different stages of a building's life cycle, including production, construction, operation, maintenance, and end-of-life [Buyle et al., 2013, Cabeza et al., 2014, Quintana-Gallardo et al., 2020, Roh et al., 2018]. The LCA process comprises four stages, as it is presented in Figure 7.

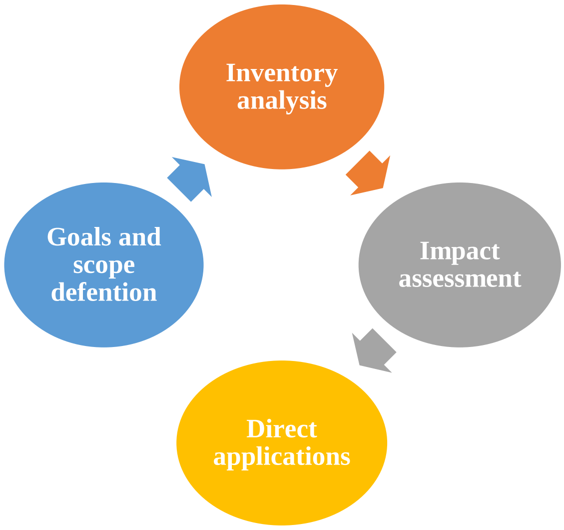


Figure 7. Life cycle assessment framework

One of the main challenges in conducting life cycle assessments in the building sector is the lack of consideration for the operation and maintenance stage after project delivery [Cheng et al., 2020]. Many current assessment standards and methods focus primarily on the planning, design, and materialization stages of a construction project [Cheng et al., 2020]. However, the operation and maintenance stage play a crucial role in reducing greenhouse gas emissions (GGE) and achieving sustainability goals throughout the building's life cycle [Cheng et al., 2020]. To address this problem, researchers have proposed integrating building information modeling (BIM) technology with LCA to develop a more comprehensive and accurate assessment method for green buildings [Cheng et al., 2020]. BIM technology allows for the representation of the physical and functional characteristics of a building, including energy consumption and performance data [Cheng et al., 2020]. By combining BIM with LCA, researchers have been able to estimate the GGE of large-scale public buildings and identify opportunities for reducing emissions throughout the building's life cycle [Cheng et al., 2020]. Thus, it’s essential to think about the buildings' environmental performance and energy efficiency. Saving money on energy bills throughout the lifetime of the building may worth the initial investment in more expensive thermally efficient designs or improvements [Giuseppe et al., 2017]. Life Cycle Costing (LCC) analysis may be useful here and in other contexts (such as demolition and recycling) to identify opportunities for savings and other factors [Kambanou et al., 2020].

Several studies have been conducted to assess the environmental benefits of using wooden materials in construction projects. A group of engineers, studied the eco-advantages of reusable mass timber homes in Japan, comparing their Global Warming Potential (GWP) to conventional systems using LCA [Passarelli, 2019]. Results showed lower GWP for the reusable system, signalling reduced environmental impact [Passarelli, 2019]. Another study investigated the life cycle environmental impacts of a wooden family house [Vilčeková et al., 2020]. The study found that wooden buildings have a substantial share in the reduction of environmental impacts and that the design of wooden houses corresponds to the increasing demands of occupants in terms of environmental, social, and energy performance [Vilčeková et al., 2020]. Talvitie et al. (2022) conducted a study on the climate benefits of wooden construction in an urban context [Talvitie et al., 2022]. The study found that wooden construction offers two environmental benefits compared to current practices: lower life-cycle emissions and carbon storage [Talvitie et al., 2022]. The use of wood-based construction materials can help reduce carbon emissions and contribute to carbon sequestration [Talvitie et al., 2022].

2.7. Inspection methods for heritage timber structures

Carrying out a complete analysis of heritage timber structures can sometimes be challenging because several factors need to be assessed in order to make sure that the timber elements are not at risk. The most precise and also standardized techniques are usually destructive techniques (DT), however their usage, especially in the case of the heritage buildings have to be avoided as much as possible. Therefore, techniques that are widely used to evaluate heritage timber conditions are called non-destructive testing (NDT) and semi-destructive testing (SDT). These techniques allow the determination of the physical and mechanical properties of the elements as well as the detection of defects in the timber while preserving their potential for end use [Kurz et al., 2015, Palaia et al., 2011, Wang et al., 2021].

2.7.1. Destructive testing

Destructive testing techniques for wood structures involve methods that require the physical alteration or removal of large wood samples for analysis. These techniques provide detailed information about the mechanical properties, structural integrity, and chemical composition of wood. Some of the destructive testing techniques used for wood structures include:

- **Chemical analysis:** This involves the extraction and analysis of wood components using various chemical methods. For example, Cheng et al. (2016) used FT-IR (Fourier Transform Infrared spectroscopy) and principal component analysis to investigate the structural modifications of wood during heat treatment [Cheng et al., 2016].
- **Mechanical testing:** Destructive mechanical testing involves subjecting wood samples to controlled loads or stresses until failure occurs. This allows for the determination of mechanical properties such as strength, stiffness, and toughness. Such as three-point bending test, four-point bending test, compression and tension (parallel or perpendicular) to grain test, Janka hardness test, and Charpy impact test. The four-point bending test method will be employed in the experiments of the research work, and a more detailed presentation will be provided in Chapter 3.5. Here, a general description is offered.

Four points bending test

One of the most used mechanical tests is the four points bending (4PB) test. It involves applying a bending load to a specimen at four points, with two outer supports and two inner loading points. The specimen is typically in the form of a beam or plate, and the bending load is applied perpendicular to the longitudinal axis of the specimen [Huang et al., 2005, Shetty & Reinikainen, 2003].

The key components and steps of the four-point bending test are [Yoshihara, 2008; Wang et al., 2023]:

- Specimen Preparation: a rectangular or cylindrical specimen is prepared with specific dimensions according to the testing standards;
- Setup: the specimen is placed on two lower supports, creating a span between them. Two loading points (rollers or rounded anvils) are positioned on the specimen, usually symmetrically along the span;
- Loading: a load is applied at the two loading points, inducing bending in the specimen. The specimen undergoes both tension and compression forces on its upper and lower surfaces.
- Measurement: the applied load and the resulting deformation of the specimen are measured. Load-displacement curves are often plotted to analyse the material's behaviour under bending;
- Analysis: the test provides information about the flexural strength, modulus of rupture, and modulus of elasticity of the material.

2.7.2. Non-destructive testing

Non-destructive testing (NDT) for timber encompasses a range of techniques aimed at assessing the properties and condition of timber without causing damage to the material. These methods are crucial for evaluating the structural integrity, mechanical properties, and overall quality of timber elements. The principal methods of non-destructive testing for timber include:

- **Waves and vibration testing methods:** these techniques measure the speed of sound through timber, providing valuable information about its stiffness and structural properties [Balasso et al., 2021], such as acoustic wave velocity method, and the ultrasonic testing [Shabani et al., 2020, Jaskowska-Lemańska et al., 2020].
- **Radiographic testing:** is a method that includes the utilization of either X-rays or gamma radiation to study the interior structure of a component. Compared to other NDT techniques, radiography offers results about the strength of the wood and assess the material’s local defectiveness [Niemz et al., 2012, Sadowski, 2022].
- **In-situ assessment (visual inspection):** involve assessing the wood's surface for signs of decay, cracks, or irregularities, examining joints and connections for structural integrity to ensure overall safety and durability.

Visual Inspection

Visual inspection is a fundamental method for assessing the condition of heritage timber structures [Hasníková et al., 2014, Niemz et al., 2012, Villamil et al., 2015, Shabani et al., 2020]. It involves a thorough examination of the visible surfaces of the timber components to identify signs of decay, insect infestation, cracks, or other forms of damage [Harun et al., 2022, Jaskowska-Lemańska et al., 2020, Pehlivan, 2023, Qin et al., 2018]. Visual inspection is typically the first step in the inspection process and provides valuable initial information about the overall health of the timber structure [Jaskowska-Lemańska et al., 2020, Qin et al., 2018].

During visual inspection, the inspector carefully examines the timber surfaces, looking for any visible signs of deterioration or damage. This can include checking for cracks, splits, warping, or discoloration [Hasníková et al., 2014, Niemz et al., 2012, Villamil et al., 2015, Shabani et al., 2020]. The presence of fungal growth, such as mold or rot, is also assessed. Insect infestation, such as wood-boring beetles or termites, is another important aspect to consider during visual inspection [Harun et al., 2022, Jaskowska-Lemańska et al., 2020, Pehlivan, 2023, Qin et al., 2018].

In addition to the general assessment of the timber surfaces, visual inspection may also involve the examination of specific structural elements, such as joints, connections, or load-bearing members. The inspector looks for signs of deterioration or damage in these critical areas, as they can significantly affect the structural integrity of the timber building [Harun et al., 2022, Jaskowska-Lemańska et al., 2020, Pehlivan, 2023, Qin et al., 2018].

Visual inspection is often complemented by the use of modern magnifying tools or cameras to get a closer look at the timber surfaces [Shabani et al., 2020]. This allows for a more detailed examination of the condition of the timber, especially in hard-to-reach or hidden areas [Shabani et al., 2020]. The use of these tools can help identify small cracks, decay pockets, or insect tunnels that may not be visible to the naked eye.

It is important to note that visual inspection alone may not provide a comprehensive assessment of the timber structure. It is often used in conjunction with other inspection methods, such as non-destructive testing (NDT) or semi-destructive testing (SDT) techniques, to gather more detailed information about the condition and structural integrity of the timber components.

2.7.3. Semi-destructive testing

Semi-destructive testing of wood involves methods that cause some damage to the material but are designed to be less destructive than fully destructive testing methods. These techniques provide information about the structural properties and condition of wood without completely compromising its integrity. They usually need only a very small amount of material.

Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is a powerful imaging technique that has revolutionized the field of microscopy by providing high-resolution images of the surface morphology of various materials. [Cheney, 2007, Mohammed, & Abdullah, 2018, Ul-Hamid, 2018].

The SEM is a method used for analysing the structural properties of materials, providing information from the scanned surface using electrons. Combined with microscopy, i.e., imaging and spectroscopy, it also offers the possibility of elemental analysis alongside the surface information.

The wavelength of high-energy (10-30 kV) accelerated electrons is much smaller compared to visible light, making scanning electron microscopy indispensable today in the field of natural science, medicine and engineering. In contrast to the resolving power (200-300 nm) and depth of field (a few μm) of optical microscopes using light, electron microscopes offer significantly higher performance with a resolution of 1 nm and a depth of field of 2-3 mm. While optical microscopes can achieve magnifications of 1000-1500 X, electron microscopes can achieve magnifications of over 10.000 X. [Goldstein et al., 1981]

2.8. The climate of Hungary

The climate of Hungary has been subject of several studies and research articles. These studies have examined various aspects of the climate, including temperature, precipitation, extreme weather events, and their impacts on different sectors such as agriculture and tourism. Hungary is a country in Eastern Europe that has a continental climate, having cold winters and mild to hot summers due to its location between 45 and 48 degrees north latitude. Even though the temperature is generally pleasant in the spring and fall, it tends to fluctuate along the geographic location. A warmer winter characterizes the southern part and a more continental climate in the east, and northern area. Because of its location, Hungary experiences the effects of all three climate types—the oceanic climate, characterized by less pronounced temperature swings and more uniformly distributed precipitation; the continental climate, characterized by more pronounced temperature swings and fairly moderate precipitation; and the Mediterranean effect, characterized by dry weather in the summer and wet weather in the winter. One or more of these can dominate at certain periods. Despite its lower elevations and smaller area, the weather of the country may exhibit significant variation for these reasons [World Bank Group, 2021].

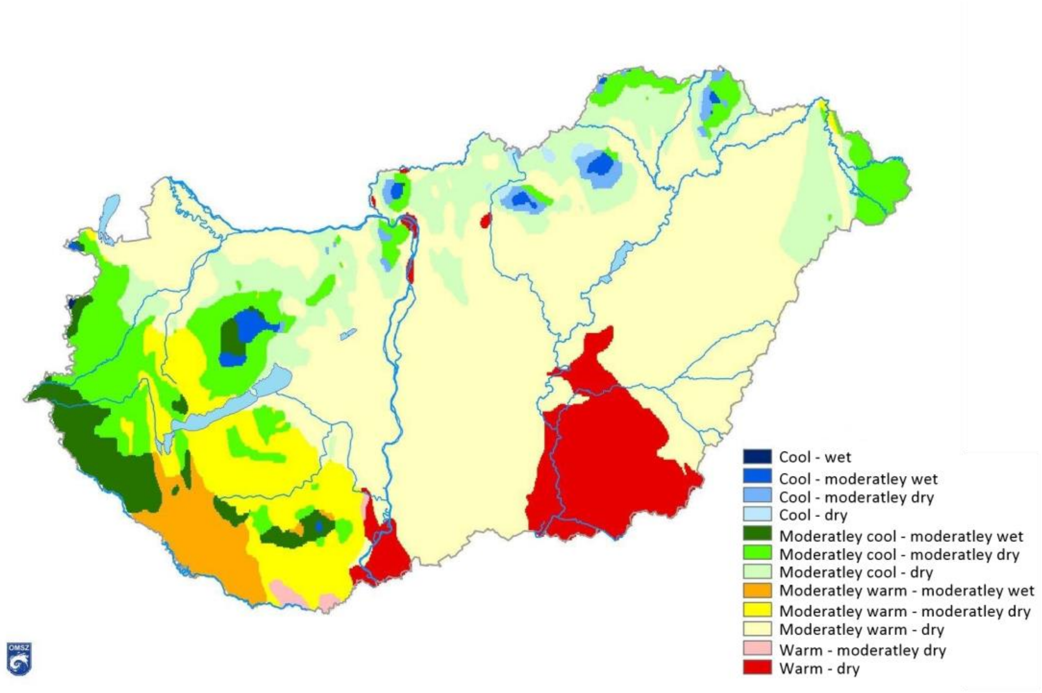


Figure 8. The Hungarian climatic design regions classification [Hungarian Meteorological Service, 2018]

Primary climate-region types in Hungary

There are four primary climate-region types that have been identified in relation to climatic changes [Mezösi et al., 2013]:

1. The western hilly region is characterized by lower temperatures, moderate increases in temperature, and little shifts in temperature extremes, as well as by increased humidity and greater than average rainfall and rainfall totals.
2. From the north to the south of Hungary, there is a west-central corridor that is expected to have a moderate temperature rise, clear changes in severe temperature events, and a moderate increase in precipitation totals with moderate changes in extreme rainfall occurrences.
3. A large region of Hungary, from the centre to the southeast, with flat topography, the highest temperatures, the highest temperature rise, and significant differences in the temperature extremes occurrences, the lowest annual precipitation totals, the maximum estimated precipitation decline, and an increasing concentration of rainfall.
4. The north-eastern border area with Slovakia, has the biggest intraregional temperature variance, the lowest annual mean temperatures, and moderate precipitation totals that result in higher humidity than the other continental regions.

Using satellite data from 2001 to 2016, the magnitude of Budapest's urban heat island has been calculated. In the heart of the city, temperatures reached as high as 5 degrees. The severity of an urban heat island (valid also for Pécs) reduces as building density increases [Dian et al., 2019, Dian et al., 2020, Mátyás et al., 2018]. Also, the 20th century saw a dramatic decline in the average yearly amount of precipitation in Hungary. When compared to the beginning of the 20th century, springtime precipitation is barely 75 % of its average. There has been no change in the amount of summer rain during the past century. There is a 12-14 % drop in the rain during the fall and winter. When compared to other times of the year, winter has the least amount of rain. Both the average intensity of precipitation and moderately severe incidents have been on the rise throughout central and western Europe during the past century. Concurrently, there was a small but noticeable increase in the duration of dry periods. The increased risk of flooding is compounded by the fact that the less quantity of precipitation that does fall does so in a more concentrated manner [Mezösi et al., 2013, Pinke et al., 2017, Schmeller et al., 2022].

Heat swings and cold spells changes

Over the period 1961-2010, heat wave occurrences have been more frequent, longer, more severe, and intense in the Carpathian Region (including Hungary), especially during the summer on the Hungarian Plain. In contrast, throughout this time span cold wave frequency, average length, severity, and intensity usually declined in every season except autumn. Heat waves were defined in this study as five or more consecutive days with maximum temperatures over the long-term 90th percentile for that day. Similarly, five or more straight days with an average temperature just below the long-term 10th percentile for minimum temperatures were considered to constitute a cold wave [Schmeller et al., 2022, Spinoni et al., 2018].

Over the whole Carpathian Region, heat wave occurrences are becoming more often, lasting longer, being more severe, and more intense, as shown by the trend study. However, cold waves tend to be less often, shorter, less intense, and less severe than warm ones. Droughts have been more often, lasting longer, and more severe in the Carpathian Region and the Mediterranean region of Europe during the 1990s. Heat waves can have disastrous impacts on drought-affected areas, and vice versa. This was the case in Central Europe during the summer of 2003 [Schmeller et al., 2022, Spinoni et al., 2018].

According to the European Environment Agency (EEA), in the interval from 2013 to 2022, the global mean near-surface temperature was 1.13 to 1.17 °C higher than the pre-industrial level, making it the warmest decade on record. Over the same time period, European land temperatures climbed by 2.04 to 2.10 °C [European Environment Agency, 2023]. The Copernicus Climate Change Service (CCCS) shows that 2022 was the hottest summer and second warmest year on record in Europe [European Parliament, 2018]. Also, since 2021, weather- and climate-related extremes caused economic losses estimated at EUR 56.6 billion in the EU Member States. Accompanied this increase in the global mean temperature a severe drought caused a 3 % annual vegetation productivity loss in the last 10 years [European Environment Agency, 2023].

2.9. The effect of the climate change on timber buildings

One of the main causes of climate change in the construction industry is the higher energy consumption during the cold winters and hot summers used for the operation of the buildings, and greenhouse gas emissions associated with the manufacturing of construction [Burciaga, 2020]. Approximately 10 % of world energy consumption is used for the manufacture of construction materials [Burciaga, 2020]. The mean values of the key climate variables temperature, precipitation, humidity, solar radiation, and wind speed are predicted to shift in different ways depending on location. It is also anticipated that the standard deviation of these climatic parameters would rise [Spinoni et al., 2018].

The complicated relationship between climatic elements affecting buildings, landscape, coastal systems, and environmental degradation deriving from probable effects of climate change is attempted to be depicted in a schematic form in the following Figure (see Figure 9). To protect its residents from the potentially hazardous effects of climate change outside, buildings create an artificial barrier between the internal and external spaces.

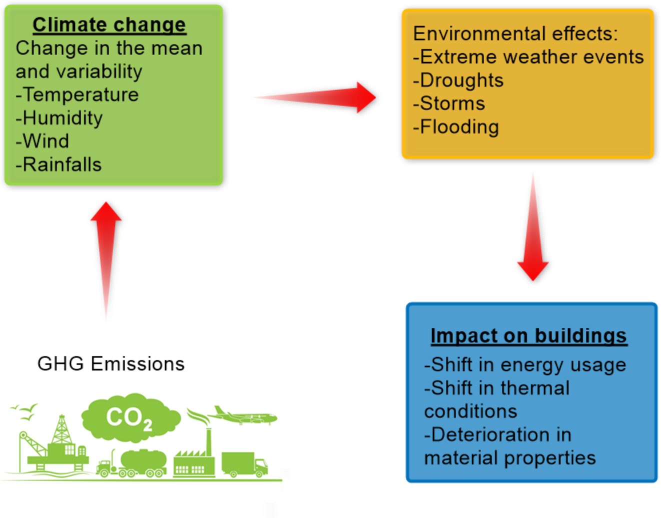


Figure 9. Climate change and impacts on buildings [Lacasse et al., 2020]

Consequently, it is evident that natural climate determinants like the sun, planets, and orbits, as well as human-caused glasshouse gas emissions, are responsible for variations in the mean values of the key climate variables such as precipitation, temperature, humidity, solar radiation, and wind. Future environmental effects suggest that the severity and frequency (length and intensity) of extreme climatic events will rise due to such changes. In tandem with these modifications, we should expect a progressive shift in the means of climatic variables like temperature, as well as a concomitant rise in sea levels due to the aforementioned warmer temperatures [Vanucchi, 2021]

The impacts of climate change on the construction industry are diverse and multifaceted. Extreme weather events, such as floods, storms, and heat waves, can directly impact construction sites, causing damage to infrastructure and delaying construction projects. Changes in temperature and precipitation patterns can also affect the performance and durability of construction materials, such as concrete structures [Benítez et al., 2020]. Climate change can accelerate the degradation of concrete structures through processes like carbonation [Benítez et al., 2020]. Rising temperatures can also increase the risk of heat stress for construction workers, impacting their health and safety.

Rising global temperatures will cause a shift from a need for heating, as measured by heating-degree weather, to a need for cooling, as measured by cooling-degree days, particularly in metropolitan cities and areas, where heat island effects may predominate in the summer. Overheating in buildings caused by negligence during high-heat events is a potential threat to the old, the sick, the disabled, and the young. As for building operations, seasonal differences in the ability to cool or heat buildings might lead to inefficient energy consumption. For decades, experts have been aware of the broad climatic characteristics linked to climate change and how they can influence construction. Consequently, the abundance of useful resources for enhancing the climate resilience of both newly constructed and older structures is indicative of the importance of this issue [Lacasse et al., 2020].

In addition to these direct impacts, climate change also poses challenges for the sustainability and resilience of the construction industry. Construction industry needs to adapt to changing climate conditions and develop strategies to mitigate its environmental footprint. Sustainability assessment and the adoption of sustainable practices are crucial for the design and construction of buildings that can withstand the impacts of climate change. This includes considering energy efficiency, renewable energy sources, and the use of environmentally friendly materials [Burciaga, 2020, Hao et al., 2019, Muqi, 2018].

Adaptation strategies are essential for the construction industry to cope with the impacts of climate change. This includes incorporating climate change considerations into building design, such as considering future climate projections and extreme weather events [Hao et al., 2019] Understanding the past climate conditions and their influence on historic buildings is also important for assessing the implications of climate change on these structures [Hao et al., 2019]. Building codes and regulations may need to be updated to ensure that new constructions are resilient to climate change [Benítez et al., 2020]. The industry can also explore innovative technologies and construction methods that reduce energy consumption and greenhouse gas emissions [Muqi, 2018].

It is known from various studies on wood, its behaviour, and its properties that wood is extremely sensitive to climatic changes, as evidenced particularly by shrinkage and swelling, but also by attributes like stiffness and strength [Lanata, 2015, Teodorescu et al., 2017]. According to timber design guidelines, it's critical to consider wood's sensitivity to moisture and dry wood below the average moisture content that is consistent with the predicted climate conditions [Lanata, 2015]. For instance, wood with a moisture content of over 20 % that is put to use will have a 20% lower resistance than the same wood with a moisture content of under 20 %.

As detailed previously, changes in climate influence the development of mould on wood. Moisture and temperature are the two main climatic factors that drive this. When the temperature is between 23 and 25 °C and the moisture content is between 35 and 50 %, fungi can grow on wood [Björngrim et al., 2016, Choidis et al., 2020, Krzywon, 2019, Pretzsch et al., 2018]. A crucial element is the length of time that an object is exposed to moisture and temperature variations. Relative humidity and temperature of the environment, as well as other environmental factors, are never constant over extended periods of time. These variables change over time, bringing with them favorable and unfavorable fungi growth conditions that result in mould growth on wood [Björngrim et al., 2016, Krzywon, 2019].

In addition to mould risk, climate change can also affect the degradation of building materials in timber structures. It is anticipated that climate change will have an impact on the degradation of building materials in cultural heritage sites and buildings [Kherais et al., (2022a), Kherais et al., (2022b), Kherais et al., (2022c)]. This is particularly relevant for timber historic buildings, as they are vulnerable to bio-deterioration. Higher temperature and humidity levels resulting from climate change can accelerate the decay of building materials, leading to invaluable damages [Choidis et al., 2020].

2.10. Protection of timber structures against climate components

To ensure the durability and safety of timber structures, it is important to protect them against climatic elements, especially changes in temperature and moisture content. Several methods can be employed to achieve this:

- Proper design and construction: designing timber structures with appropriate details and construction techniques can help minimize moisture ingress. This includes ensuring proper flashing and sealing of joints and connections [Kalbe et al., 2020].
- Moisture barriers: installing moisture and temperature barriers, such as waterproof membranes or coatings, can prevent the penetration of moisture into the timber structure [Kim et al., 2020]. These barriers should be applied to all exposed surfaces, including the end-grain, which is particularly vulnerable to moisture ingress [Kalbe et al., 2020].
- Reflective coatings: applying reflective coatings to the exterior surfaces of timber structures reduces the absorption of solar radiation and minimizes heat transfer. These coatings reflect a significant portion of sunlight, thereby reducing the temperature of the timber [Tsapko et al., 2020].
- Monitoring: regular monitoring of moisture levels and temperature degrees in timber structures can help identify potential issues and allow for timely intervention. Various methods, such as in-situ sensors or active sensing techniques, can be used to measure and monitor these values [Schmidt, 2019, Zhang et al., 2018].
- Maintenance and repair: regular maintenance and timely repair of any damaged or deteriorated areas can help prevent moisture and temperature related issues. This includes addressing leaks, cracks, or any signs of moisture intrusion [Liu et al., 2022].
- Treatment and preservatives: applying appropriate wood treatments and preservatives can enhance the moisture resistance of timber structures. These treatments can include water repellents, fungicides, or borate-based preservatives [Zhang et al., 2018].

3. Methodology

3.1. General description

The fundamental principle employed in this research was to examine the extent of the impact of climate change on heritage wooden buildings in Hungary. Consequently, the adopted approach involved studying various climate factors over a period of more than 100 years, analysing these factors, correlating them with the moisture content of the structural elements, measured during four seasons at the chosen locations, and determining how these changes affected the facility, including the occurrence of cracks and failures. This process was conducted concurrently with a meticulous and comprehensive examination of the facility. Subsequently, the influence of changing moisture content on the structural properties of wood was investigated through laboratory tests such as the four-point bending test and the scanning electron microscopy method. This methodology was applied to two distinct examples in Hungary, as described below.

3.2. Sites introduction

Civil Közösségek Háza - Civil Communities House

The Civil Communities House dates back to the 19th century. It's located in Pécs at Szent István square. From its construction in the early 19th century until today, the house has passed through four renovation stages. These renovations were made on the whole structure except the roof level; thus, the originality is still preserved [CKH, 2021]. The roof level nowadays is used as a storage area. Figure 10 shows the location of the house and the exterior and the interior parts of the house.

Figure 10 (a). The location of the Civil Communities House

Figure 10 (b). The exterior facade of the Civil Communities House [own photo]

Figure 10 (c). One of the events rooms in the Civil Communities House [own photo]

Figure 10 (d). Roof level of the Civil Communities House [own photo]

Makovecz Imre kilátó - Makovecz Imre Lookout Tower

The Makovecz Imre Tower is a lookout tower in the second district of Budapest, at the top of Kis-Hárs-hegy, on the border of Kurucles and Lipótmező districts. It was built in 1977, and it was renovated twice. The first renovation was from 2006 to 2008, the second was in 2018 by removing the railings, strengthening the supporting structure resting on the central iron column, placing more stable railings and repainting the tower [Wikipedia, 2022]. Figure 11 shows the tower.

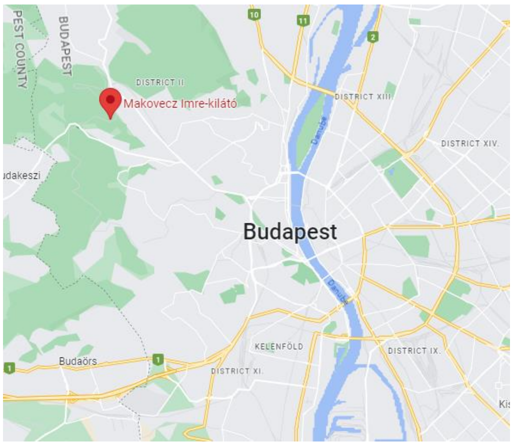


Figure 11 (a). The location of the Makovecz Imre lookout-tower

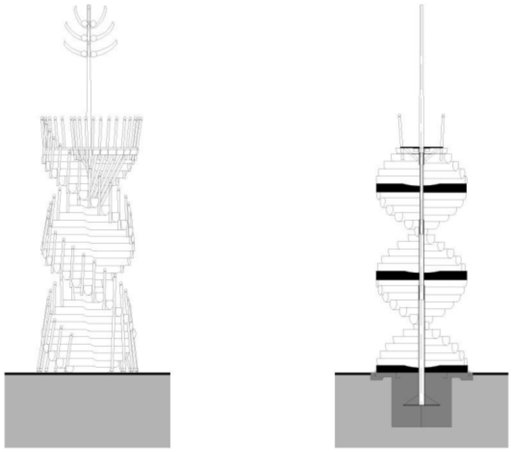


Figure 11 (b). Side view of the tower [Makovecz, I. (n.d.)]

Figure 11 (c). Makovecz Imre Lookout Tower [own photo]

3.3. Collecting climate data

The acquisition of climate data consists of two main phases, elucidated as follows:

Climatic History of the Site

This initial stage encompasses the retrieval of meteorological data spanning the past 120 years, as documented by the Royal Hungarian Central Institute of Meteorological and Earth Magnetism (OMSZ). The dataset under scrutiny encompasses crucial parameters, namely annual maximum and minimum temperature values, the tally of days characterized by extreme heat and frost, and the cumulative precipitation volume.

Climatic factors associated with wood

Subsequently, in this phase, temperature (T), relative humidity (RH), and moisture content were quantified employing specialized instrumentation. Temperature and relative humidity were ascertained using the Kimo AQ200 device (see Figure 12 (a)), while moisture content was determined utilizing the Testo 606-1 (see Figure 12 (b)) apparatus. The data collection process encompassed all four seasons for both study sites and was executed via a regimen of daily or weekly site visits (depending on opening hours and, affected by COVIS-19 closures). Notably, these measurements were conducted exclusively on the surface of the wood, as invasive or destructive measurement techniques were not permissible for this investigation.

Figure 12. a) Kimo AQ200 b) Testo 606-1

3.4. Non-destructive visual inspection

The visual inspection phase constitutes the primary foundation of this research endeavour, given the heritage status attributed to both sites, which mandates strict adherence to non-destructive testing methodologies exclusively. This stage includes the following steps:

Access and safety

Ensure safe access to all areas of the timber structure, including elevated or hard-to-reach locations.

Initial observation

A general visual assessment of the entire timber structure from a distance to identify any visible signs of deterioration, damage, or irregularities. Noting any apparent structural changes, cracks, or deformations.

Close-up examination

Systematically inspect the timber components, starting from one end and progressing to the other. Using a flashlight to examine hidden or dimly lit areas. Paying close attention to critical structural elements such as beams, columns, joints, and connections.

Surface condition

Evaluating the surface condition of the timber, looking for: cracks, checks, or splits in the wood. Signs of rot, decay, or fungal growth. Insect infestations, including exit holes or tunnels. Excessive moisture or water stains. Paint or coating integrity and peeling.

Structural integrity

Assess the structural integrity of load-bearing members: check for bending, sagging, or deflection. Verify the connection points for signs of movement or separation. Look for evidence of excessive stress or overloading.

Moisture content

Using Testo 606-1 to measure the moisture content of the timber in different areas, taking care of statistical representativeness.

3.5. Four points bending test

Four-point bending test (4PB) is a material testing method used to determine the flexural strength and deformation behaviour of a material. In this test, a sample or specimen is supported at two points and loaded at two points, creating a bending moment.

The four-point bending tests have been conducted according to the Hungarian specifications (MSZ EN 408:2011 & MSZ EN 384:2010) using a displacement control system, where the load increment was controlled, its speed was set for 5 mm/min [Hungarian Standards Institution, (2010), Hungarian Standards Institution, (2011)]. Before starting the test, the environmental T and RH were measured. The surface MC of each sample was measured using a Testo 606-1 device. According to the standards, the samples were assembled in the centre of the supports, the distance between the two supports was 900 mm with a span of loading equal to 300 mm. The testing machine (Instron static hydraulic - Satec series (see Figure 13)) was connected to a computing system which allowed to measure the load and the deflection every 0.1 s.

Figure 13. Instron static hydraulic machine - Satec series [own photo]

3.6. Scanning electron microscopy (SEM)

The primary objective underlying the utilization of Scanning Electron Microscopy (SEM) in this study is to conduct a comparative analysis of the dimensions of timber cells, specifically their size and wall thickness, both prior to and following water absorption. Additionally, it aims to discern and evaluate any anticipated alterations ensuing the application of protective coatings on the timber elements. This investigation involved the testing of small specimens, measuring several millimetres, extracted from different structural components situated of the Civil Communities House roof structure, where a specific permission was asked from the maintainer. Samples taken from the laboratory testing specimens were also subject of the SEM measurements. The SEM analysis was performed employing the Tescan SEM instrument (produced by TESCAN GROUP, a.s.), as shown in Figure 14.

Figure 14. Tescan SEM device [own photo]

4. Analysis and results

4.1. Civil Közösségek Háza - Civil Communities House

4.1.1. Historical meteorological analysis

As previously noted, timber, being a natural material, undergoes direct interactions with climatic factors. To comprehensively understand and analyse the behaviour of timber structures, it became imperative to study the climatic history of the areas housing the examined sites. This enables a correlation between the performance of the timber structures and the climatic conditions prevalent in those locations. Considering the selected structures as heritage assets, the climatic interval covered in the analysis spans from the beginning of the 20th century, encompassing a period of more than 100 years. The study delved into various factors, focusing on specific meteorological parameters to better comprehend the influence of climate on the timber structures. These factors include:

- The count of summer days (defined as days with a temperature higher than 25 °C);

- The count of heat days (characterized by temperatures above 30 °C);
- The count of winter days (days with a temperatures below 0 °C);
- The count of frost days (marked by temperatures dropping below10 °C);
- Yearly maximum and minimum temperatures;
- Average yearly precipitation levels.

For the collection of meteorological data, information was sourced from the Hungarian Meteorological Service (OMSZ). It is noteworthy that the official published data spans from 1901 to 2020, encompassing a considerable timeframe to capture the climatic variations influencing the timber structures over the years.

Pécs meteorological study

The climate elements in Pécs exhibit fluctuations, as depicted in the upcoming figures. To ensure precise examination of the climate records, the figures below are generated using a best-fit polynomial of the 5th degree for simulation.

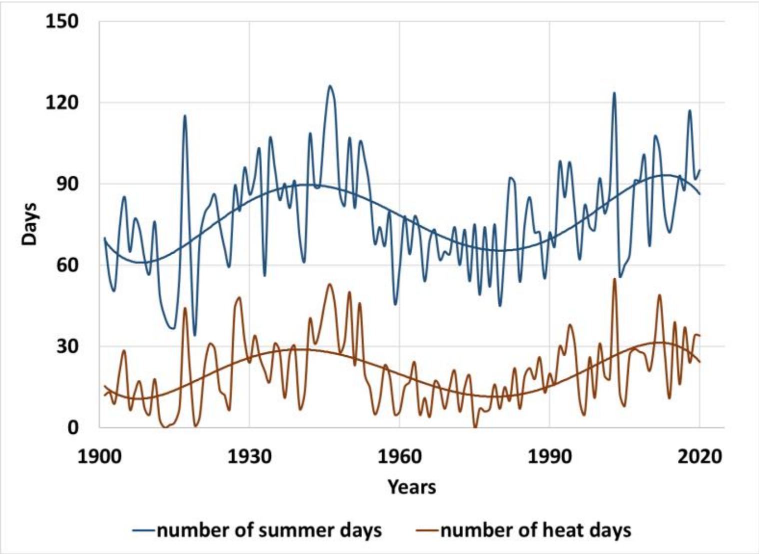


Figure 15. Number of summer days and heat days for Pécs region

Figure 15 provides insights that can be linked to climate change, as outlined below:

- Increasing number of heat days
  One discernible trend in the data reveals a rise in the number of heat days over the years, particularly in recent decades. Notable instances such as the years 2003, 2012, and 2018, characterized by a high number of heat days, align with the broader global pattern of more frequent and intense heatwaves associated with climate change.
- Variability and climate change
  The variability in the data, with periods of both increase and decrease in the number of heat days, aligns with expectations in a changing climate. Climate change does not necessarily translate to a linear temperature increase every year; instead, it can manifest as increased variability and an increased likelihood of extreme events.

- Patterns
  The number of summer and heat days exhibit a cyclical pattern, fluctuating approximately every 30-40 year (wavy pattern).This pattern is evident from 1910 to 1940, showing an increase, followed by a decrease from 1940 to 1980, then another increase from 1980 to 2010. Subsequently there is a decrease, suggesting that in the next 20 years, winter conditions may dominate.

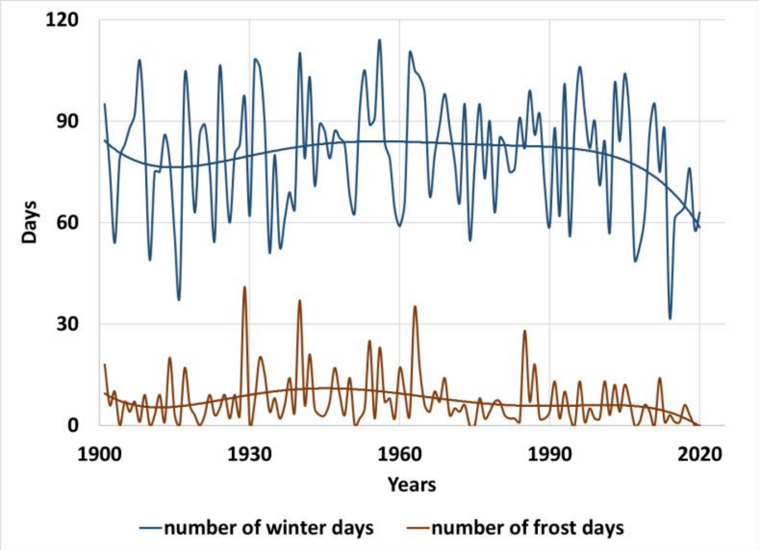


Figure 16. Number of winter days and frost days for Pécs region

Contrary to the preceding dataset, the number of winter and frost days, when represented as a polynomial function (best fit), exhibits a nearly constant rate or slope over the last 110 years (see Figure 16). However, an abrupt decline is evident in the last decade, specifically in the count of winter days. This observation aligns with the earlier finding from the chart, indicating that the next 20 years are expected to be dominated by winter conditions. Nevertheless, it implies that the upcoming winters may be less severe than those in previous years. It's essential to note that the definition of winter days in this context includes temperatures below 0 °C, meaning that days with temperatures ranging from 0 to 10 °C are still considered part of a winter period.

Table 1 provides a statistical breakdown of the meteorological data for Pécs. For a comprehensive dataset covering the years 1901 to 2020, please refer to Table A.1 in appendix A.

Table 1. Statistical calculations for the meteorological data of Pécs region (1901-2020)

	Yearly max temperature (°C)	Yearly summer days	Yearly Heat days	Yearly min temperature (°C)	Yearly winter days	Yearly frost days
Avg (μ)	34.39	77.27	20.48	-14.45	79.92	7.23
Standard deviation (σ)	2.24	18.82	12.93	4.20	16.95	7.74
Variance (σ^2)	5.02	354.16	167.19	17.63	287.19	59.89
Maximum	41.30	126.00	55.00	-5.00	114.00	41.00
Minimum	29.70	34.00	0.00	-27.00	32.00	0.00
Avg (last 20 years)	34.95	90.36	29.55	-12.78	69.27	3.00
Standard deviation (last 20 years)	1.87	14.97	10.97	3.77	17.46	4.12

Figure 17 represents the yearly precipitation amount. To analyse the data, four periods have been defined, each equal to 30 years.

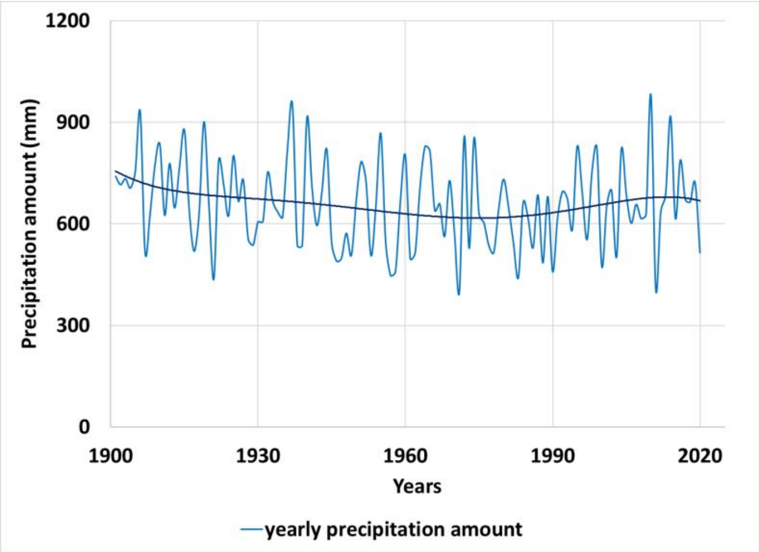


Figure 17. Yearly precipitation amount `in Pécs region

1901-1930

This period exhibits a combination of precipitation patterns, with some years experiencing relatively high precipitation (e.g., 1901, 1910) and others recording lower values (e.g., 1916, 1921). Notable variability during these decades reflects natural climate fluctuations. However, the overall trend in this period indicates a general decrease in the amount of precipitation, as illustrated by the best-fit line.

1931-1960

The data during this period continues to display variability, with an overall decrease, as indicated by the best-fit line. However, there are instances of extreme precipitation events, such as 1937, which recorded 952.2 mm.

1961-1990

This period includes years with both high and low precipitation, reflecting the ongoing variability. Notably, the early 1970s (e.g., 1972) and 1980s exhibit varying precipitation patterns. Additionally, there was an extreme drought year in 1983, with a recorded precipitation of 440.7 mm. In the last 10 years, the best-fit line has shown a positive slope, indicating an increase in the precipitation amount.

1991-2020

The latter part of the dataset continues to exhibit variability, including years with high precipitation (e.g., 2010) and lower precipitation (e.g., 2015). There is an increase in the occurrence of extreme precipitation events, aligning with expectations of global climate change.

Several conclusions can be drawn based on the analysis of the meteorological data:

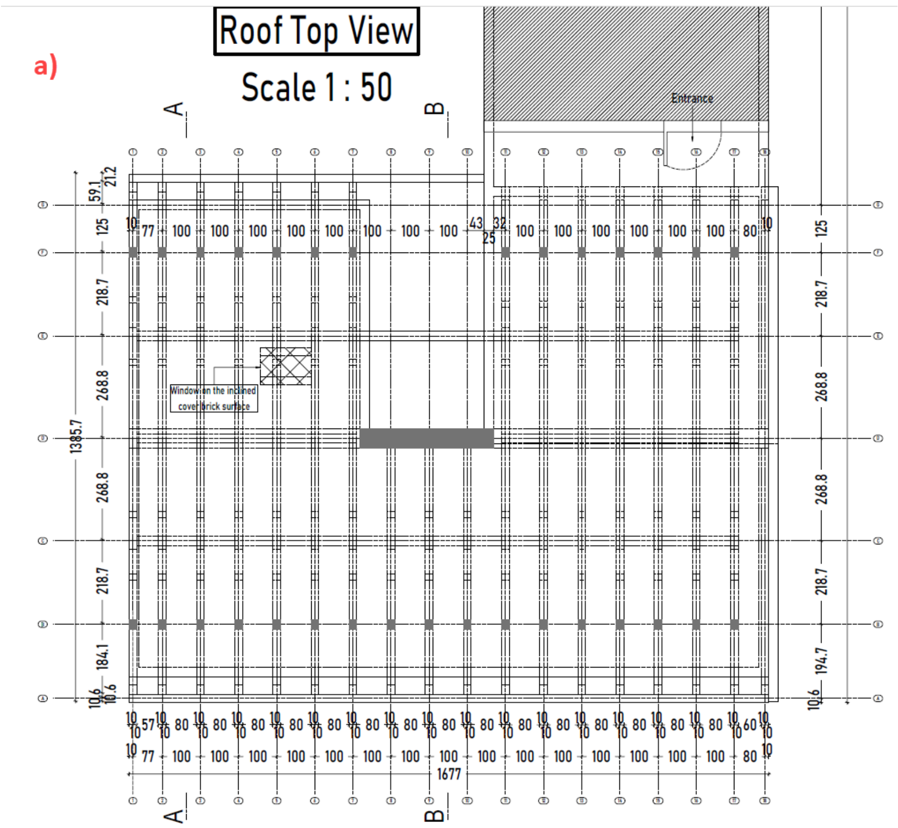
- The last increasing period of summer days and heat days concluded in 2013. Consequently, the appearance of an averaged minimum for the number of summer and heat days per year can be predicted for the next 30 years. However, it is important to note that this does not necessarily mean that the same minimum value will be reached as observed 40 years ago. Additionally, the variation around the best-fit line is extremely high, therefore the "minimum valley" is not translated to the annual breakdown level.
- Less winter days (defined as days with a minimum temperature below 0 °C) can be expected for the next years, which is considered an effect of global warming. However, the anticipated "summer day's valley" could potentially moderate this effect, leading to longer and less severe winter seasons.
- The maximum and minimum temperature values do not exhibit a clear increasing or decreasing tendency.
- An increase in climate humidity is anticipated due to the expected rise in the precipitation amount.

The examination of meteorological data highlights significant variability in climate factors over the past 120 years, impacting the studied cultural heritage site in Pécs, the Civil Community House. These fluctuations have adversely affected wood integrity, involving processes such as volumetric changes, alterations in moisture content, exposure to ultraviolet radiation, and wetting from rainfall. As a hygroscopic and orthotropic material, wood undergoes recurrent swelling and shrinkage cycles, resulting in the development of cracks and significant deformation in timber elements. These structural alterations diminish the mechanical and functional efficacy, creating a conducive environment for biological deterioration in the form of fungi and insects. The effects of the climate conditions (especially MC) will be analysed in details in the upcoming sub-chapters.

4.1.2. Site visual inspection

After completing the meteorological analysis, I organized several visits to the Civil Community House to conduct a visual inspection of the roof structure. The examination revealed that the wooden roof was constructed as a queen post truss system, probably to minimize costs and cover the large floor area of approximately 190 m^2. The roof is supported by a single brick wall in the middle, and its plan view resembles a U shape (see Figure 18). However, a proper ventilation system is absent. The predominant wood used in construction is pine (Pinus silvestris).

Figure 19 displays the positions of cracks and splits identified in the roof. Table 2 provides a detailed overview of the cracks and defects observed.



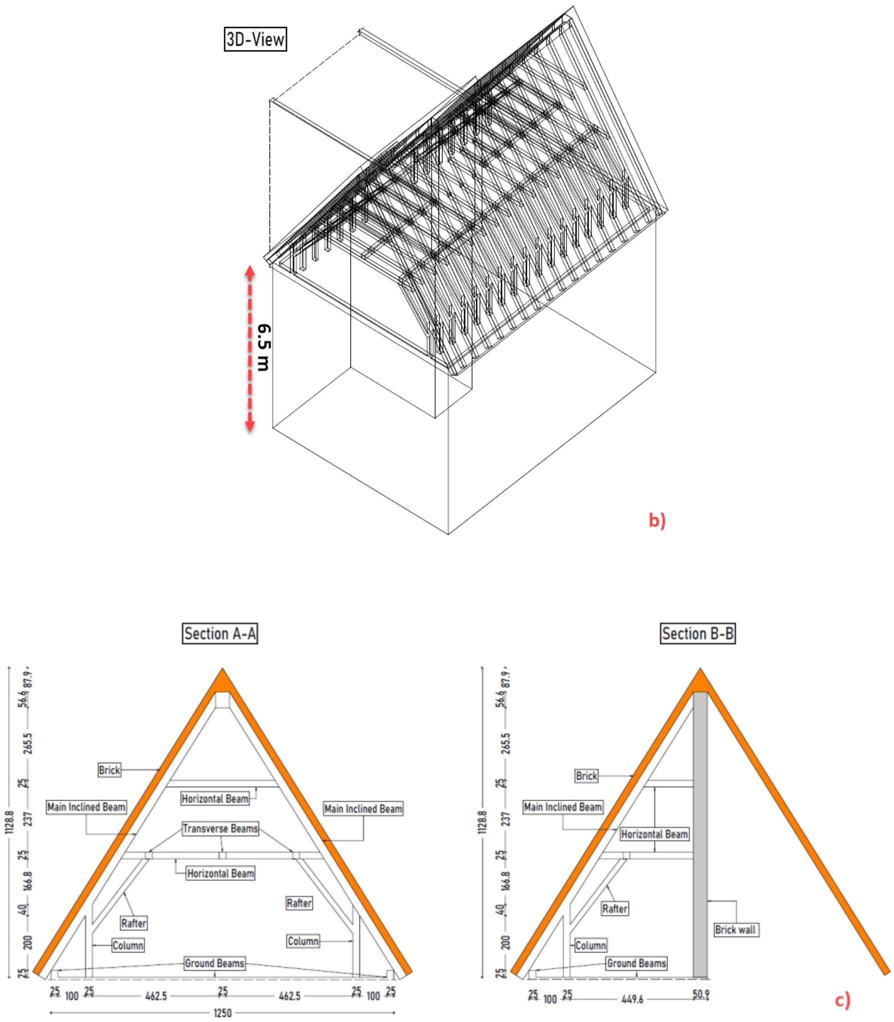


Figure 18. Roof sketch based on the visual inspection: a) plan view; b)3D view; c) section view

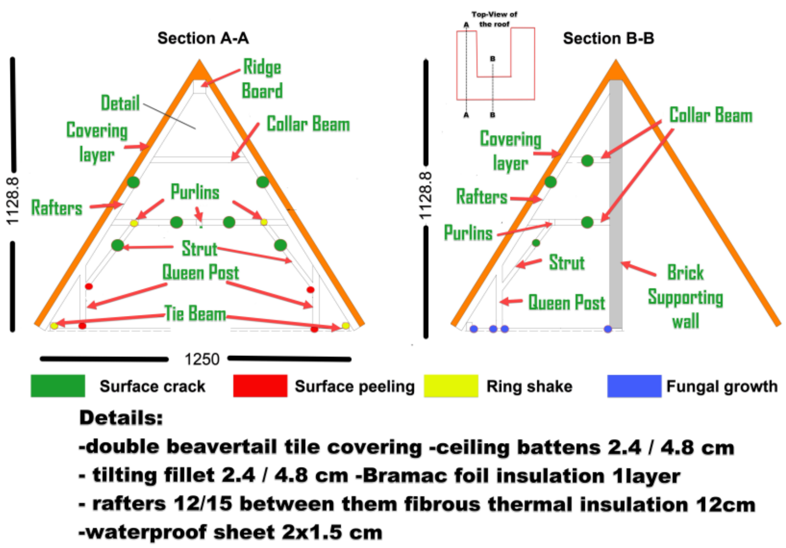


Figure 19. Positions of cracks and defects found in the roof of Civil Community House

Table 2. Visual inspection results

Defect type	Description	Formation reason	Photo	Affected elements
Ring shakes	Longitudinal separation of wood fibres in the tangential direction	Wood ageing, and site conditions		Mainly tie beams and some purlins
Surface peeling	Loss of the wood fibres along the element, few mm from the surface	Constant change of MC and site conditions		Posts and struts
Surface whitening	Tendency of the surface colour to white	High MC		Posts and struts

Surface crack	Mass loss of the wooden material, 3-4 cm peeling along the element	Wood ageing and load bearing combined with MC change		Struts ends and posts ends.
Fungal Growth	Fungi growth on the wooden surface	Climate conditions and high MC		Tie beams and posts
Longitudinal cracks	Cracks spread along the element ranging between 2 and 30 cm	Structural loads and site conditions		All structura l element types
Discolouring	Elements lose their original colour to become more faded	High M.C		All structura l element types

The primary causes of the damages are attributed to changes in MC and the natural aging of wood, commonly associated with climate change cycles. Additionally, the absence of surface treatment and rehabilitation has exacerbated these issues. Notably, struts and posts have incurred significant damage, with the colour of the elements becoming notably whiter at higher elevations. The timber elements, lacking any protective layer, have been exposed to the elements, and the top covering layers of the roof have exceeded their expected service life, typically ranging between 40 to 50 years. Consequently, nearly all elements have undergone deterioration, and it can be estimated that approximately 30–40% of the roof elements are severely degraded.

Nevertheless, the investigated period is relatively brief, and the visual inspection, along with the analysis of meteorological data, provides insights into the entire structural history. The absence of any roof-level reconstruction and the lack of a proper insulation layer have contributed to the anticipated failures. The meteorological data examined for the Pécs region indicates that over the past few decades, fluctuations in temperature and relative humidity have similarly influenced the moisture content of the timber, aligning with the patterns observed during the studied period.

4.1.3. On-site measurements

To substantiate the conclusions and deductions drawn from the meteorological analysis and visual inspection of the structure, a comprehensive examination of the wooden elements in the roof and the surrounding climate factors was necessary. Measurements were conducted over four seasons to thoroughly assess and study the condition of the timber elements throughout the year. The measurements were conducted during the day, approximately at the same hour. However, due to variations in opening hours and the temporary closures imposed by COVID-19, it was challenging to avoid fluctuations in the measurement of climatic factors. Regrettably, installing an on-site automatic measurement device for these factors was not feasible. Commencing on July 9, 2020, the measurements continued until June 29, 2021, encompassing a full annual cycle to capture the variations in the timber's response to changing climatic conditions.

In these measurements:

- I measured the MC values for both damaged and undamaged timber elements using the Testo 606-1 device. The MC values were computed as the average of measurements taken along the element, with 3-5 spots measured, each spot subjected to three measurements (refer to Figure 20). The measurements were conducted on various structural elements, including columns, beams, and rafters. Notably, the measurements focused only on the wood surface due to the restrictions against destructive measurements.
- I recorded outdoor and indoor temperature and relative humidity using KIMO AQ 200 device. Outdoor measurements taken in the shade to eliminate the direct influence of sunlight. (see Figure 21).

Note: refer to Table A.2 in appendix A for a comprehensive overview of all data collected throughout the year.

Figure 20. Moisture content measurements in the timber elements of the roof

Figure 21. Devices for the outdoor and indoor measurements of temperature and relative humidity

The following figures (Figures 22 to 27) represent the results and charts of the on-site measurements across the four seasons. From these figures, the following summary for each season can be derived:

Spring season

- Both T and RH exhibited fluctuations throughout the season, with an outdoor T range of 2-33 °C and an outdoor RH range of 30-95 %. The average amplitude of outdoor T was 3.3 °C, where amplitude is defined as the difference between two consecutive measurements. The average amplitude of the outdoor RH was 12.3%;
- Indoor temperature values consistently remained slightly lower than the outdoor RH values, with a difference of only 2-3 °C;

- Indoor RH values consistently registered higher levels, with a margin of 1-3 % throughout the season;
- There is an inverse relationship between T and RH along the season, in accordance with natural climate conditions;
- MC values for beams ranged between 9-22 %, while values for columns and rafters ranged between 13-25 %. The average amplitude of MC was 1.3 %;
- The rate of changes in T, RH and MC – which are related as frequency – was very high during the spring season. However, it remained slightly below the values observed in the autumn season;
- The MC values mirrored the fluctuations in climate factors for all timber elements, indicating significant risks to the structural integrity of the elements.

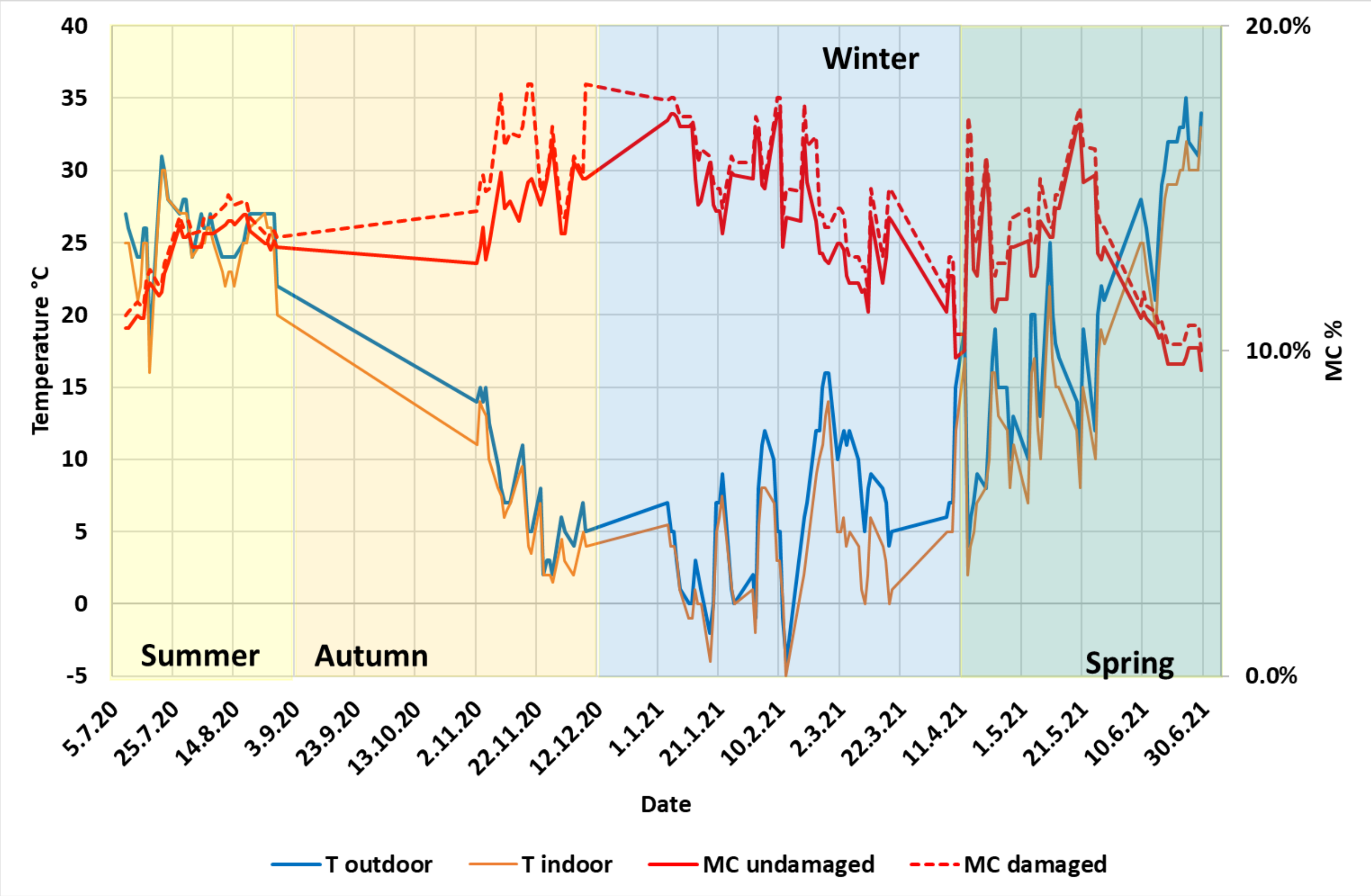


Figure 22. Beams moisture content and temperature vs. date

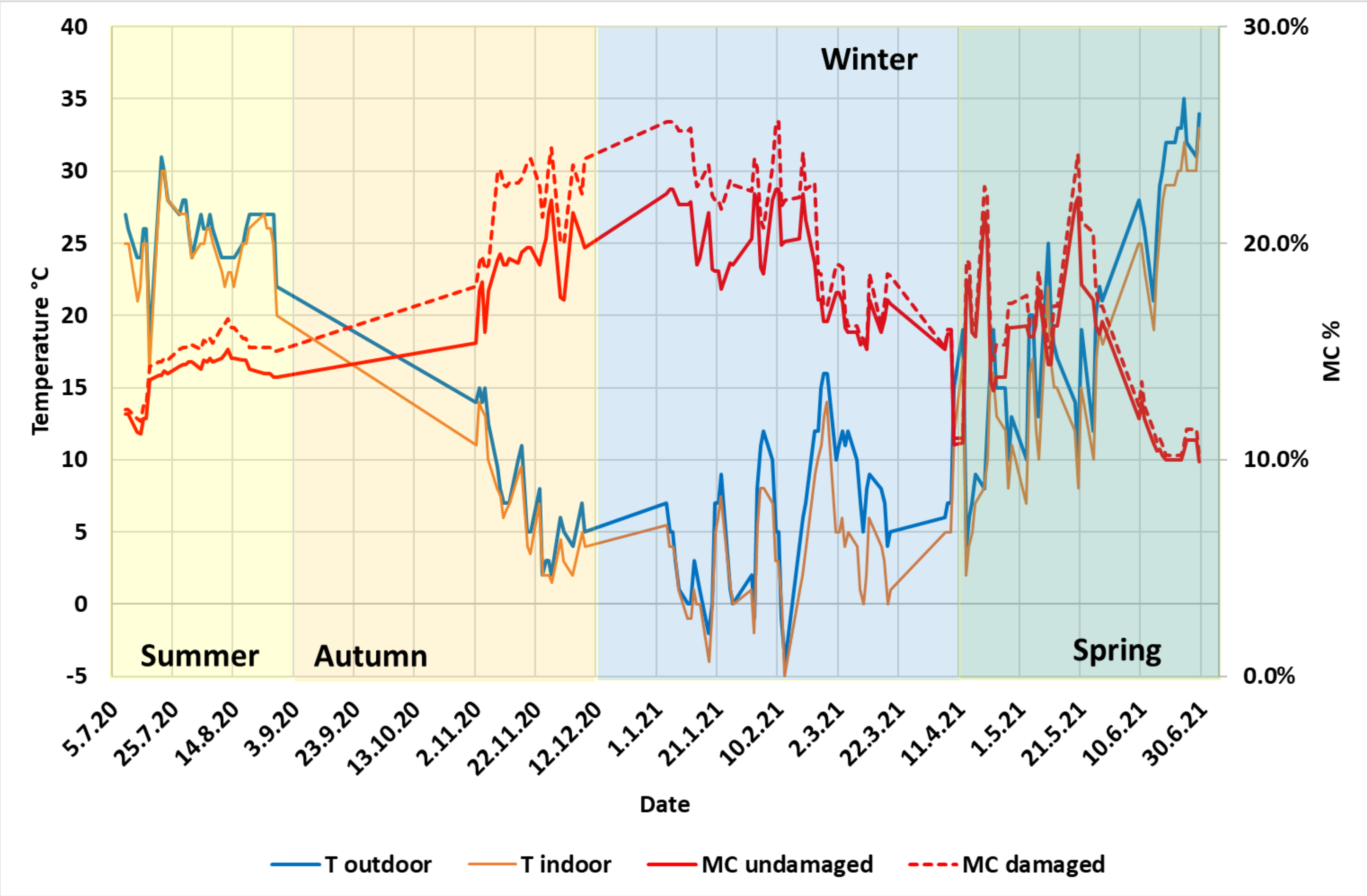


Figure 23. Columns moisture content and temperature vs. date

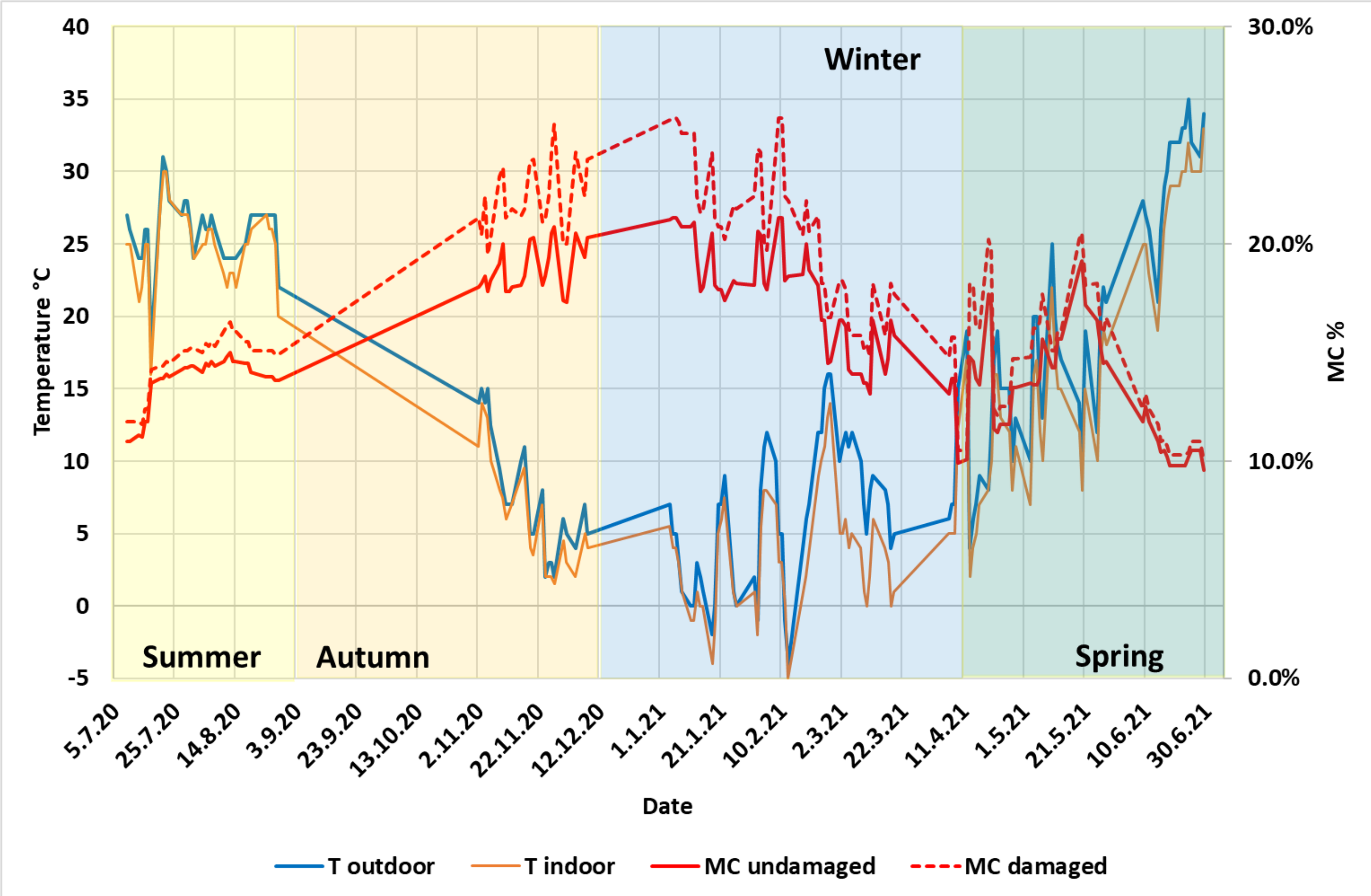


Figure 24. Rafters moisture content and temperature vs. date

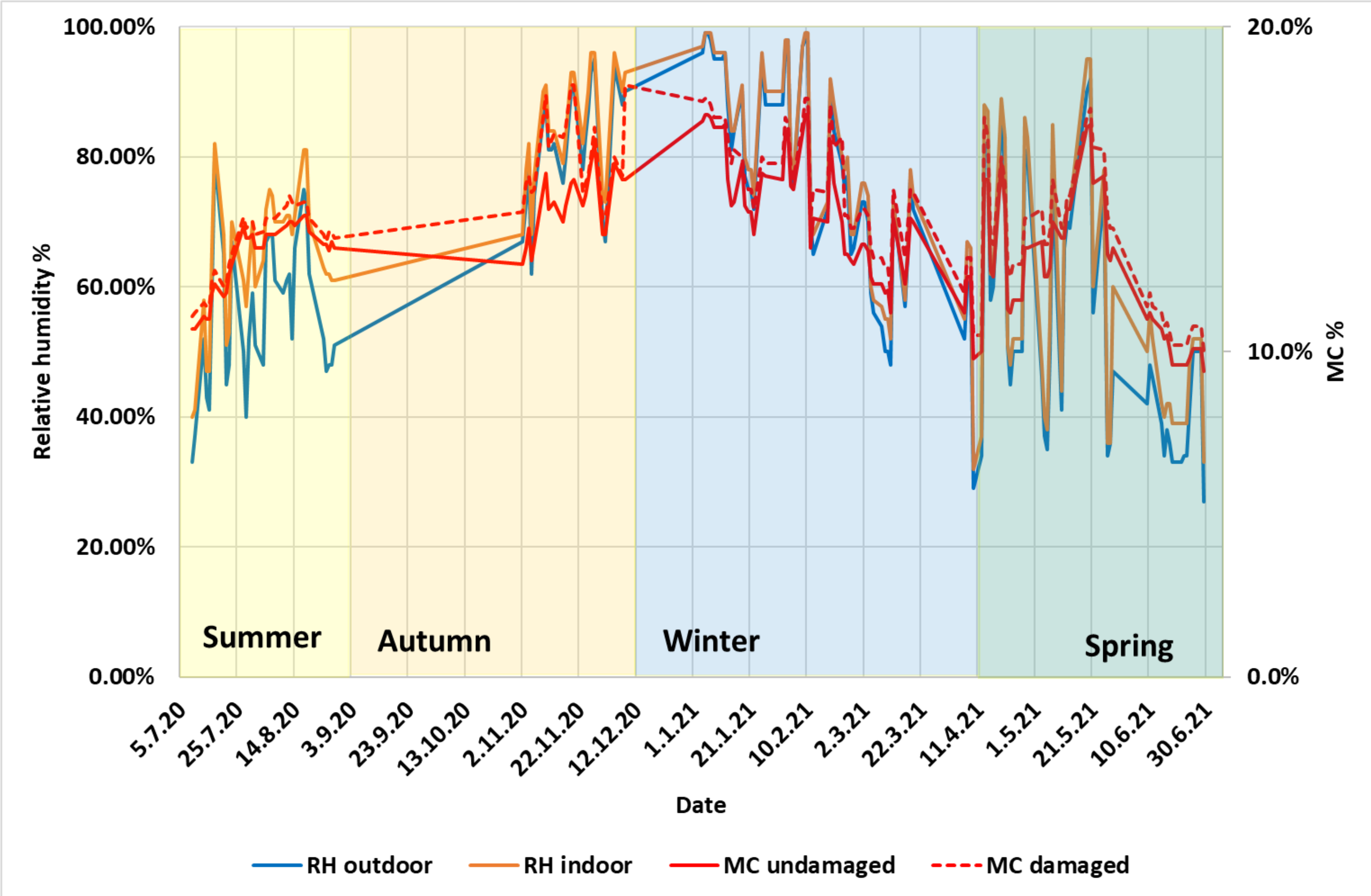


Figure 25. Beams moisture content and relative humidity vs. date

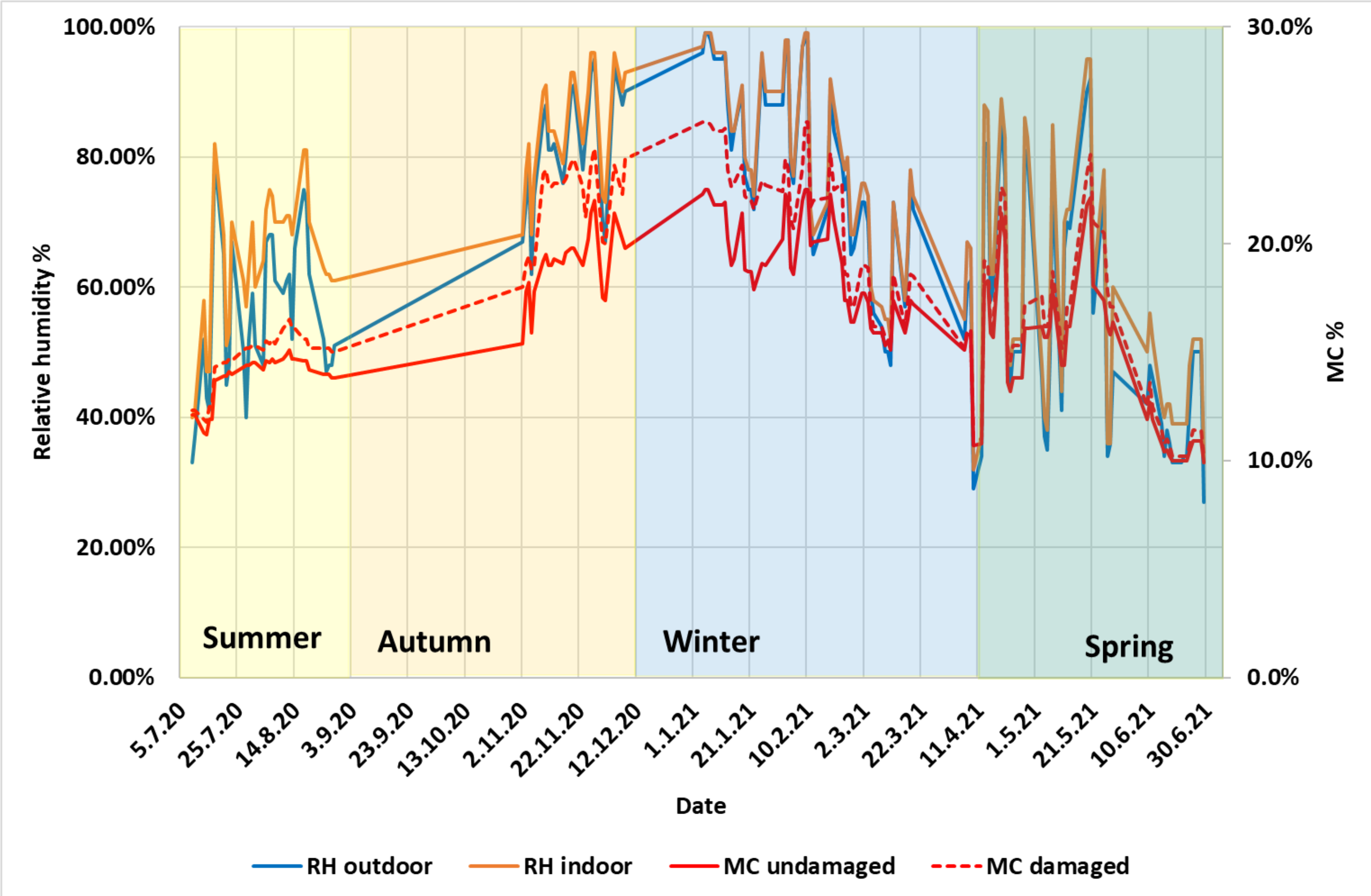


Figure 26. Columns moisture content and relative humidity vs. date

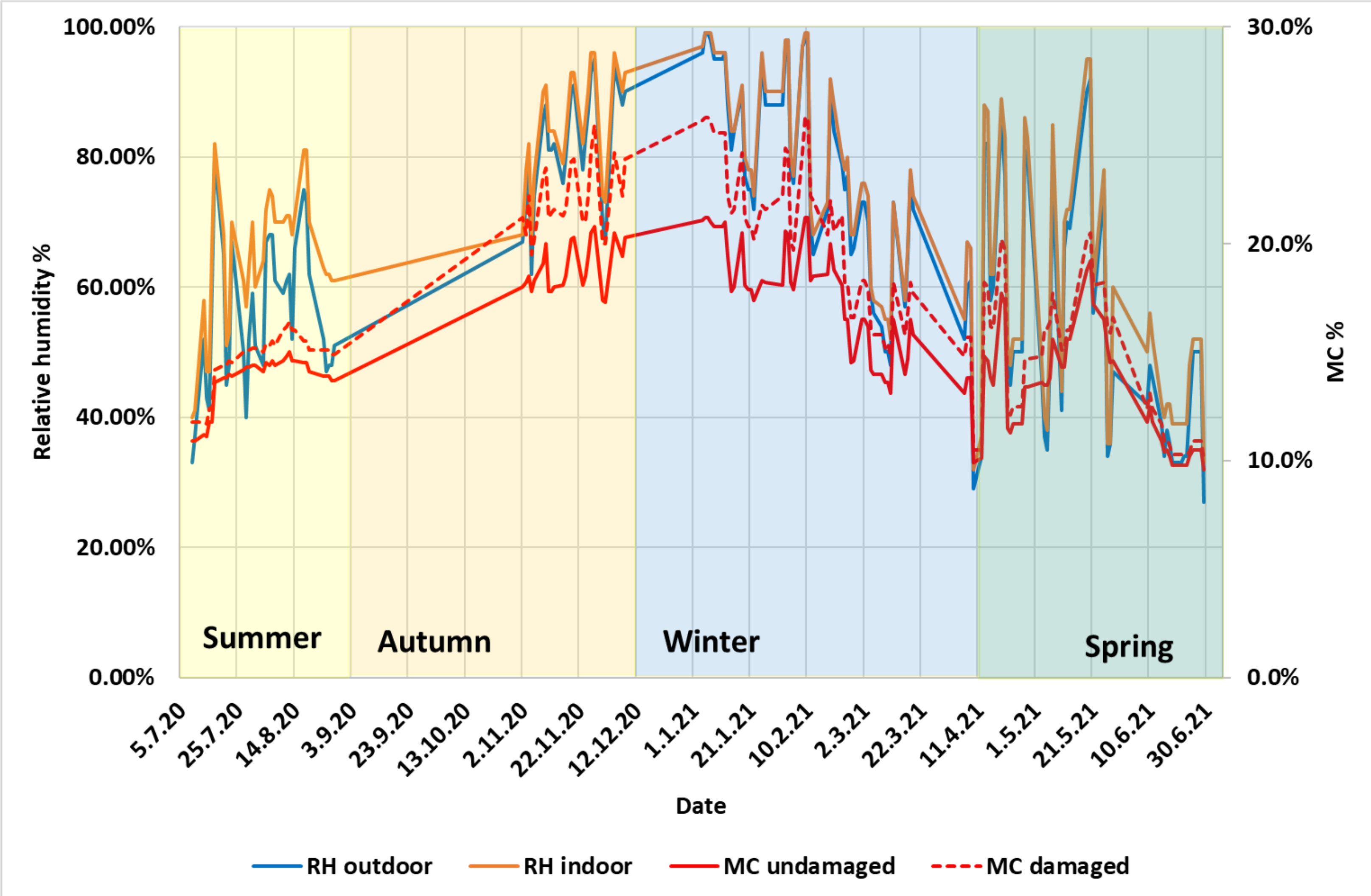


Figure 27. Rafters moisture content and relative humidity vs. date

Summer season

- The outdoor temperature ranged between 18-30 °C, with indoor temperature consistently registering slightly lower values, typically by only 1-2 °C. The average amplitude of the outdoor temperature was 1.5 °C;
- Outdoor RH values fluctuated between 35-80 %, while indoor RH values consistently exceeded outdoor values by 7-11 %. The average amplitude of the outdoor RH was 7.0 %;
- Both temperature (T) and relative humidity (RH) values exhibited an approximately steady rate, with lower fluctuations compared to the spring season. Consequently, the changes in moisture content (MC) values for the structural elements also demonstrated a steady rate;
- MC values for all structural elements ranged between 10-14 %. The average amplitude of MC was 0.3 %, with frequencies (for MC, RH and T) below the levels observed during autumn and spring.

Autumn season

- Outdoor temperatures, ranging between 2-15 °C, exhibit a difference of 1-2 °C between indoor and outdoor values. Relative humidity (RH) values increase within the range of 60-95 %, with a difference of 10-14 % between indoor and outdoor values. The average amplitude of the outdoor temperature was 1.3 °C. The average amplitude of the outdoor RH was 4.9 %;
- MC values for beams ranged between 13-18 %, while values for rafters and columns ranged between 16-24 %. The average amplitude of the MC was 0.7 %. The frequencies of T, RH and MC fluctuations were highest during the autumn season;
- Autumn measurements displayed tendencies similar to summer; the change in MC did not closely follow the daily RH values. However, the average MC values demostrated similar increasing and decreasing tendencies as the average of indoor and outdoor RH values.

Winter season

- A high fluctuation rate is noticeable in this season for both T and RH, with a T range of -4-14 °C and an RH range of 50-98 %. The average amplitude of the outdoor temperature was 2.4 °C. The average amplitude of the outdoor RH was 8.4 %;
- Indoor temperature values consistently remained slightly lower than the outdoor values, typically by only 2-3 °C;
- Indoor RH values consistently registered higher levels, with a margin of 2-4 % throughout the season;
- There is an inverse relationship between temperature (T) and relative humidity (RH) along the season, in accordance with natural climate conditions;
- MC values for beams ranged between 11-18 %, while values for columns and rafters ranged between 13-25 %. The average amplitude of MC was 1.5 %;
- The frequencies of T, RH and MC fluctuations were the lowest during the winter season;

- The MC values mirrored the fluctuations in climate factors for all timber elements, indicating significant risks to the structural integrity of the elements.

Based on these measurements, the primary damages to the wooden elements in the roof occur during the spring and winter seasons due to high fluctuation in RH and T values. This leads to the absorption and release of the water, aiming to reach the equivalent moisture content point. Consequently, the wooden cell size undergoes changes, experiencing shrinkage and swelling, which generate internal stresses leading to the development of new cracks and splits.

These results might be accentuated with the anticipated results from the meteorological study, indicating an extended winter season in the future and an expected increase in humidity fluctuation. Consequently, the timber elements will be exposed to more severe conditions, resulting in increased deterioration.

4.1.4. Statistical calculations and data evaluation

To assess the reliability of the measurement results, statistical calculations have been performed for all the seasons. Table 3 displays the calculated statistical values for all the seasons, while Table 4 presents the correlation between the MC and the climate factors.

Table 3. Statistical evaluation of the measured data for all seasons (D – damaged, UND – undamaged)

	Min-Value	Max-Value	Avg-Value	Variance	Standard Deviation
	Spring				
T_{out} °C	4.00	35.00	19.04	80.25	8.95
T_{in} °C	2.00	33.00	16.62	76.62	8.75
RH_{out} %	27.00	92.00	53.00	3.37	18.36
RH_{in} %	32.00	95.00	57.27	3.42	18.5
MC% (UND Beam)	9.40	17.00	12.29	0.04	2.08
MC% (D Beam)	10.00	17.50	13.04	0.05	2.17
MC% (UND Rafter)	9.60	19.20	13.11	0.07	2.58
MC% (D Rafter)	10.00	20.50	14.36	0.10	3.14
MC% (UND Column)	9.90	22.10	14.49	0.12	3.41
MC% (D Column)	10.10	24.10	15.36	0.15	3.84
	Summer				
T_{out} °C	18.00	31.00	25.91	5.41	2.32
T_{in} °C	16.00	30.00	24.85	7.46	2.73
RH_{out} %	33.00	80.00	55.62	1.28	11.33
RH_{in} %	40.00	82.00	64.15	1.11	10.53
MC% (UND Beam)	10.70	14.20	12.95	0.01	1.09
MC% (D Beam)	11.10	14.80	13.37	0.01	1.13

MC% (UND Rafter)	10.90	15.00	13.71	0.01	1.20
MC% (D Rafter)	11.70	16.40	14.64	0.02	1.35
MC% (UND Column)	11.20	15.10	13.88	0.01	1.06
MC% (D Column)	11.80	16.50	14.77	0.02	1.30
	Autumn				
T_{out} °C	2.00	15.00	7.70	16.75	4.09
T_{in} °C	1.50	14.00	6.47	15.01	3.87
RH_{out} %	62.00	95.00	81.46	0.85	9.22
RH_{in} %	68.00	96.00	84.58	0.73	8.55
MC% (UND Beam)	12.70	16.40	14.55	0.01	1.00
MC% (D Beam)	14.10	18.20	16.06	0.02	1.29
MC% (UND Rafter)	17.30	20.80	18.87	0.01	1.12
MC% (D Rafter)	19.50	25.50	22.05	0.03	1.62
MC% (UND Column)	15.40	22.00	19.08	0.02	1.58
MC% (D Column)	18.00	24.40	21.93	0.04	1.94
	Winter				
T_{out} °C	-4.00	16.00	6.184	24.23	4.92
T_{in} °C	-5.00	14.00	3.459	16.19	4.02
RH_{out} %	48.00	99.00	78.63	2.23	14.93
RH_{in} %	52.00	99.00	80.49	2.00	14.13
MC% (UND Beam)	11.20	17.3	14.58	0.03	1.81
MC% (D Beam)	11.80	17.8	15.37	0.03	1.66
MC% (UND Rafter)	13.10	21.2	17.8	0.06	2.48
MC% (D Rafter)	14.80	25.8	20.67	0.12	3.43
MC% (UND Column)	15.10	22.5	19.13	0.06	2.37
MC% (D Column)	15.20	25.6	21.2	0.11	3.26

Table 4. Correlation factor between MC and climate components

Correlation between MC		
	$RH_{-Indoor}$	$T_{-Indoor}$
Undamaged Beams	0.90	-0.60
Damaged Beams	0.89	-0.65
Undamaged Rafters	0.89	-0.71
Damaged Rafters	0.87	-0.76
Undamaged Columns	0.87	-0.80
Damaged Columns	0.87	-0.79

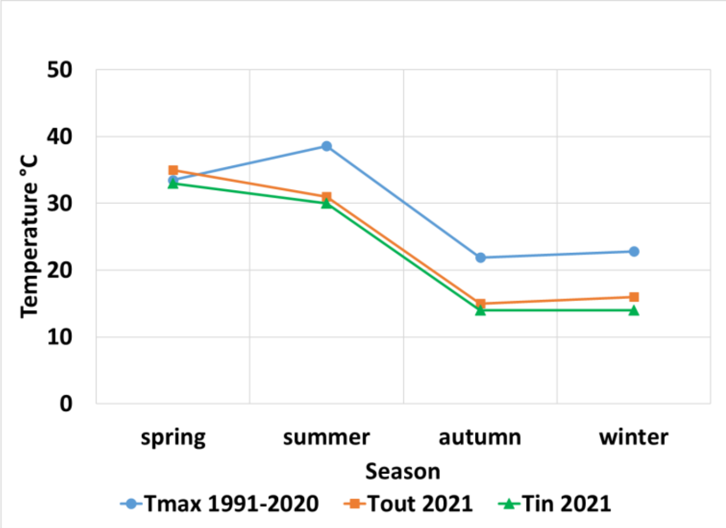


Figure 28. Maximum temperatures (Tmax) for the period 1991-2020,, outdoor (Tout) and indoor (Tin) temperatures for the year 2021 versus seasons

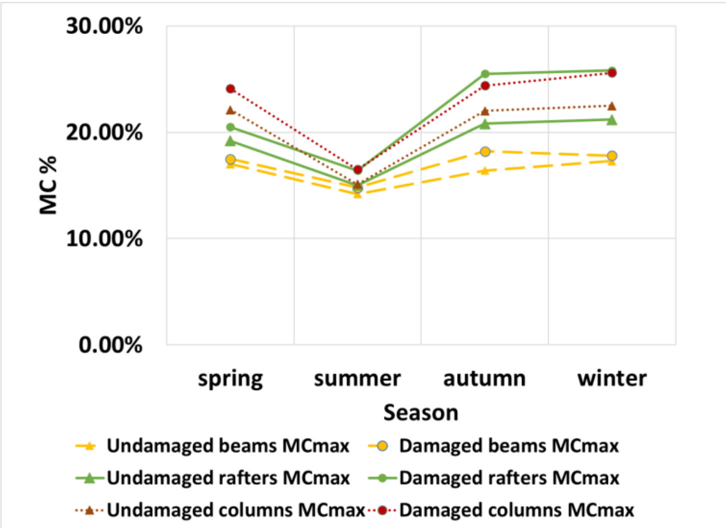


Figure 29. Maximum MC values for the studied structural elements versus seasons

If we compare the maximum average temperatures for Hungary, for the period between 1991 and 2020 with the on-site measured temperatures during the four seasons in 2021 (Figure 28), it becomes evident, that the measured daytime temperatures exhibit a similar trend to the latest 30-year period. According to the Hungarian Meteorological Service, the average yearly temperature change from 1981 to 2020, within a 90% confidence interval, is of 1.7 °C. The seasonal change in maximum temperatures from 1981 to 2020 is as follows: 1.4 °C for spring, 2.1 °C for summer, 1.5 °C for autumn and 1.9 °C for winter. The largest significant temperature change is observed in summer.

Precipitation not only exhibits variability over time but also in space, posing a greater challenge in detecting long-term trends compared to temperature. According to data from the Hungarian Meteorological Service, there is a decreasing trend in the number of rainy days on a national average as we approach the present, starting from 1901. While days with precipitation exceeding 20 mm have increased, the duration of dry periods (defined as the longest period when daily precipitation does not reach 1 mm) has also extended since the early 20th century. Furthermore, the daily intensity, also known as average daily precipitation (the ratio of the total precipitation over a given period to the number of rainy days), has witnessed an increase during the summer months. This rise in average daily precipitation implies that precipitation is increasingly concentrated in the form of short, intense showers and thunderstorms. Importantly, this precipitation trend strongly correlates with the measured relative humidity values.

Based on on-site indoor seasonal measurements (refer to Figures 22 to 27 and Table 4 for Pécs), the most significant temperature fluctuations, characterized by short frequencies and large amplitudes, are observed during the spring period, followed by fluctuations in winter temperatures. The most considerable RH fluctuations occur during summer and winter periods. Corresponding to the changes in temperature and RH, MC fluctuations for all three types of timber elements (beams, rafters, columns) are most pronounced during spring, followed by the winter period.

It is noteworthy that MC values for all three timber elements exhibit high constancy during the summer period, despite relatively short RH fluctuation frequencies. However, the amplitude of RH fluctuations in summer is much lower than during spring and even the winter period. This suggests that RH values alone cannot fully explain the changes in MC in the timber elements.

Furthermore, despite the Hungarian Meteorological Service indicating the largest temperature rise in Hungary during summer, the timber elements are less affected in this season compared to spring when they experience the most significant impact. Therefore, it can be asserted that solely considering the average global or regional temperature change does not allow for precise prediction or modeling of the future behavior of timber structures. Fluctuations in temperature and RH, potentially measured on-site, must be taken into account.

The statistical data confirm the stability of moisture content (MC) values for the structural elements in both summer and autumn seasons. Despite the high dispersion in temperature (T) values in autumn, the MC values exhibit small variance (σ^2) and standard deviation (σ) due to the uniformity in relative humidity (RH) values. Summer is considered the most stable season because of the smallest σ^2 and σ values. The highest dispersion in T and RH data is observed in spring and winter, with the highest values of σ^2 and σ, leading to high dispersion in MC values in the structural elements. Thus, the most severe impact on the roof occurred during spring and winter.

The data indicate that the impact of RH on MC values is greater than the impact of temperature. Higher dispersion in RH results in high σ^2 and σ values and lower stability in MC values. To quantify this result, the correlation factor between the climate components and MC for the entire measuring period has been calculated and is shown in Table 5. The table illustrates that RH has a greater impact on MC values than temperature. Damaged elements are more affected than undamaged ones, and as the bearing load increases on the element, the impact becomes more significant. For example, in this roof system, the columns are the main structural elements resisting the loads and are the most affected.

All results from the above presented analyses can be summarized as follows:

- The roof experiences the most strain at the beginning and end of the year (winter season);
- Urgent rehabilitation is required for the roof, and over time, it may harm the underfloor level as well;
- RH, and to a lesser extent, temperature values affect the equilibrium moisture content of the wood. With changes in RH and temperature, the EMC adjusts, causing the wood to release or absorb moisture to re-acclimate. This re-acclimation period is when warping, cracking, and splitting can occur in the wood;
- Over the last 120 years, Pécs has undergone numerous temperature fluctuations and changes in heating and cooling periods. Since wood is a natural material directly affected by climate components, this historical roof structure has suffered considerably, necessitating this study to assess the wood's condition;
- There is a relationship between the load capacity of the structural element and the moisture content values. In the floor system, columns and rafters carry more load, resulting in higher moisture content values.
- Indoor humidity or humidity values, in general, have a more significant effect on MC values than temperature values. The correlation between indoor humidity and MC values is around 88%, whereas between MC and temperature values, it is around 75%.

4.2. Makovecz Imre kilátó- Makovecz Imre Lookout Tower

4.2.1. Historical meteorological analysis

The Makovecz Imre Tower is situated in the Budapest area, specifically in the Buda hills. This region is located in the Central-Northern part of Hungary, characterized by intraregional temperature variance and moderate precipitation totals, leading to higher humidity compared to other continental regions. Consequently, the climate conditions of this area had to be analysed separately from the Pécs region, based on data from the Hungarian Meteorological Service.

The data evaluation reveals that Budapest's climate has undergone fluctuations over the past 120 years, but it demonstrates greater stability compared to Pécs. In contrast to Pécs, the average number of summer days has been increasing since 1975. Consequently, a prolonged summer period can be anticipated in the next two decades (see Figure 30). The graph illustrating the number of winter days over the years shows a significant decline starting in 1999, with the last period of increased winter days recorded in 1930 (see Figure 31). This clearly indicates that Budapest is more vulnerable to the impacts of global warming than Pécs. The precipitation amount graph reveals a post-1990 increase in yearly precipitation, although Budapest's average yearly amount lags behind Pécs by 100–150 mm (see Figure 32).

Note: For the complete data from 1901 to 2020, please refer to Table A.3 in appendix A.

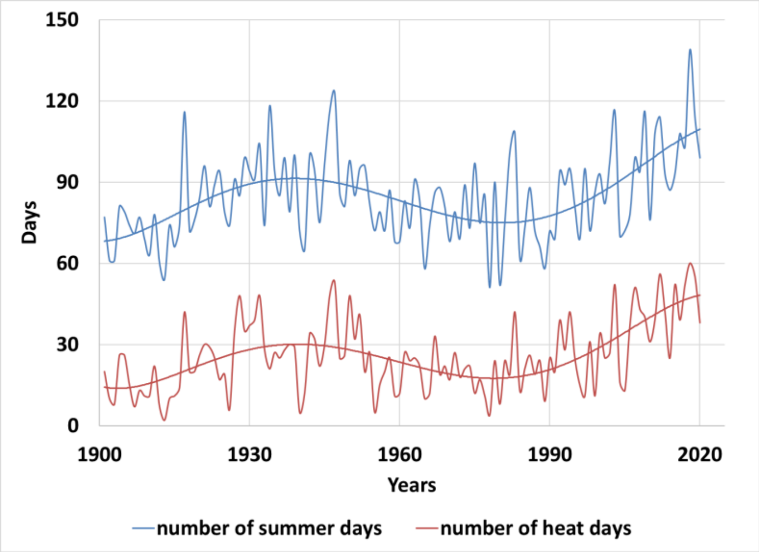


Figure 30. Number of summer days and heat days for Budapest region

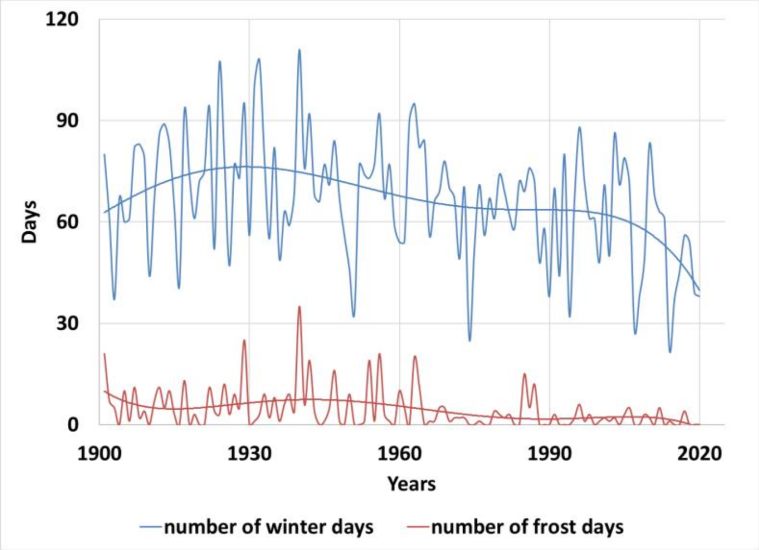


Figure 31. Number of winter days and frost days for Budapest region

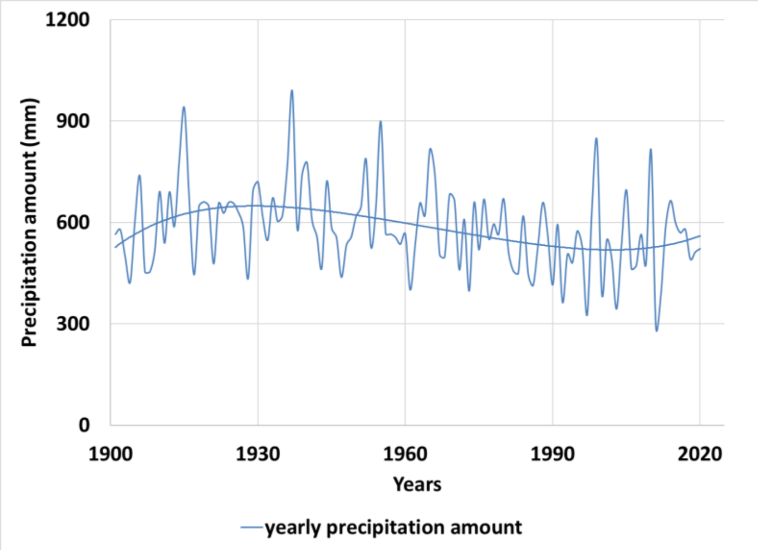


Figure 32. Yearly precipitation amount for Budapest region

4.2.2 Site visual inspection

The visual inspection reveals the tower to be in excellent condition. The stairs have a thickness of approximately 25 cm, with a width ranging from 20 to 30 cm and a length varying between 90 and 105 cm. Due to the helix form of the stairs, the column cross-section measures 12x12 cm². The wooden surface remains in good condition and vibrant colour, thanks to protective paint. However, it is worth noting that the colour begins to fade gradually from the centre towards the fence, a consequence of exposure to sunlight. Cracks are evident in various locations on the tower, attributed to environmental factors such as rain and wind, as well as the live load from people moving about (see Figure 33).

Figure 33. Cracks in the Makovecz Imre lookout tower [own photo]

4.2.3 On-site measurements

In this stage I measured T, RH, and MC for the wooden elements of the tower. The measurements were conducted over four seasons through weekly visits to comprehensively assess and monitor the condition of the timber elements of the tower throughout the year. The measurements started on July 10, 2021, and finished on April 29, 2022. The measurement procedure involved striking each wooden element at 10 different spots along its length and recording the average values. The primary elements measured were the columns (designated as C), stairs (designated as S), and fences (designated as F). The tower was segmented into five elevations, progressing from the top to the bottom. Columns in elevation 1 were denoted as C1, and a similar process was applied to the other parts. The process is illustrated in Figure 34 and Figure 35.

Figure 34. On-site measurement process in the Makovecz Imre lookout tower [own photo]

Figure 35. On-site measurements on the timber elements of the tower [own photo]

The following figures (Figures 36 to 41) depict the results and charts from the site measurements of the columns, stairs, and fences conducted over the four seasons. Throughout the measured period, the maximum temperature and relative humidity reached 31.3 °C and 94 %, respectively, while the minimum temperature and relative humidity were 2 °C and 30 %, respectively. All the elements fall under class 1 as per Eurocode [CEN, 2006], where the MC is less than or equal to 12 %, unless the columns in the winter season reach an MC of 13.8 %, classifying the columns as class 2 timber elements. The column MC values ranged between 10 and 14 %. Notably, columns at higher elevations exhibited greater MC values. The stair elements recorded MC values that varied in the range of LO – 8 %, LO being a value below the detectable limit, while the fences recorded MC values varied in the range of small values that varied in the range of LO – 9 %.

Recorded seasonal average values reveal notable variations in temperature, RH and MC. Spring emerges as the season with the most significant changes:

- Average outdoor T amplitudes: 4.7 °C for spring, 3.1 °C for summer, 4.9 °C for autumn and 3.7 °C for winter;
- Average outdoor RH amplitudes: 38 % for spring, 13 % for summer, 20 % for autumn and 16 % for winter.
- Average MC amplitudes for columns, rafters and fences followed the T and RH values: 0.9 % for spring, 0.7 % for summer, 0.7 % for autumn and 0.5 % for winter;
- The frequencies peak in the winter season, summer, spring and autumn seasons closely trail, showing minimal differences. Frequency is defined as the rate of the change of rate of fluctuation in the recorded values of T, RH and MC values – how often these values change from one measurement to the next within a given time period, associated with the season.

Note: If the MC is less than 6 %, the Testo 606-1 device presents the result as LO.

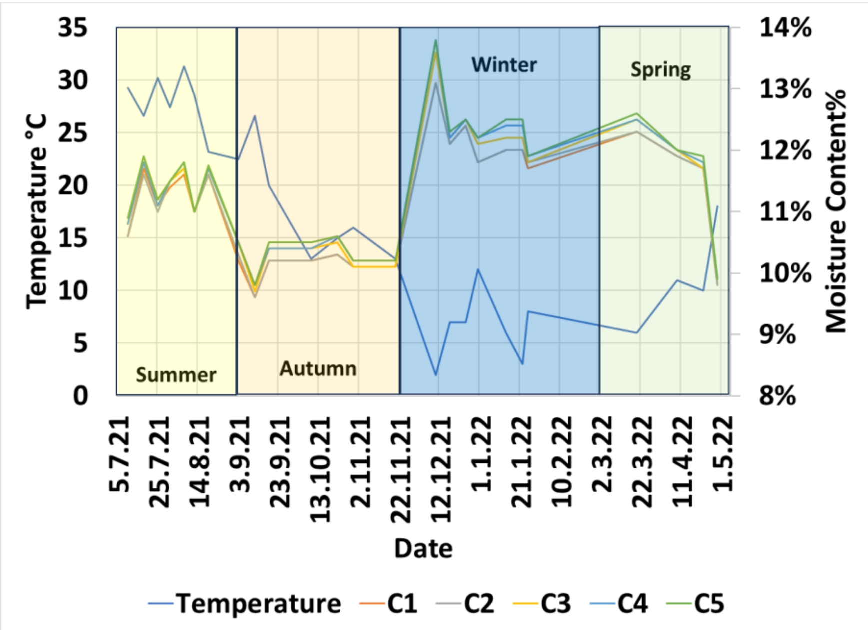


Figure 36. Columns moisture content and temperature vs. date (Makovecz Imre tower)

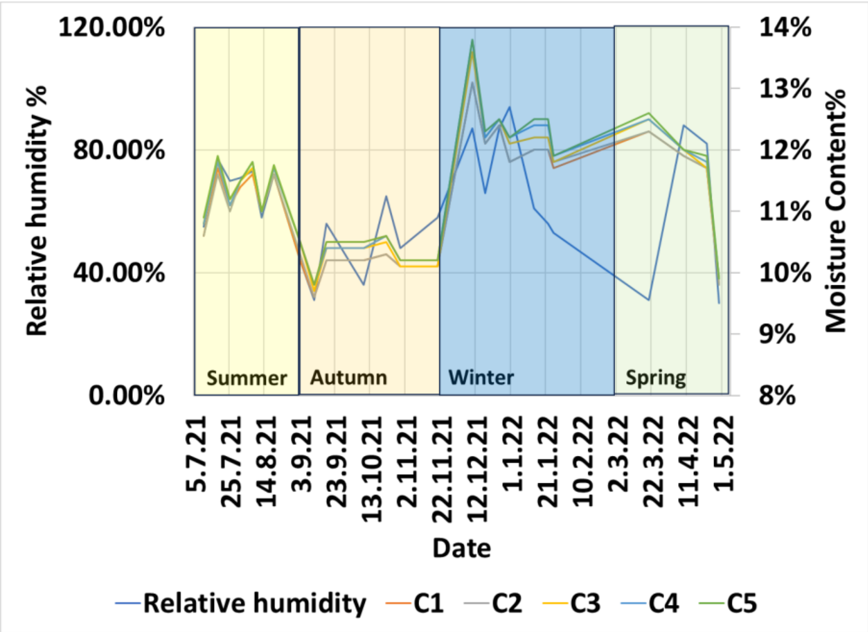


Figure 37. Columns moisture content and relative humidity vs. date (Makovecz Imre tower)

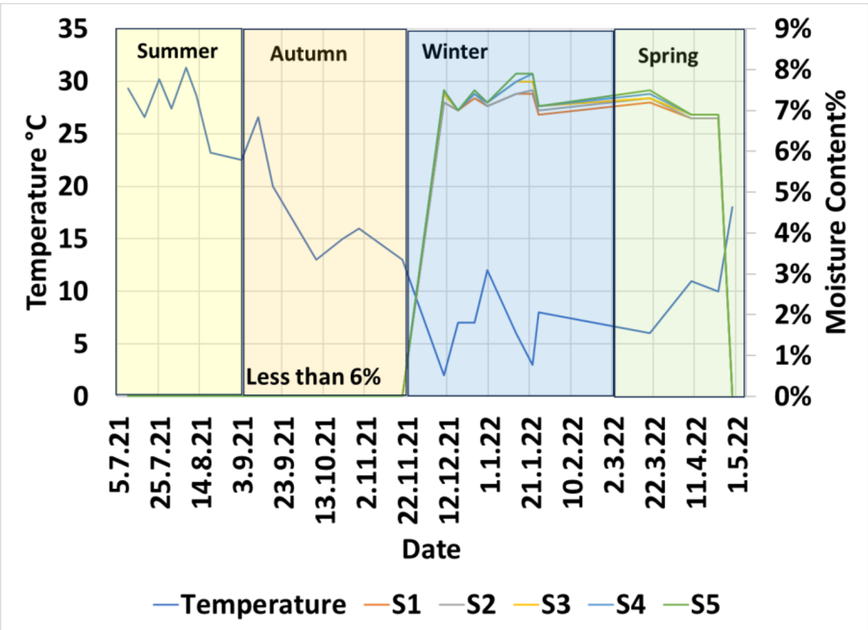


Figure 38. Stairs moisture content and temperature vs. date (Makovecz Imre tower)

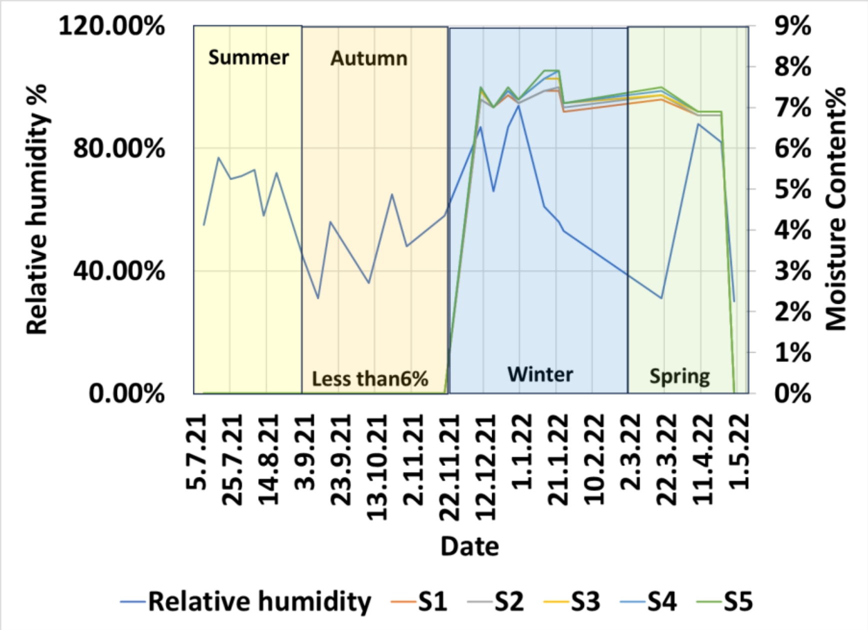


Figure 39. Stairs moisture content and relative humidity vs. date (Makovecz Imre tower)

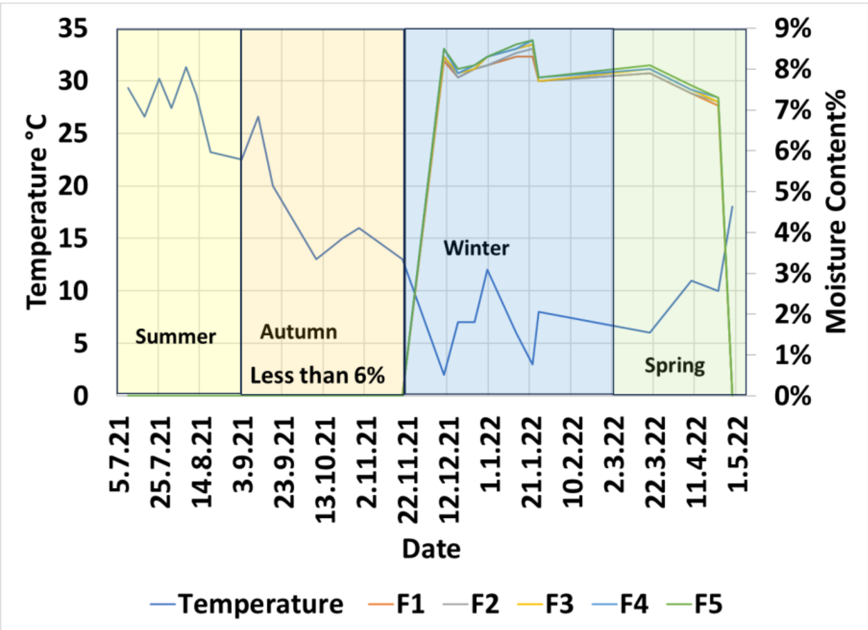


Figure 40. Fences moisture content and temperature vs. date (Makovecz Imre tower)

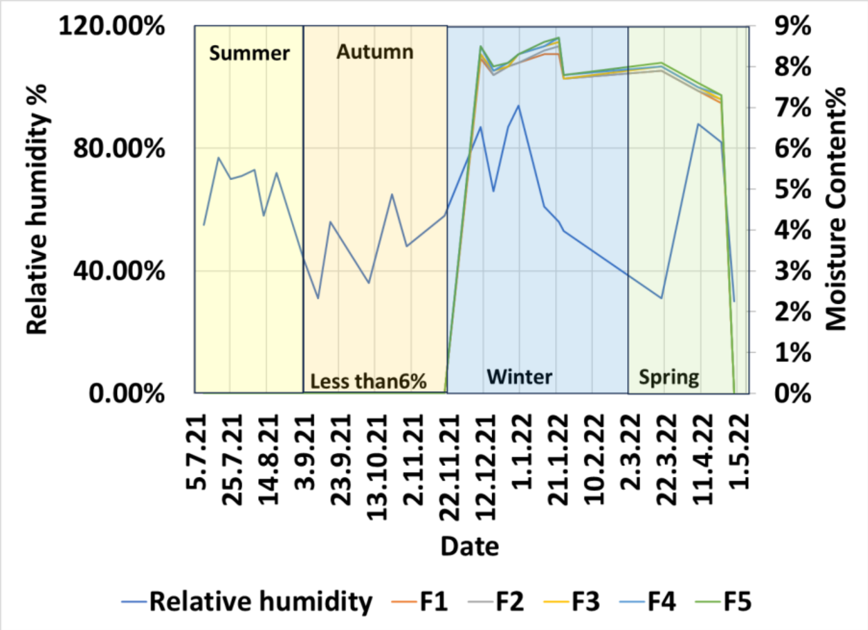


Figure 41. Fences moisture content and relative humidity vs. date (Makovecz Imre tower)

In general, all the elements exhibited high stability against changes in climate factors, as evidenced by the narrow range of MC values, in contrast to the Civil Community House in Pécs. This can be attributed to the tower's renovation in 2018, which accounts for the low MC values observed in the elements. Furthermore, the painted layer on the surface serves as a protective barrier, shielding the wooden elements from the impact of weather changes and surrounding conditions. These results underscore the significance of regular evaluation and renovation practices.

4.2.4. Statistical calculations and data evaluation

Similar to the evaluation conducted for the Civil Community House, I have analysed the measurement results by statistical calculations across all seasons. Table 5 displays the calculated statistical values for each season, while Table 6 illustrates the correlation between the MC and the climate factors.

Table 5. Statistical evaluation of the measured data for all seasons

	Min Value	Max Value	Avg Value	Variance	Standard Deviation
	Spring				
T °C	6.0	18.0	11.3	24.92	4.99
RH %	30.0	88.0	57.8	0.100	0.32
MC % (Columns)	9.8	12.6	11.5	0.0001	0.01
MC % (Stairs)	LO	7.5	7.0	0.00001	0.002
MC % (Fences)	LO	8.1	7.6	0.00001	0.003
	Summer				
T °C	23.2	31.3	28.1	7.2	2.7
RH %	55.0	77.0	68.0	0.007	0.08
MC % (Columns)	10.6	11.9	11.4	0.00001	0.004

MC % (Stairs)	LO	LO	LO	LO	LO
MC % (Fences)	LO	LO	LO	LO	LO
	Autumn				
T °C	13.0	26.6	18.0	26.9	5.18
RH %	31.0	65.0	48.3	0.015	0.12
MC % (Columns)	9.6	10.6	10.2	0.00001	0.003
MC % (Stairs)	LO	LO	LO	LO	LO
MC % (Fences)	LO	LO	LO	LO	LO
	Winter				
T °C	2	12	6.4	10.95	3.31
RH %	53.0	94.0	72.0	0.03	0.17
MC % (Columns)	11.7	13.8	12.3	0.00003	0.01
MC % (Stairs)	6.9	7.9	7.3	0.00001	0.003
MC % (Fences)	7.7	8.7	8.2	0.00001	0.003

Table 6. Correlation factor between MC and climate components

Correlation between MC		
	T	RH
Columns	-0.54	0.40
Stairs	-0.25	-0.36
Fences	-0.11	-0.18

The statistical data confirmed the stability of timber elements in the tower. The low standard deviation observed in all seasons indicates that the data are closely clustered around the mean. Consequently, there is high stability and resistance against the various climate components. Despite the columns being the most affected elements, they remain in very good condition.

In terms of correlation factor results, the elements appear to be minimally affected by changes in the climate components. The correlation values, which do not generally exceed half, suggest the robust preservation of the structure. However, it's noteworthy that the columns remain the most affected elements.

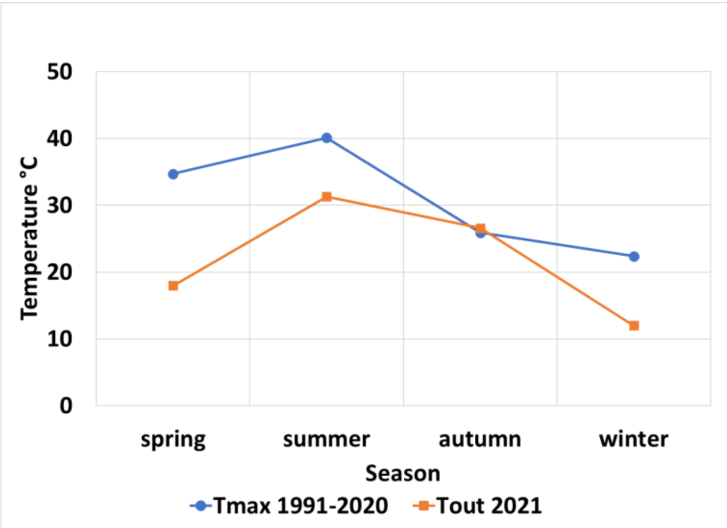


Figure 42. Seasonal average maximum temperatures for the period of 1991-2020 and 2021 (Budapest region)

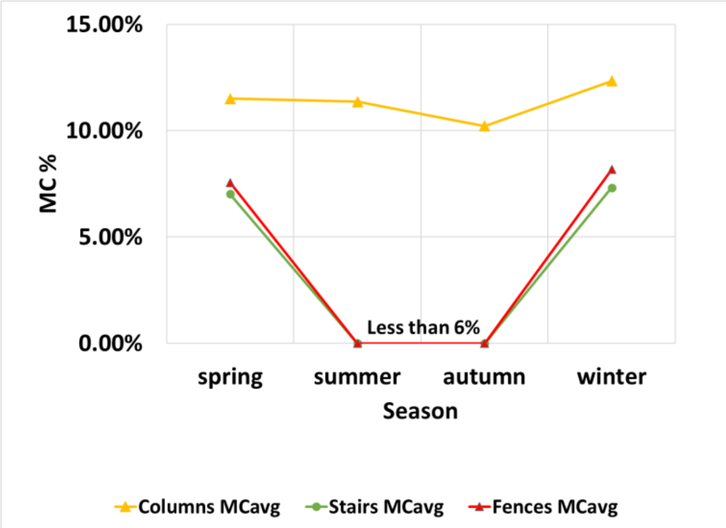


Figure 43. Seasonal average MC values for the various structural element (Budapest region)

Comparing the maximum average temperatures for Budapest from 1991 to 2020 with the on-site measured temperatures during the studied four seasons from 2021 to 2022 (see Figure 42), it is evident that, despite the absence the absence of measured maximum temperature values for the studied period, the measured daytime temperatures exhibit a similar trend to the latest 30-years period. Notably, the seasonal MC values are the highest for columns (Figure 43).

According to the on-site outdoor seasonal measurements (see Figures 36 to 41 and Table 5 for Buda-Hills), the most significant temperature fluctuations, characterized by short frequencies and large amplitudes, are observed for the winter period. Short frequencies of temperature fluctuation are also noted for the summer period, but with shorter amplitudes. Meanwhile, large amplitudes are found for temperature fluctuations during the autumn period. The RH fluctuations exhibit a high frequency for the summer, outdoor measurements, autumn, and winter periods, with the largest amplitudes observed for the summer and winter periods. In alignment with the temperature and RH variations, MC fluctuations for all three types of timber elements (columns, stairs and fences) are notable during the winter period. However, during the spring and summer periods, the surface MC values fall below the detection limit (6%).

4.3. Four points bending test

To complete the research process and understanding the impact of climate factors in Hungary on moisture content of the wooden elements, leading to structural damage, numerous samples underwent laboratory testing using the 4PB testing technique. In this test, I assessed the influence of changes in MC on the mechanical properties of timber, both with and without cover material. The primary mechanical property parameters characterizing timber members under bending load include modulus of rupture (MOR) and modulus of elasticity (MOE). MOR is defined as the specimen's maximum strength just before failure, and MOE is defined as the ratio between the active stress load and the resulting strain (deformation) that the wood exhibits along its length.

4.3.1. Testing samples

Softwood samples (Picea abies) with a cross-section of 50×50 mm^2 were acquired from Pécs Lambéria Diszkont Kft.. The samples were obtained in the form of 4 m long wooden boards, subsequently cut into 1 m long pieces, resulting in a total of 120 pieces of C16 Spruce (Picea Abies) being examined.

I conducted tests on three sample groups (see Figure 44, 45, and 46) using four-point bending tests in accordance with Hungarian standards. An Instron testing machine was employed, and the load and deflection were monitored at 0.1 s intervals.

The average mechanical properties for the samples were 52.29 MPa for MOR, 11.2 GPa for MOE, with an average density of 366 kg/m^3. Following the cutting process, the samples were categorized into groups A, B and C. Group A comprised samples tested under natural conditions (room T at 23.8 °C and RH at 29.3 %). Group B consisted of samples submerged in water (pH 6.5, total hardness 50 CaO mg/l) for 7 days until reaching a fully saturated state, while group C underwent testing under the same conditions as group B but was coated with a protective material before submersion. The protective material used, Sadolin Extra, is a commercially available outdoor silk-gloss thick glaze designed to protect and decorate outdoor wooden surfaces. According to the manufacturer, it offers long-lasting protection against weather and UV radiation from the sun. Additionally, it has a water-repellent effect and is absorbed by the wood.

Figure 44. Group A samples [own photo]

Figure 45. Group B samples [own photo]

Figure 46. Group C samples [own photo]

4.3.2. Testing and analysis

To calculate MOR and MOE values for the tested sample, the load analysis was conducted as follows:

- Shear force diagrams and the bending moment diagrams were generated for each sample to identify the maximum shear force and maximum bending moment (see Figure 47). The force values applied to the samples were obtained from the testing machine. The maximum shear value was equal to the half of the product of the maximum force and the loading span distance ($\frac{F.a}{2}$), where F represents the maximum load value when the sample reaches the breaking point and a is the loading span distance (which is equal to 300 mm).

$\sigma = \frac{3Fa}{bh^2}$,

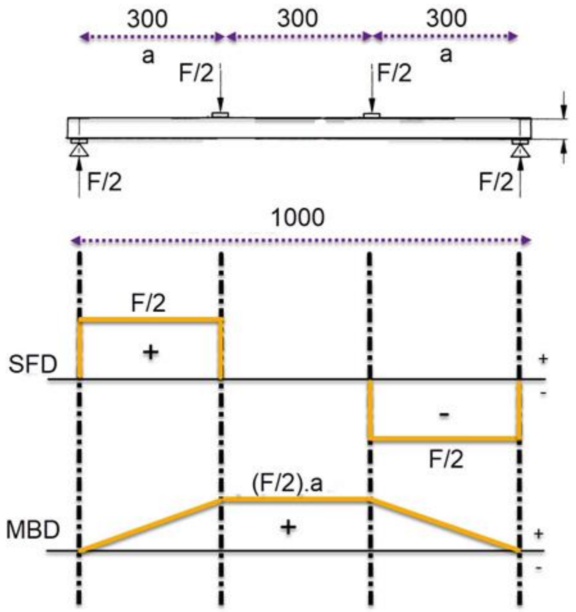


Figure 47. Load analysis of the testing sample

- Utilizing the load and displacement (extension) data imported from the machine, a load vs. displacement curve has been generated for each sample (see Figure 48);

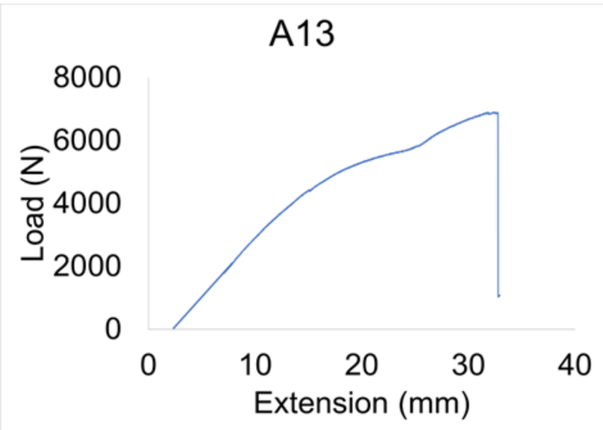


Figure 48. Load vs. displacement curve generated by the testing machine for sample A13

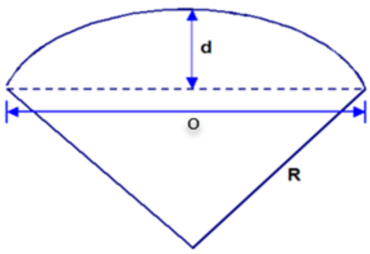
- The MOR and the strain (ε) values of each sample were calculated using the following equations, respectively:

$$\sigma = \frac{3Fa}{bh^2}, \quad (1)$$

$$MOR = \frac{a(F_{\max}/2)(h/2)}{bh^3/12} = \frac{3F_{\max}a}{bh^2}, \quad (2)$$

$$\varepsilon = \frac{h}{2R},\tag{3}$$

where h and b are the depth and width of the cross section, and R is the radius of the measured curvature, using the displacement values (d) and the full span length (o) which was equal to 900 mm (see Figure 49).



$$R = \frac{o^2 + 4d^2}{8d}$$

Figure 49. Radius of curvature

- As MOR and strain values are generated for each sample, a stress vs. strain diagram can be constructed to calculate MOE values. The MOE is determined as the slope of the linear part in the diagram (see Figure 50).

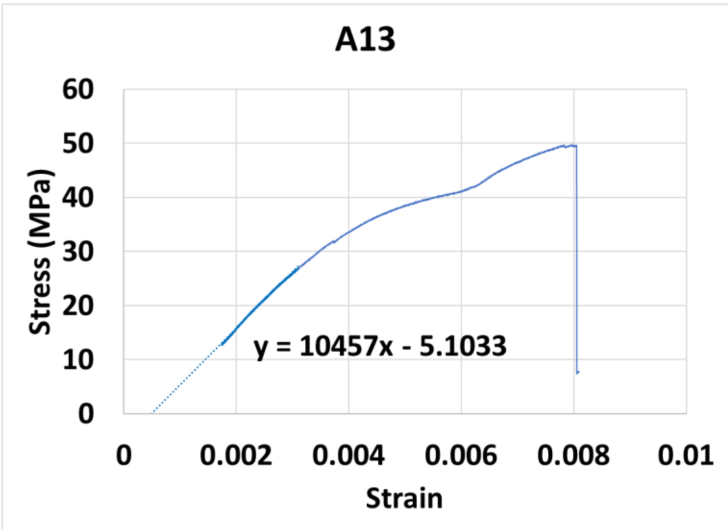


Figure 50. Stress vs. strain diagram for sample A13

- Surface MC was calculated using the Testo 606-1 for each sample. To accurately calculate the MC and density, a 9 cm long piece was cut from each sample and weighted, with its mass denoted as m_1 (measured in a temperature range of 22 – 23 °C). The 9 cm samples were then dried using a furnace until three consecutive stable weight readings were obtained, denoted as m_{dry}. The cross sectional dimensions of the

9 cm sample were measured using a calliper (see Figure 51). Therefore, density and MC are given by:

$$MC = \frac{m_1 - m_{dry}}{m_{dry}}. \quad (4)$$

$$Density = \frac{m_{dry}}{\text{Volume}}. \quad (5)$$

Note: the same procedure has been applied to all samples.

- For group A only, as each sample has a different MC value, and to facilitate result comparison, the MOE and MOR values were standardized to an MC value of 12 %, following the guidelines outlined in ISO 13061-3:2014 and ISO 13061-4:2014. This standardization was achieved using the following equations:

$$MOE_{12} = \frac{MOE}{1 - \alpha(MC - 12)}. \quad (6)$$

$$MOR_{12} = MOR\big(1 + \beta(MC - 12)\big). \quad (7)$$

where α and β are the correction factors, equal to 0.02 and 0.04, respectively.

Note: Please refer to Table A.5 in the appendix where all the samples' dimensions, densities, MC, MOR, MOE are presented.

Figure 51. a) geometry measurements b) weight measurements c) drying samples d) surface MC measurement

4.3.3. Fracture behaviour of samples

The initial observations on the fracture behaviour of the samples could be made based on their failure modes. The test revealed various types of failures, which can be summarized as follows (see Figure 52):

- Simple tension (ST): This occurs when there is direct pulling in two sections of the wood on the underside of the beam due to tensile stress parallel to the grain. It is a common occurrence in straight-grained beams, especially in seasoned wood (refer to Figure 52a);
- Cross-grained tension (CGT): This type of failure is caused by a tensile force acting obliquely to the grain. It is common when the beam has diagonal, spiral, or other forms of cross-grain on its lower side. Since the tensile strength of wood across the grain is much lower than that parallel to the grain, cross-grained timber often fails in this manner (see Figure 52b);
- Brittle or brash tension (BT): In this type of failure, the beam breaks cleanly through, extending entirely through its cross-section. It is characteristic of brittle wood that fails suddenly without warning, resembling the fracture pattern of chalk. The surface of the fracture is described as brash (see Figure 52c).
- Buckling failure (BF): Buckling occurs in the compression fibers, typically in a sidewise direction. Buckling results in a clearly marked and generally sudden failure (see Figure 52d).

Figure 52. Failure modes found during the test for the case of group A, a) simple tension failure; b) cross-grained tension failure; c) brash tension failure; d) buckling failure

Group A samples exhibited brittle behaviour with diverse failure modes. Simple tension failures occurred in 27 % of the samples, brash tension failure in 3 % of the samples, buckling failure in 13.5 % of the samples, and cross-grained tension failure in 56.5 % of the samples. For group B samples, buckling failure was predominant, observed in 83 % of the cases, often accompanied by a few millimetres of crack width spread along the sample. The remaining 17 % of samples in group B exhibited cross-grained tension failure. In group C, 63.5 % of the samples experienced cross-grained tension failure, 23.5 % had buckling failure, and 13 % had simple tension failure.

The variation of failure modes within group A can be attributed to the natural state of the wood, which is considered a brittle material. As the MC increased, the fracture behaviour of the timber sample shifted toward a ductile or semi-ductile nature. This change increased the potential for achieving higher displacements without significantly compromising material strength. In contrast, group C samples absorbed the glazing material in an approximately 0.5 mm depth (as also shown by the SEM measurements – see subsection 4.4.2), thereby shielding the wood cells from moisture preserving brittle behaviour in most samples. Generally, ductile behaviour is better over brittle behaviour because ductile materials can undergo extensive plastic deformation before failure, offering resistance to sudden fractures or failures. Additionally, ductile materials exhibit visible deformations as warning signs of impending failure, allowing for timely repairs or replacements to prevent catastrophic incidents. The fracture behaviour of wood varies with species, with the main controlling factor for every wooden species being the MC. Achieving ductility in timber corresponds to a higher MC, resulting in increased strain values. However, this also leads to reduced resistance and strength against static and dynamic loads. In contrast, brittle behaviour provides higher strength values with an acceptable strain value. The optimal scenario occurs in group C, where both resistance and deformation capacity increase. This explains why different design annexes prefer brittle behaviour in timber elements and underscores the importance of selecting appropriate glazing (covering) materials.

4.3.4. Mechanical properties of the samples

Figure 53 shows the stress versus strain diagram for sample with maximum and minimum rupture strength from each group. As illustrated in Figure 53, group B samples exhibit deformation (elongation), recording higher strain values with lower stress values compared to group A and C. Additionally, group B samples display nonlinear elastic deformation, indicating an increase in MC, which provides an explanation for the buckling failure in this group.

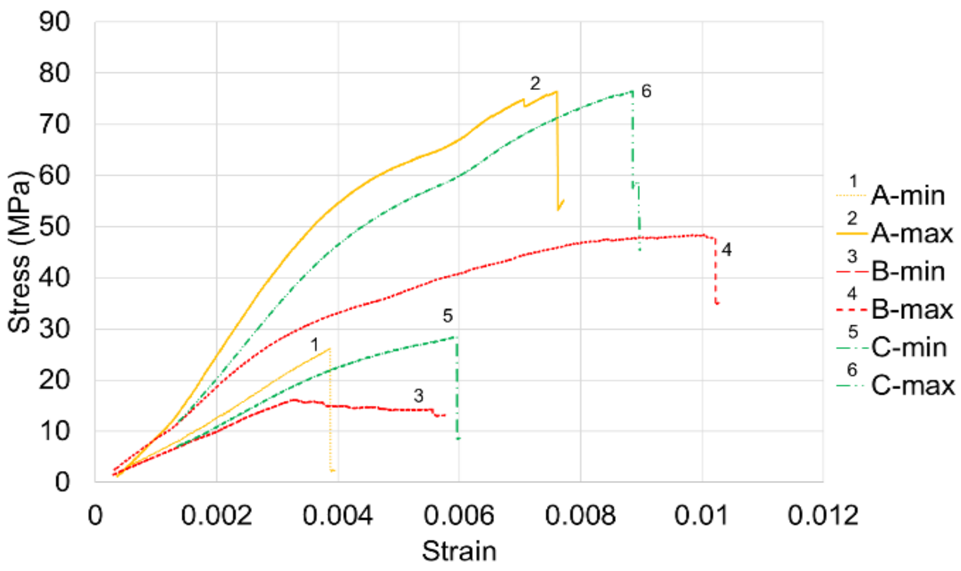


Figure 53. Stress vs. strain diagram for maximum and minimum strength of rupture for the tested groups

The crack widths in groups A and C varied between 5 and 70 mm, as shown in Figure 54. However, for group B, the crack width was around 5 mm, reflecting the challenges in detecting buckling failure. This discrepancy in crack widths can be attributed to the differences in failure modes among the testing groups, highlighting the risks associated with an increase in moisture content due to exposure to climate components. As strain increases (indicating higher ductility), the MOR and MOE values decrease (refer to Table 7). This type of failure is particularly concerning for compression elements such as columns and bracing elements, which are essential structural components in roofs and towers.

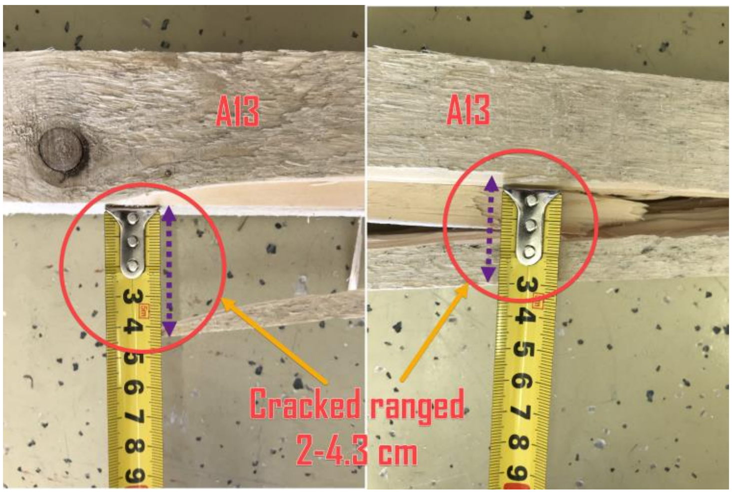


Figure 54. Crack width measurements for A13

Table 7. Strain and MOR, MOE correlation coefficient (R)

	Group A	Group B	Group C
$R_{strain\ \&\ MOR}$	0.69	-0.21	0.74
$R_{strain\ \&\ MOE}$	0.50	-0.09	0.37

The density and MC values under natural conditions and after the wetting are shown in Table 8. Wood samples with higher density absorb a greater amount of water under natural conditions, which persists after the surface treatment of the samples with a coating layer. Furthermore, the MC of non-coated samples increased by an average of 2 times after full wetting, while coated sample experienced only 1.7 times increase in MC.

Table 8. Density and MC values for the studied groups of samples

	Group A	Group B	Group C
Density (kg/m^3)	335-512	263-399	303-500
MC (%) natural conditions	9-14	17-35	2.5-19
MC (%) after wetting	-	34-65	14-30

The values of MOR and MOE were influenced by the density of the samples, lower density values were accompanied by lower MOR and MOE values (see Figure 55 and Figure 56).

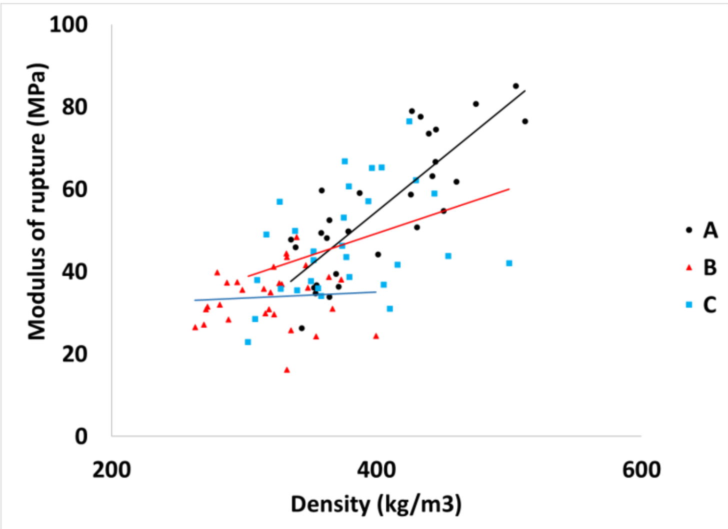


Figure 55. Density vs MOR

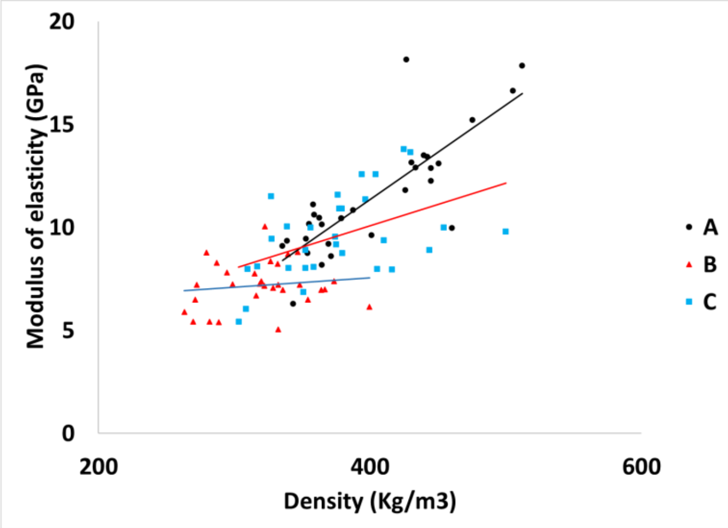


Figure 56. Density vs MOE

Table 9 shows the mechanical properties of the tested samples. The values for Group A are corrected for MC of 12%, while the samples from groups B and C samples were measured in a fully saturated state.

Table 9: Mechanical properties results based on four points bending test

		Mean values (30 samples)	Standard Deviation (σ)
Group A	MOR_{12} (MPa)	52.29	14.32
	MOE_{12} (GPa)	11.21	2.68
Group B	MOR_{Sat} (MPa)	33.86	16.23
	MOE_{Sat} (GPa)	7.20	5.05
Group C	MOR_{Sat} (MPa)	46.73	12.78
	MOE_{Sat} (GPa)	9.59	2.03

As shown in Table 9, the increase of MC in group B results in a significant decrease in the mechanical properties of the wood samples. The degradation, indicated by the reduction in MOR and MOE values, was 35% compared to group A tested at room temperature. For group C, the degradation values were 11% and 15% for MOR and MOE, respectively.

Figure 57 and Figure 58 illustrate the MOR and MOE values for groups A, B, and C of samples. These figures emphasize the superior strength of the samples in their natural state (group A), the significant weakening of fully saturated samples (group B), and the transitional nature of glazed samples (group C) positioned between the two extremes, but more close to the group A. When wood samples are surface treated, their mechanical properties are much less influenced by the MC, even under full water saturation, which is an extreme circumstance. Therefore, an optimal state of ductility in wood can be achieved, and only minimal mechanical deterioration occurs with the proper choice of a surface treating material. The measurements provide valuable insights into the effects of moisture content on rupture characteristics (see

Figure 52 and Figure 53) and the modulus of the tested samples, enhancing the understanding of material behaviour under different moisture content conditions.

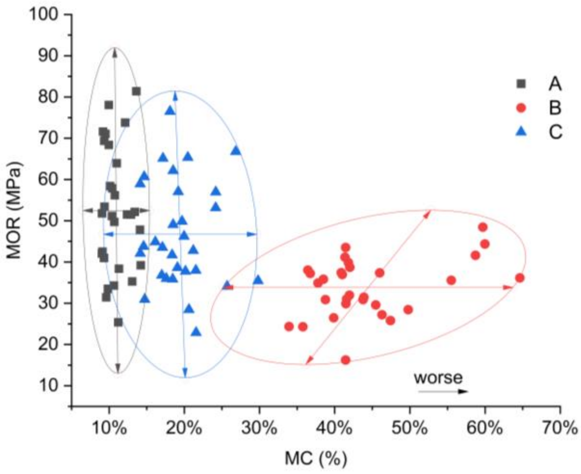


Figure 57. MOR vs. MC - 95% confidence ellipse graphs for the three groups of tested samples

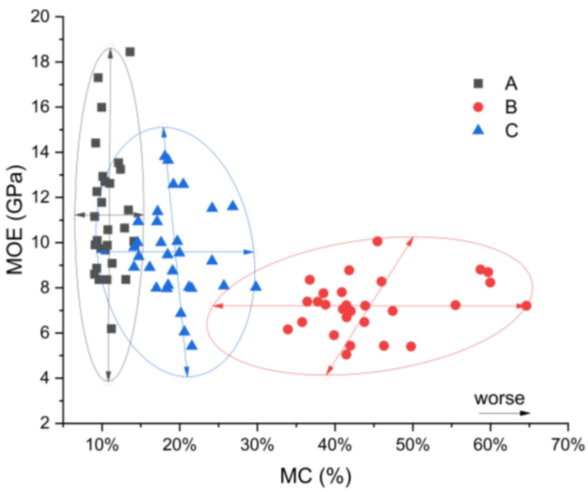


Figure 58. MOE vs. MC - 95% confidence ellipse graphs for the three groups of tested samples

After determining the mechanical properties of the samples, I calculated the characteristic strength value (strength grade) for the three groups using MSZ EN 408-2010 standard. The characteristic value of the groups can be determined based on the result belonging to the 5% quantile, with different correction factors. The 5% quantile represents a lower threshold with a probability of occurring less than 5%. This implies that the lowest result out of 30 flexural strength results is used to calculate the characteristic value.

According to MSZ EN 408-2010 standard 3 correction factors were used:

- Depth factor $K_h = (\frac{150}{h})^{0.2}$, where h is the depth of the samples and is approximately equal to 50 mm. Thus $K_h = 1.25$.

- Sample correction factor K_s, a factor to adjust the number of samples and their size. It was obtained from Figure 61.
- K_v, a factor taking into account the low variability of f_{05} values between samples for machine grades in comparison with visual grades. For machine grades with f_{mk} greater than 30 MPa and all visual grades, $K_v = 1.0$. For machine grades with f_{mk} equal to or less than 30 MPa, $K_v = 1.12$.

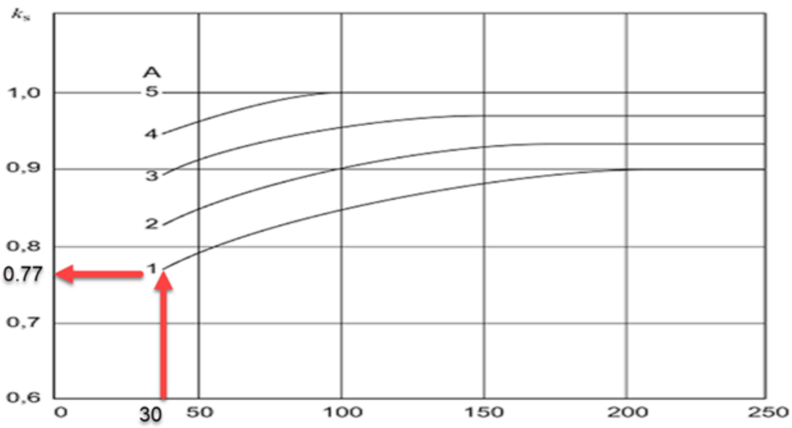


Figure 59. Sample correction factor: K_s [Hungarian Standards Institution, 2010]

Thus, the characteristic strength value of each group is shown in Table 11.

Table 10: Strength grade calculation for tested groups

	Group A			
MOR_{avg} (MPa)	5% quartile	$MOR_{0.05}$ (MPa)	25.04	Modified value (MPa)
52.29	K_h	1.25		20.03
	K_s	0.77		15.42 – C16
	K_v	1.00		
	Group B			
MOR_{avg} (MPa)	5% quartile	$MOR_{0.05}$ (MPa)	18.57	Modified value (MPa)
33.86	K_h	1.25		14.87
	K_s	0.77		11.44 – C12
	K_v	1.00		
	Group C			
MOR_{avg} (MPa)	5% quartile	$MOR_{0.05}$ (MPa)	23.73	Modified value (MPa)
46.73	K_h	1.25		18.98
	K_s	0.77		14.62 – C14
	K_v	1.00		

As indicated by the values represented in Table 10, the significance of coating layers in timber structural elements can be underlined. The initial grade of the timber samples is C16 (group A), but after exposure to water, the grade dropped to C12 in group B. It is worth noting that C12 is not permitted for use in construction work, and the minimum allowable strength grade is C14. In the presence of the coating layer (group C), the grade increased again to C14, which is an acceptable strength grade for construction purposes. It is important to consider that group C samples were submerged in water, reaching full saturation of timber elements. However, in real-life applications, we can anticipate high resistance and the same strength grading with proper preservation of the elements.

4.3.4. Data evaluation

The results of the test were expressed using Poisson's distribution. I opted for this distribution due to its symmetry about the mean axis, considering the handling of MOR and MOE values as discrete values (see Figure 60 and Figure 61).

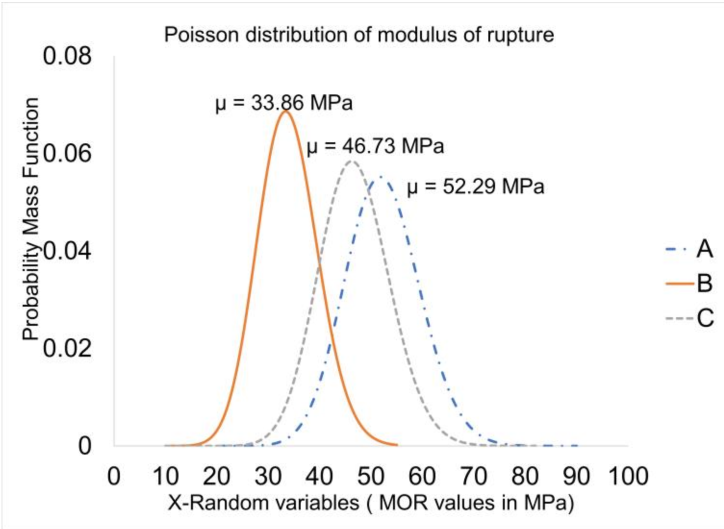


Figure 60: Modulus of rupture representation in terms of Poisson's distribution

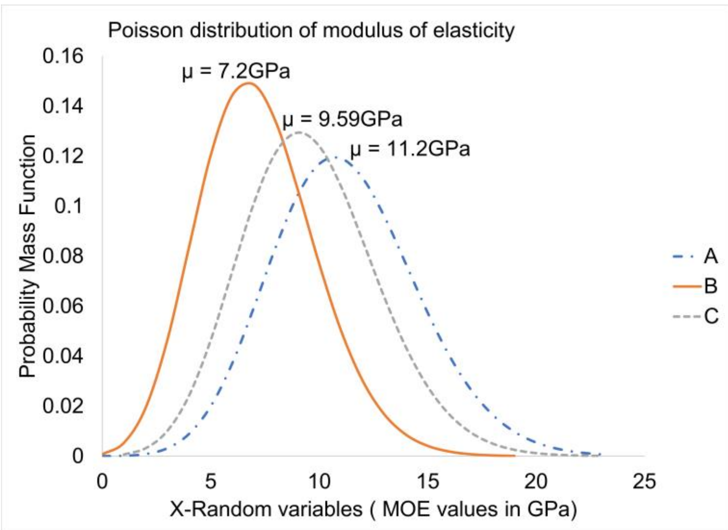


Figure 61. Modulus of elasticity representation in terms of Poisson's distribution

In Figures 60 and 61, the MOR and MOE values of group B and C samples have shifted to the left compared to group A samples, indicating a degradation of the mechanical properties. Figure 60 shows that the probability of having a sample with MOR equal to 52 MPa in group A is almost equal to 6 % while it is 4.2 % in group C. For group B to have the same MOR value, the probability is almost zero. Figure 61 shows similar degradation results regarding the MOE values. To have a sample where MOE equals 11 GPa in groups A and C, the probability is 12 %. Attaining the same value in group B has a probability of 6%. All these statistics highlight the positive impact of a protecting layer. Using linear regression and calculating the correlation factors as an average in all groups, the MC increase has a greater negative impact on the MOR values with a correlation factor equal to -25 % than the MOE values with a correlation factor equal to -18 %.

4.4. SEM measurements

4.4.1. Semi destructive SEM measurements on samples taken from the Civil Communities House

To better visualize the effect of the MC on the wooden cells, I collected small wood samples from the roof of the house, making a conscious effort to minimize any potential damage as much as possible. I specifically collected detached pieces or pieces from less visible areas. The total number of collected wooden pieces was 11 pieces:

The collected samples were chosen according to the following criteria (see Figure 62):

- Structural diversity: the samples were selected from various structural elements such as girders, columns, and inclined and horizontal bracing.
- Condition of the samples: samples were chosen from both damaged and undamaged elements.
- Position of the element in the roof: samples were selected from positions that were either exposed to sunlight or shaded.

Figure 62. Collected samples for SEM

The objective of the SEM measurements was to acquire detailed information on the cellular structure of wood, identifying any deterioration at the microscopic level or structural anomalies. The microscopic analysis not only aids in understanding the material's current condition but also provides valuable insights into the environmental influences (especially humidity) on the wood over time. Therefore, the sample pieces taken from the site (House of Civil Communities) were initially examined in their dry state (MC below 6%). Subsequently, the MC was systematically increased, following the MC classification levels outlined in Eurocode 5 [CEN, 2006]. The MC classes in Eurocode 5 are defined as follows:

- Class 1: MC is between 0-12 %;
- Class 2: MC is between 12-20%;
- Class 3: MC is higher than 20 %, at a temperature of 20 °C.

Table 11 shows examples on SEM images of a wooden sample taken from a damaged girder, exposed to sunlight. The cell size and wall thickness have been measured in a minimum of 10 locations on a single image (magnification: 900x), and an average value has been calculated for each sample.

The results of SEM measurements can be summarized as follows (see Figure 63):

- Both damaged and undamaged samples, regardless of the structural element's location, exhibited an increase in the walls thickness corresponding to the increase in MC;
- Damaged elements were more significantly affected by increased MC: the average increase in wall thickness in the damaged elements was 3.5 μm, while in the undamaged elements, it was 2 μm;
- The effect of exposure to sunlight could not be detected;
- The wall thickness increase for the 2nd and 3rd class MC samples was found to be approximately the same (see subsection 4.4.2 and Table 13), with values for the 3rd class MC being slightly higher;
- A smaller proportion of the samples (27 %) reached their limit of water absorption capacity at an average value of 12.7 % MC. The wall thickness value for these samples proved to be approximately the same as for the 2nd and the 3rd MC classes. For the remaining of the samples (73%), the water content could be increased to 22.7 % as in average (Table 13).

The increases in the wall thickness and volume of the wooden cells (swelling and expansion) impacts the structural integrity and shape of the wood, especially if the expansion is uneven or occurs in specific directions. This latter can cause cracking or warping across the material. Changes in cell volume can also affect the mechanical properties, such as stiffness and strength. The absorbed water creates a humid environment for fungi growth. Understanding and managing these effects are crucial in applications where dimensional stability and structural integrity of wood are important considerations.

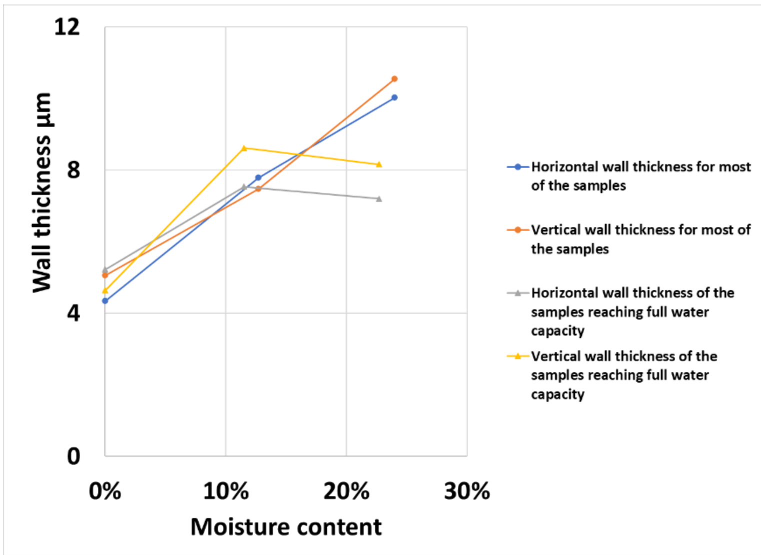
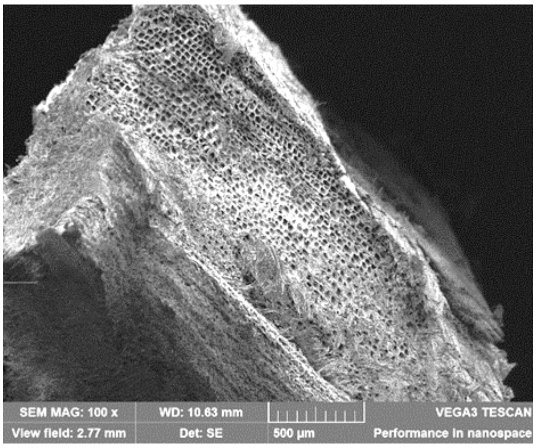
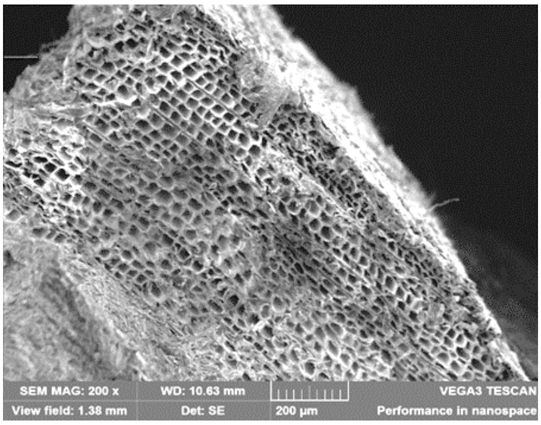
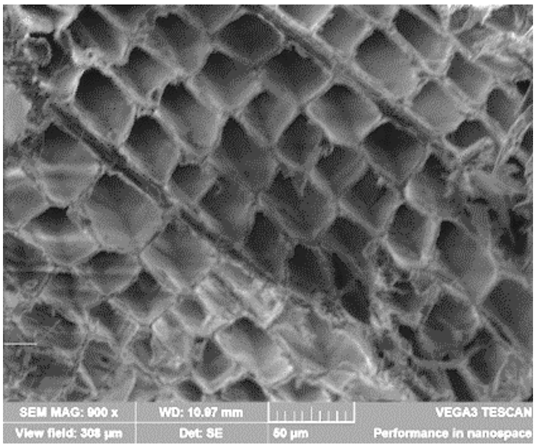
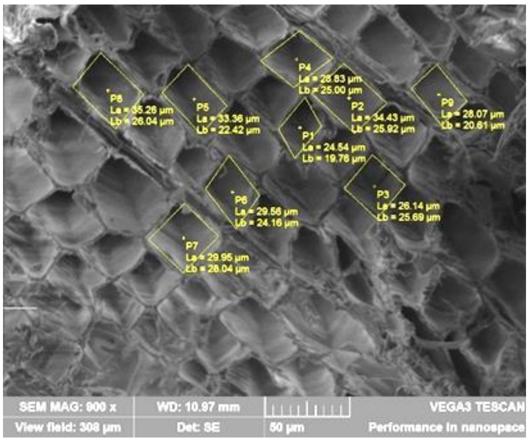
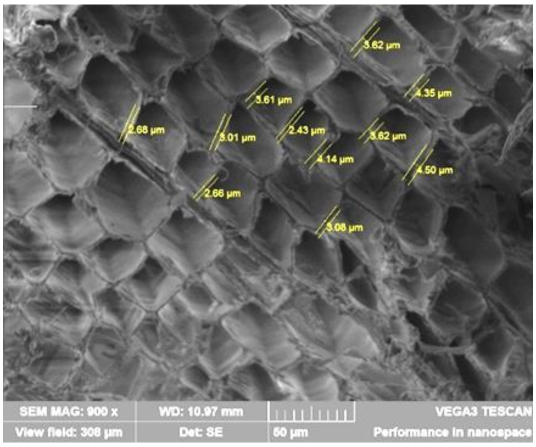
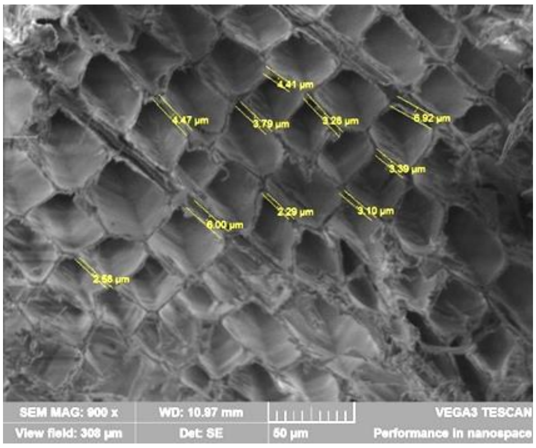
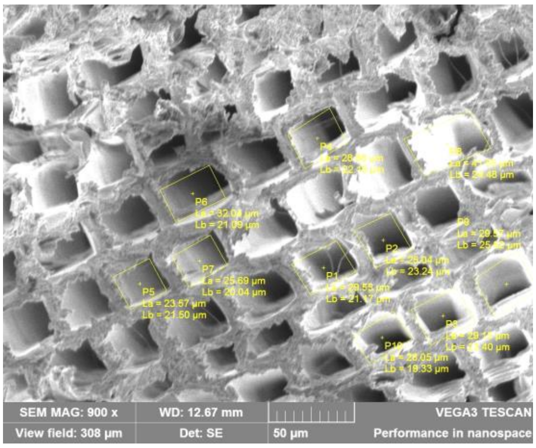
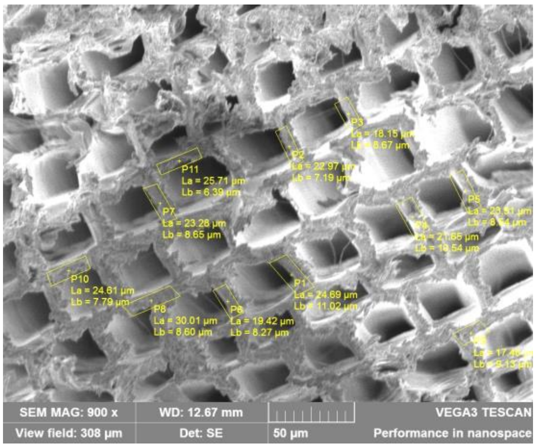
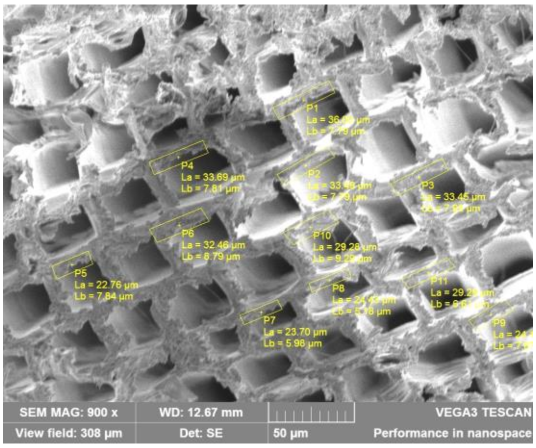
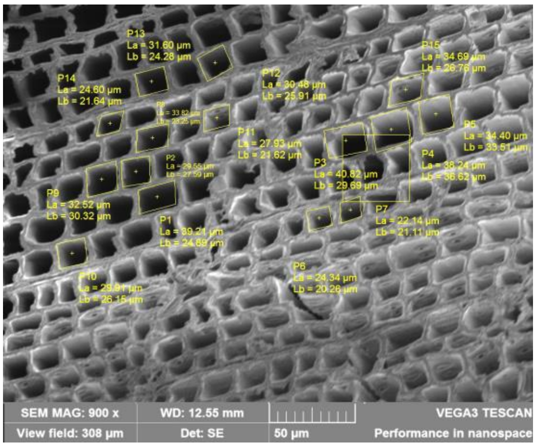


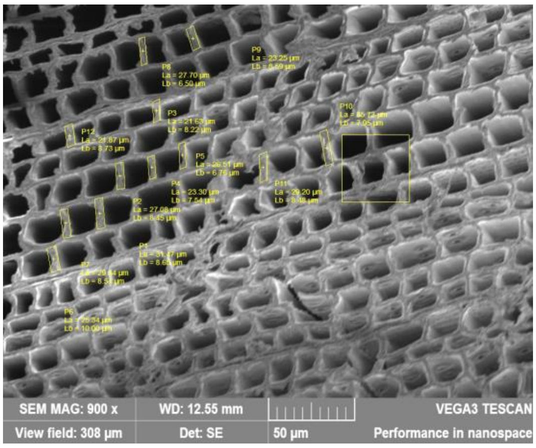
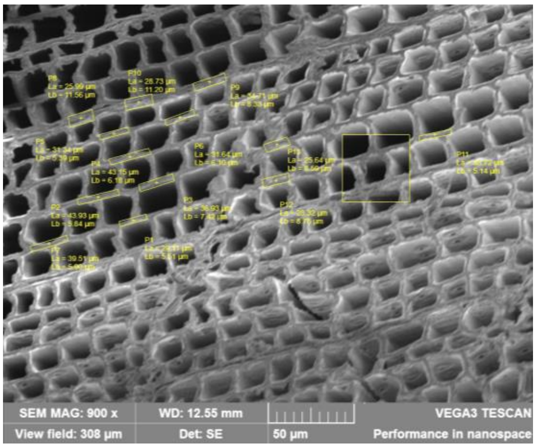
Figure 63. SEM results, MC vs. wall thickness

Table 11. SEM measurements for a damaged sample taken from a girder exposed to sunlight

Magnification	Class 1 (MC less than 6%)
100x	
200x	

500x	
900x (cell size measurement)	
900x (wall thickness measurement)	
900x (wall thickness measurement)	
	Class 2 (MC = 12.7%)

<table>
<tr><td>900x (cell size measurement)</td><td>
</td></tr>
<tr><td>900x (wall thickness measurement)</td><td>
</td></tr>
<tr><td>900x (wall thickness measurement)</td><td>
</td></tr>
<tr><td></td><td>Class 3 (MC = 22.9%)</td></tr>
<tr><td>900x (cell size measurement)</td><td>
</td></tr>
</table>

<table>
<tr><td>900x (wall thickness measurement)</td><td>
</td></tr>
<tr><td>900x (wall thickness measurement)</td><td>
</td></tr>
</table>

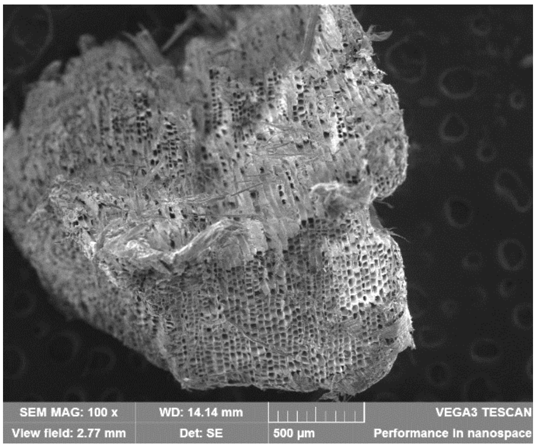
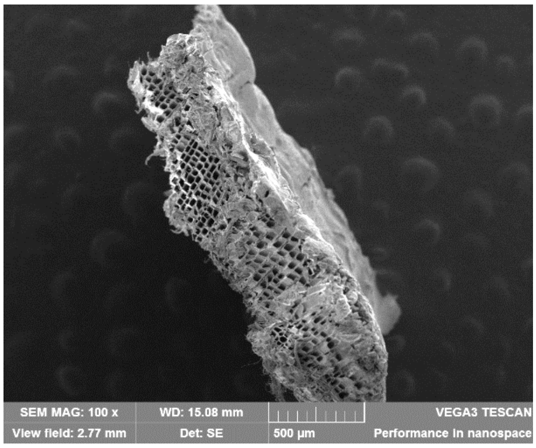
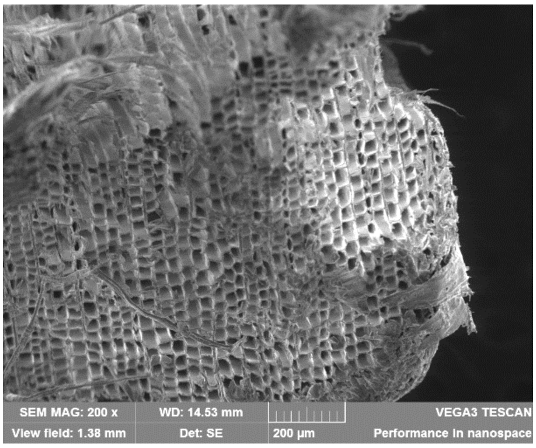
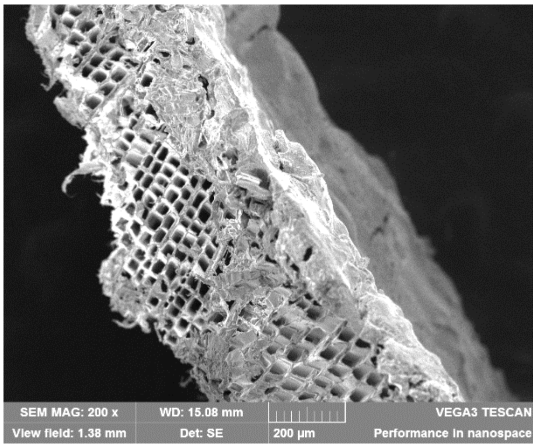
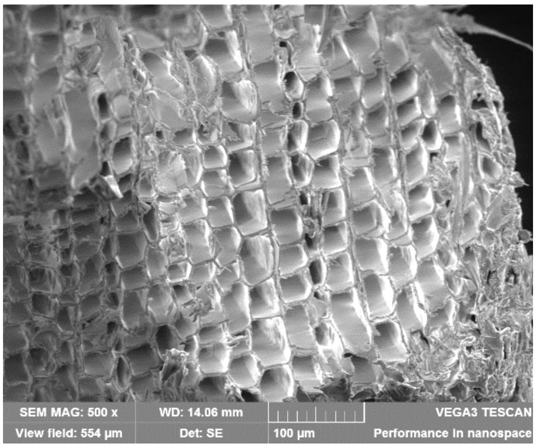
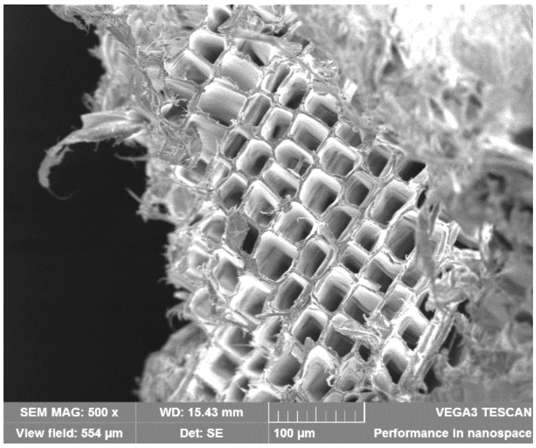
4.4.2. SEM measurement on new Picea Abies samples

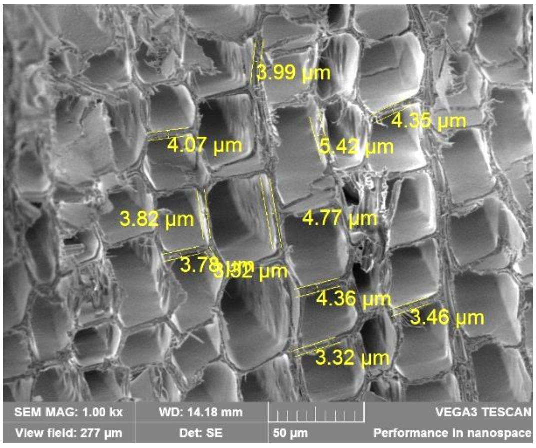
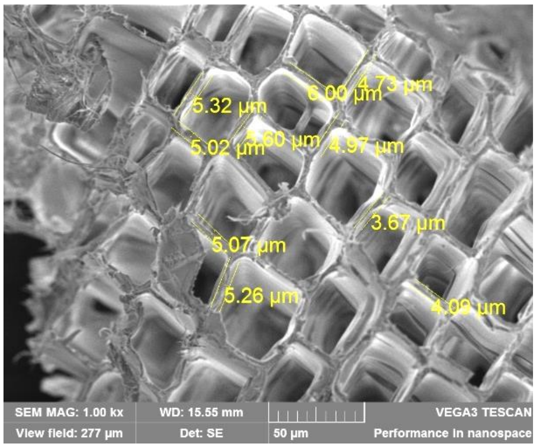
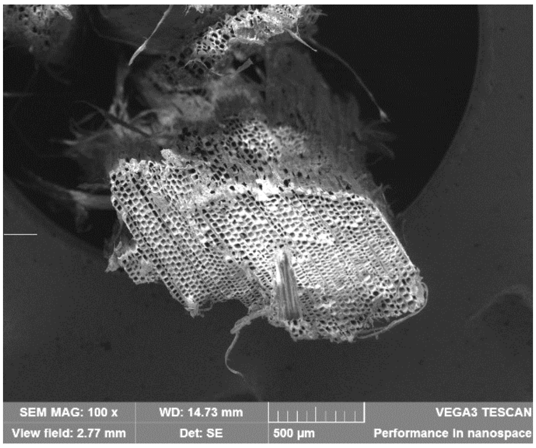
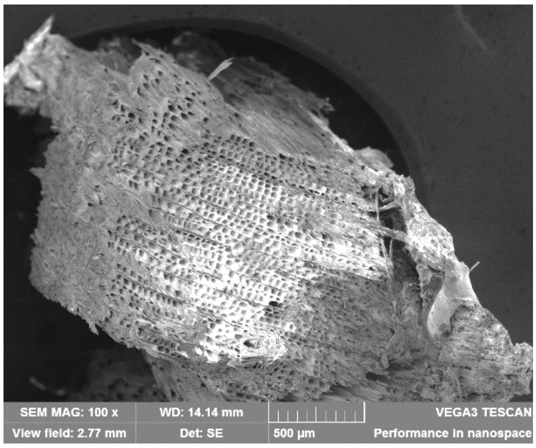
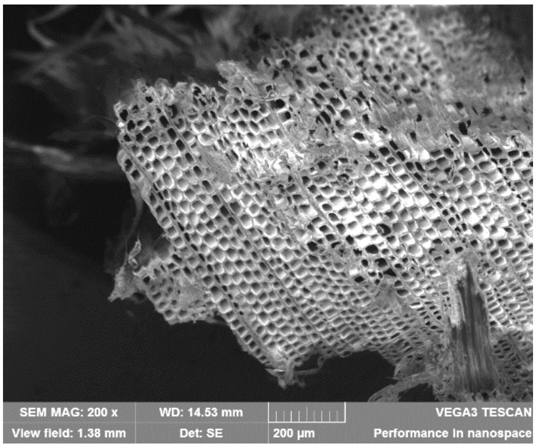
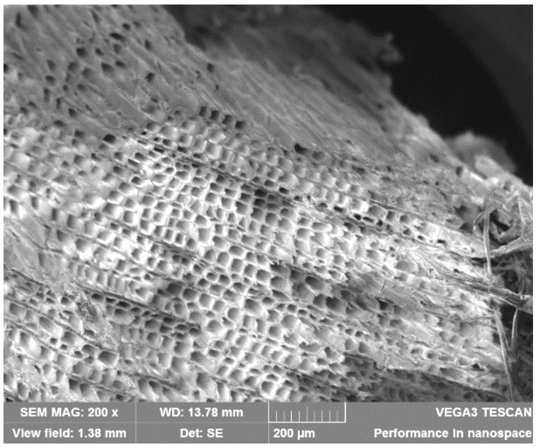
To compare the micro-characteristics of the cultural heritage building wooden elements with the Picea Abies wood specimens, I employed a similar procedure for measuring the cell wall as described in the previous section. The samples were obtained from the test specimens that underwent the four-point bending analysis. Samples were collected from both painted and unpainted wood pieces and were assessed under two distinct conditions: dry (achieved by pre-exposing the samples to furnace conditions) and wet (accomplished by immersing the samples in water-filled containers).

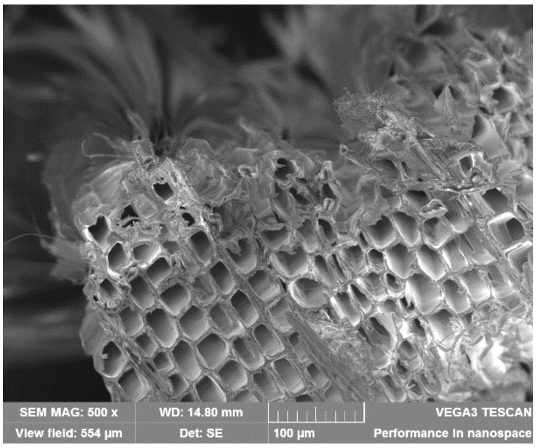
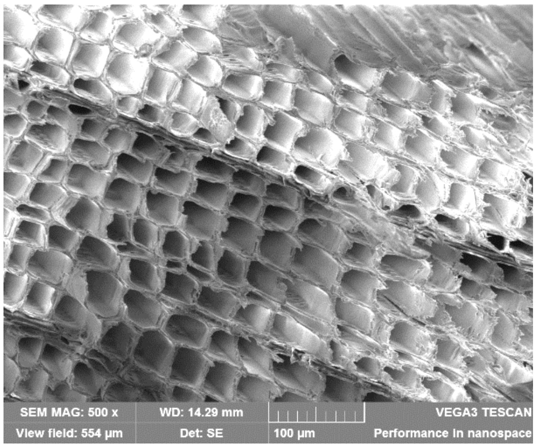
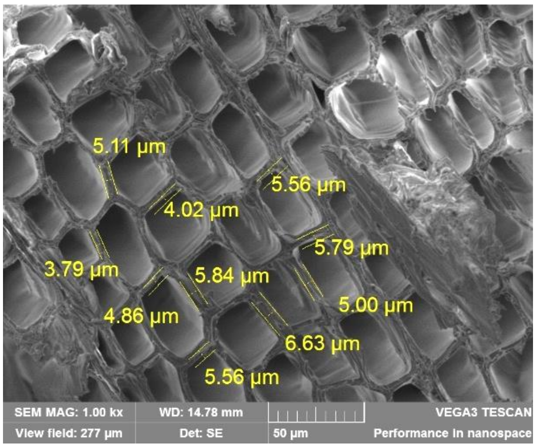
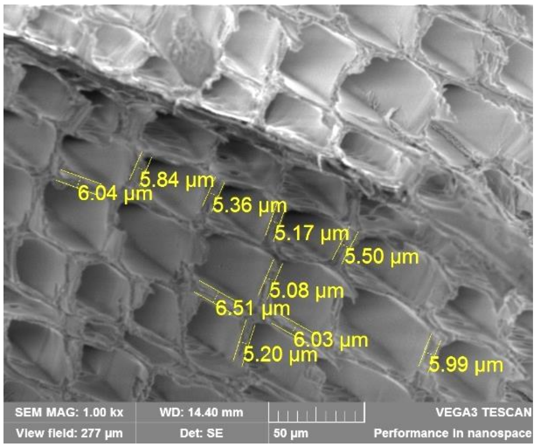
Three samples for each studied group, with approximately the same density, have been chosen. The taken SEM images are presented in Table 12, and the results of the measurements are presented in Table 13.

In the SEM images, the penetration depth of the applied protective glaze could be clearly observed and measured. The material was absorbed by the cells, filling them. The approximate penetration depth was 500 µm from the wood surface. Figure 64 illustrates an example of the penetration depth measurement.

Table 12: Examples of SEM measurements on Picea Abies samples

Magnification	Dry	
	Unpainted	Painted
100x		
200x		
500x		

1000x (wall thickness measurement)		
Magnification	Wet	
	Untreated	Surface-treated
100x		
200x		

500x		
1000x (wall thickness measurement)		

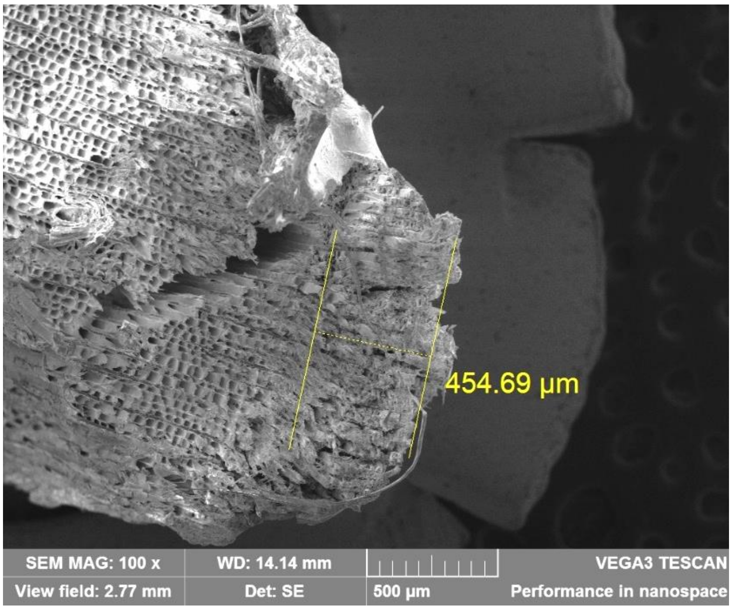


Figure 64: Protecting layer penetration depth in SEM measurements

Table 13: Average wall thickness from SEM measurements

	Average walls thickness (µm)						
	Samples from the roof			Samples from 4PBD			
	Moisture content %			MC % - untreated		MC % - surface-treated	
	0%	12.70%	>20%	Dry (<6%)	Wet (35.8%)	Dry (<6%)	Wet (21.6%)
Beams	4.2	6.3	6.6	4.4	5.3	4.2	6.2
Columns	4.5	7.8	8.7				
Rafters	4.4	7.9	9.0				
Average	4.4	7.4	8.1				
Random error (µm)	0.6	0.6	0.6	0.5	0.9	0.9	1.2

By comparing the results, the following conclusions could be drawn:

- An increase in wooden cell wall thickness can be observed in both cases, for the old roof samples and the newly procured samples as well;
- The old samples were more significantly affected by the MC increase (cell wall thickness increase between 2.4 µm and 4,6 µm), the cell wall thickness increased with the increase of the MC, while in the case of the new samples a more restrained increase was observed (0.9 to 2,0 µm);
- No significant difference was observed between the untreated and surface-treated samples, reinforcing the findings from the analysis of weather conditions. It is evident that the most influential weather factor causing substantial damage to wooden elements is not solely humidity, precipitation, or temperature, but rather the fluctuations in these factors over time. As a result, the surface treatment of wood becomes increasingly crucial in mitigating the effects of aging on the material. This underscores the importance of protective measures against the dynamic changes in environmental conditions to ensure the long-term durability and resilience of wooden elements.

5. Conclusions

Conclusions related to the Thesis 1.

- Over the past 30 years, Pécs has changed its climatic zone from moderate-warm – moderate-wet to warm - moderate-dry climate, while the Budapest region has changed its climatic zone from moderate-warm – moderate-dry to warm-dry climatic zone (Hungarian Meteorological Service), indicating a temperature increase in both cases by more than 1 °C, accompanied by a decrease in precipitation. These climate change features are valid for the continental climate of Hungary, following global warming trends, although the increase in temperature and the decrease in precipitation have a smaller impact on the behaviour of the wooden components of buildings, compared to the significant seasonal fluctuations of these climate parameters. According to the Hungarian Meteorological Service, the largest seasonal increase in the maximum temperatures from 1981 to 2020 occurs in summer: 2.1 °C.

- According to on-site indoor seasonal measurements in Pécs, the most significant fluctuations in temperature and RH were observed during the spring season, characterized by high amplitudes and frequencies. The average amplitude of the outdoor T was 3.3 °C, while the average amplitude of the outdoor RH was 12.3 %. Consequently, the MC fluctuations for all three types of timber elements (beams, rafters, and columns) were most significant during the spring season, with an average MC amplitude of 1.3 %. The calculated standard deviations for the measured T, RH, and MC during spring exceeded the values of other seasons by 13 to 74 %, indicating that the variation in climate factors and MC during the spring season was the highest. Despite the high frequencies and amplitudes of RH fluctuations in summer, the MC values for all three timber elements showed high constancy during this period. The MC range for beams, columns and rafters was found to be between 10 and 14 %, with an average MC amplitude value of 0.3 %.
- According to on-site outdoor seasonal measurements for Buda-Hills, the most significant temperature fluctuations, characterized by high frequencies and large amplitudes, were observed during the spring period. The average amplitude of outdoor T for spring was 4.7 °C, while the average amplitude of outdoor RH amplitudes was 38 %. Consequently, the MC fluctuations in all three types of timber elements (columns, stairs, and fences) were most significant during the spring season, with an average MC amplitude of 0.9 %. Consistent with the T, RH, and MC amplitudes, the calculated standard deviations for T, RH ,and MC were also the highest in spring, exceeding the values for the other seasons by 0 to 75 %. Relatively high frequencies of temperature fluctuation were also found for summer period, but with smaller amplitudes. The RH fluctuations exhibited high frequencies for summer, autumn and winter periods, although they were even more pronounced during the winter season. During the spring and summer periods the surface MC values were below the detection limit. Therefore, it can be concluded, that the increase of the regional and seasonal temperature values and the change of regional precipitation as effect of the global warming do not provide a complete explanation for the moisture content changes in the timber elements. Besides taking into account the changes of the yearly and/or seasonal average

temperature and relative humidity values, the seasonal effects of the temperature and relative humidity fluctuations, the frequency and the amplitude of fluctuations – possibly based on on-site measurements – have also to be considered.

Conclusions related to the Thesis 2.

- The on-site measured high temperature and relative humidity fluctuations, especially during the spring period, induced the re-acclimation process of the wood, because of the dynamic water absorption and release processes, until the equilibrium moisture content was reached. Since the examined roof structure of the Civil Community House (Pécs) was never subjected to renovation, and the roof timber elements surface was never protected, the re-acclimation process was repeated extensively over many decades especially during the spring period and had been intensified over the last several decades thanks to the global warming. The scanning electron microscopy measurements of cell wall thickness of dry and saturated wooden samples showed that the full water capacity of the damaged elements was higher than that of undamaged elements. Thus, damaged elements absorb more water, which brings along the re-acclimation, and newer damaging will take place, this way a self-exciting circular process will be induced. This was also demonstrated by the moisture content values of the damaged elements over the full seasonal study, which remained below the values of the undamaged ones.

- The outdoor on-site measurements showed that the surface treated (pained) wooden elements (Buda-Hills) are much less sensitive to the re-acclimation process. Damaged and undamaged elements could not be significantly separated for the Buda-Hills outdoor site timber structure, which had been renovated for the second time in 2018 by removing the railings, strengthening the supporting structure, resting on the central iron column, placing more stable railings and repainting the tower.

- The correlation constants between the moisture content and temperature and moisture content and relative humidity for the Buda-Hills site timber structure, for load-bearing elements was: -0.54 and 0.40, respectively; for non-load-bearing elements, was between -0.1 and -0.25 for moisture content – temperature correlation, and between -0.18 and -0.38 for moisture content – relative humidity correlation. In the absence of periodic rehabilitation for the studied Pécs site timber structure, the correlation factor increased to -0.71 for temperature – moisture content and to 0.87 for relative humidity – moisture content.

Conclusions related to the Thesis 3.

The analysis of the results of the four-point bending test method on three sets of softwood (Picea Abies) samples, using the stress vs. strain diagram, showed that with the increasing moisture content the fracture behaviour of timber elements changes from brittle to ductile or semi-ductile behaviour, increasing the possibility of achieving high displacements combined with weak resistance and strength against static and dynamic loads. The change of the fracture behaviour leads to a significant change in the failure mode in the samples. Samples in Group A exhibited brittle behaviour with varying failure modes. Among these, 27% experienced simple tension failures, 3% had brash tension failures, 13.5% displayed buckling failure, and 56.5% demonstrated cross-grained tension failure. On the other hand, Group B samples predominantly exhibited buckling failure (83%), accompanied by a slight spread of crack width in a few millimetres along the samples. The remaining 17% of Group B samples showed cross-grained tension failure. In Group C, cross-grained tension failure was observed in 63.5% of the samples, buckling failure in 23.5%, and simple tension failure in 13%. Therefore, I have stated that structural timber elements in the absence of protection are highly affected by fluctuating weather factors, especially the relative humidity and temperature. Because of increased moisture content of timber elements, load bearing capacity of the structural support system is expected to decrease.

Conclusions related to the Thesis 4.

The grade of the timber samples is C16 (group A), using a four-point bending test, and after exposing samples (group B) to water, the rate dropped to C12 (18.2% average moisture content increase), noting that C12 is not allowed to be used in construction work and the minimum allowable strength grade is C14. Noting that this grade drop includes a decrease in both the modulus of elasticity and the modulus of rupture by 35% But under the same testing conditions and in the presence of the coating layer (group C), the moisture content increased only by 10.4%, the modulus of rupture decreased by 11%, and the modulus of elasticity decreased by 15% compared to the values measured for dry sample conditions. Thus, the grade dropped to C14, which is an acceptable strength grade for construction purposes. But in real-life applications, we can expect high resistance and the same strength grading in cases of proper preservation of the elements. Because reaching full saturation requires very severe weather conditions.

6. Scientific theses

Thesis 1. Regional climate change effects on timber structures

Related publications [Kherais et al., (2020), Kherais et al., (2022b), Kherais et al., (2022c)]

Based on visual inspection results, on-site weather parameter measurements, timber moisture content measurements during four seasons, and statistical analysis of the collected data, I have demonstrated that the fluctuations in temperature and relative humidity values, both, indoors (in the Pécs region) and outdoors (in the Buda-Hills region), exert a greater impact on timber building elements than the average annual and/or seasonal temperature increase. Despite the largest seasonal increase in the maximum temperatures occurring in summer (2.1 °C from 1981 to 2020) and a decrease in precipitation quantity, attributed to global warming effects.

1a. I have demonstrated that fluctuations in outdoor temperature and relative humidity have the most significant impact on untreated indoor timber structures during the spring season. The average amplitude of outdoor temperature, outdoor relative humidity, and moisture content for beams, rafters, and columns measured during spring exceeded the values recorded during the rest of the year, with rates ranging between 28 and 79 %. Similarly, the calculated standard deviations for the measured temperature, relative humidity, and moisture content during spring surpassed the values of other seasons by 13 to 74 %, indicating that the variation in climate factors and moisture content of the wood during the spring season was the highest.

1b. I have demonstrated that fluctuations in indoor temperature and relative humidity have the most significant impact on surface-treated outdoor timber structures during the spring season. The average amplitude of outdoor temperature, outdoor relative humidity, and moisture content for columns, stairs, and fences measured during spring exceeded the values recorded during the rest of the year, with rates ranging between 19 and 66 %. Similarly, the calculated standard deviations for the measured temperature, relative humidity, and moisture content during spring surpassed the values of other seasons by 34 to 75 %, indicating that the variation in climate factors and moisture content of the wood during the spring season was the highest.

Therefore, by considering only the average global or regional temperature and yearly precipitation values, the precise prediction or modelling of the future behaviour of new and cultural heritage timber structures becomes challenging. I recommend that, for future structural integrity calculations, behaviour modelling, or lifetime prediction of timber structures, in addition to changes in yearly and seasonal average temperature and relative humidity values, the seasonal effects of the temperature and relative humidity fluctuations, as well as the frequency and the amplitude of fluctuations – preferably based on on-site measurements – should also be taken into account.

Thesis 2. Interdependence between climate factors, surface treatment and aging of timber elements

<u>Related publications [Kherais et al., (2020), Kherais et al., (2022b), Kherais et al., (2022c)]</u>

Using on-site moisture content measurements indoors and outdoors, along with semi-destructive scanning electron microscopy measurements, I demonstrated the circular dependency among moisture content, the re-acclimation process of the wood, and the aging of timber elements.

2a. Using scanning electron microscopy measurements, I assessed the cell wall thickness in dry and saturated wooden samples obtained from untreated indoor timber elements (Pécs site). I demonstrated that damaged wooden elements exhibit a higher susceptibility to an increase in moisture content. The average increase in wall thickness for the damaged elements was 3.5 µm, whereas for the undamaged elements, it was 2 µm. The dynamic water absorption and release processes, particularly pronounced in more damaged elements, triggered a re-acclimation process in the wood to achieve equilibrium moisture content. Due to the lack of renovation and surface protection for the examined roof structure of the Civil Communities House (Pécs), this re-acclimation occurred extensively over many decades. In recent decades, the processes intensified further due to global warming. Consequently, damaged elements absorbed more water, initiating a re-acclimation process that led to additional damage, creating a self-perpetuating circular cycle. This pattern was evident in the moisture content values of damaged elements throughout the seasonal study, consistently remaining 1-3 % higher than those of undamaged elements. Therefore, I concluded that the moisture fluctuations in untreated timber elements give rise to a self-sustaining circular damage process, wherein greater wood damage leads to more significant moisture content fluctuations, resulting in further damage.

2b. Based on the calculated correlation coefficients between timber moisture content and climate factors for surface-treated outdoor timber elements at the Buda-Hills site, I have demonstrated that load-bearing functional elements are more susceptible to variations in climate factors than non-structural elements. Specifically, the correlation coefficients between moisture content and temperature, and moisture content and relative humidity for the load-bearing elements were -0.54 and 0.40, respectively. In contrast, for non-load-bearing elements, the correlation coefficients ranged between -0.10 and -0.25 for moisture content–temperature correlation, and between -0.18 and -0.38 for moisture content–relative humidity correlation.

In the absence of periodic rehabilitation for the studied timber structure at the Pécs site, the correlation coefficient increased to -0.71 for temperature–moisture content and to 0.87 for relative humidity–moisture content. Therefore, I have concluded that, especially in the case of cultural heritage building timber elements, preserving the structural integrity of wooden elements requires tailored surface treatment methods. These methods should be designed to suit both the location and the building, taking into consideration climatic conditions, and preserving the character of the structure.

Thesis 3. Relationship between the fracture behaviour of the softwood and moisture content

Related publications [Kherais et al., (2020), Kherais et al., (2023), Kherais et al., (2022a)]

Using the four-point bending test method on three sets of softwood (Picea Abies) samples, I have demonstrated, that as moisture content increases, the fracture behaviour of timber elements shifts from brittle to ductile or semi-ductile behaviour. This transition enhances the possibility of achieving high displacements, but comes at the cost of weaker resistance and strength against static and dynamic loads. Among the low moisture content test samples, tha majority (56.5%) exhibited cross-grained tension failure, which transitioned to buckling failure (83% of failures) with increased moisture content, expected under bending load effects.

I concluded that structural timber elements, in the absence of protection, are highly affected by fluctuating weather factors, especially the relative humidity and temperature. The increased moisture content of timber elements is expected to decrease the load-bearing capacity of the structural support system. Conversely, the surface-treated set of samples showed reduced susceptibility to the moisture, with the fracture behaviour of the majority of the samples (63.5%) being brittle, exhibiting cross-grained tension failure. Based on the four-point bending mechanical tests, I have demonstrated that even a commercially available outdoor silk-gloss thick glaze protecting layer significantly mitigates the effect of the moisture change by improving its mechanical resistance.

Thesis 4 Relationship between the moisture content and mechanical properties of softwood

Related publications [Kherais et al., (2020), Kherais et al., (2023), Kherais et al., (2022a)]

I have demonstrated that under extreme conditions involving full water saturation of wood, the mechanical properties of softwood timber elements can still be maintained within the minimum allowable strength grade. Conducting a four-point bending mechanical test on a statistically significant sample number, I have proven that the full water saturation (18.2 % average moisture content increase) of the wood material decreases both the modulus of elasticity and modulus of rupture by 35%, thereby changing the timber grade to the prohibited category for construction.

In contrast, I have also proven that the commercially available outdoor silk-gloss thick glaze surface treatment, combined with full water saturation (10.4 % average moisture content increase) of the wood, maintains the modulus of rupture decrease at 11 %, and the modulus of elasticity decreases at 15 % compared to values measured for dry sample conditions. Consequently, I concluded that even under extreme weathering conditions, such as severe and frequent heavy rainfall, flash floods, and extremely humid environments, the mechanical properties of surface-treated softwood elements with load-bearing functions can be maintained in the safe category.

7. Publication list

7.1. Scientific articles

Kherais, M., Csébfalvi, A., & Len, A. (2020). The climate impact on timber structures. Int. J. Optim. Civil Eng, 11(1), 143-154. **Status: Published**

Kherais, M., Csébfalvi, A., & Len, A. (2022b). Moisture content changing of a historic roof structure in terms of climate effects, Pollack Periodica, 17(3), 141-146. doi: https://doi.org/10.1556/606.2022.00546 **Status: Published**

Kherais, M., Csébfalvi, A., & Len, A., Fülöp, A., Pál-Schreiner, J. (2023). The effect of moisture content on the mechanical properties of wood structure, Pollack Periodica. doi: 10.1556/606.2023.00917 **Status: In press**

7.2. Conference articles

Kherais, M., Csébfalvi, A., Len, A., & Fülöp, A. (2022a). How to protect wooden structures from damages caused by weather changes - study case. 25th Spring Wind Conference, 339-350. **Status: Published**

Kherais, M., Csébfalvi, A., & Len, A. (2022c). Moisture Content Impact on Wooden Structures. 10th Jubilee Interdisciplinary Doctoral Conference 2021, 395-407. **Status: Published**

7.3. Conference lectures

Conference name	Lecture title	Date	Location
16th Miklós Iványi International PHD & DLA Symposium	Expected impact of climate change on the physical properties and load-bearing capacity of timber structures	27/10/2020	Online
XIX. Szentágothai János Multidiszciplináris Konferencia	Effect of Moisture Content on Wooden Structures	26/03/2021	Pécs - Hungary
17th Miklós Iványi International PHD & DLA Symposium	Evaluation of measurements on roof structure of a historic building and comparison of the results as a function of environmental changes	26/10/2021	Pécs - Hungary
10th Jubilee Interdisciplinary Doctoral Conference	Moisture Content Impact on Wooden Structures	13/11/2021	Pécs - Hungary

XXV. Tavaszi Szél Konferencia 2022	How to protect wooden structures from damage caused by weather changes (Study Case)	07/05/2022	Pécs - Hungary
MIK PARTNERS Szakmai Nap 2022 és Baranya Megyei Mérnöki Kamara 25. Jubileumi Mérnöknap	Climate impact on timber structures	20/10/2022	Pécs - Hungary
11th Jubilee Interdisciplinary Doctoral Conference	Change of mechanical properties of timber structures caused by the moisture content variations	26/11/2022	Online

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