OSLO METROPOLITAN UNIVERSITY
OsloMet – storbyuniversitetet

Department of Civil Engineering and Energy Technology
Mailing address: P.O.Box 4 St. Olavs plass, NO-0130 Oslo, Norway
Visiting adress: Pilestredet 35, Oslo

Telephon: 67 23 50 00
www.oslomet.no

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MASTER THESIS

TITLE OF THE MASTER THESIS: Transient U-value and moisture buffering effect of solid timber elements and interaction with various HVAC strategies *(Dynamisk U-verdi og fuktbuffring i massivtre og samspill mellom ulike VVS strategier)*	DATE: June 15th 2020 NUMBER OF PAGES: 131
AUTHOR: Vegard Sørlie Tennfjord	SUPERVISOR: Dimitrios Kraniotis, Oslo Metropolitan University

SUMMARY

A hygroscopic material has the capability to absorb and release moisture from the surrounding environment, so-called moisture buffering. Wood holds excellent hygroscopic characteristics. A combination of hygrothermal properties allows the wood to potentially save energy, thus lower the ventilation rates. The purpose of this thesis is to evaluate the hygroscopic characteristics of wood and its effect when exposed to an indoor environment. Through laboratory experiments of solid timber elements and numerical simulations of a school building built in solid timber, the interaction between solid timber and the indoor environment will be investigated. The research attempt to bring answers to the following research questions:

- How does thermal transmittance of solid timber vary under different indoor environments?
- How does hygroscopic properties of solid timber affect the HVAC system and how the latter might be optimized?

3 KEYWORDS
Solid timber
Hygroscopic characteristics
Thermal transmittance

Acknowledgements

This master thesis has been prepared at Oslo Metropolitan University during the spring of 2020, and conclude the Structural Engineering and Building Technology master program. With the desire to write a relevant thesis focusing on sustainability and sustainable development, the research aim to investigate exposed solid timber's hygroscopic characteristics and how it might influence the indoor environment.

The research process has demanded a great deal of advice and guidance. Supervisor Dimitrios Kraniotis has contributed with theoretical and structural input to the thesis through weekly meetings. He has provided invaluable assistance ordering solid timber elements, setting up the climate chamber and numerical simulation implementations. I am forever grateful for all help he has provided the research, always being available for questions. Especially during the national lock down due to the pandemic situation preventing physical meetings. His dedication to make it possible for me to return to OsloMet to finish the experiments was also incomparable.

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Oslo Metropolitan University,
June 15, 2020

Vegard Sørlie Tennfjord

Abstract

40% of the global energy usage and 35% of greenhouse gas emissions are accounted for by the sector alone. To prevent further escalation, current energy policies prioritize energy and efficiency strategies. Focus on energy and efficiency has lead to the establishment of sustainable buildings. Sustainable buildings aim to reduce the environmental footprint by selecting materials that save energy and reduce emissions. Low embodied energy materials have these characteristics. A low embodied material demand less energy from extraction to destruction than high embodied energy ones. Wood is a low embodied material. Striving towards sustainability, solid timber has become frequently more used. In addition to be a low embodied energy material it also holds the potential to influence a buildings energy demand if utilized correctly. Being a living material, timber have the ability to absorb and release moisture, called moisture buffering. Moisture buffering is know as a hygroscopic property. Wood's buffering potential contribute to reduce humidity variations, allowing more energy efficient buildings. Evaluating the effects of wood's hygroscopic characteristics to an indoor environment when exposed lead to the following research question.

- How does thermal transmittance of solid timber vary under different indoor environments.
- How does hygroscopic properties of solid timber affect the HVAC system and how the latter might be optimized.

Two solid timber elements from separate manufacturers was investigated through climate chamber laboratory experiments. A steady state test to obtain a heat conductivity. Secondly, moisture was supplied for a dynamic evaluation. The elements was exposed to eight hours of increased moisture content, then 16 hours of dehumidification. Three different humidity cycles of 40%, 50% and 60% was performed. Growing moisture content was found to improve both elements thermal transmittance. The cross-laminated element saw the greatest improvement reducing the U-value by 0,04 W/m^{2}K. Moisture buffering was therefore found to be an significant attribute to an improved thermal transmittance.

In addition, a school building built in solid timber was simulated to inspect the hygroscopic characteristics affect on the HVAC. Different ventilation control methods was also addressed. Exposed wood was found to be equally as energy efficient as other surfaces. However, the indoor environment was far from acceptable. Six optimized exposed wood simulations was therefore performed, trying to optimize the buildings indoor environment. Assigned optimization steps amended different parts of the indoor environment, favourable for the controlling method used. A HVAC system that utilizes solid timber's hygroscopic characteristics was found to be critical to improve the indoor environment.

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1 Introduction

1.1 Climate change

The Polar ice is melting, spring comes earlier then ever and temperatures are rising all over the world. What was considered only a vague possibility a few decades ago, is now happening. Climate change has become a reality [16] and is putting the future of our planet at risk. The European Commission states that immediate climate actions are necessary, considering that over the last two decades the planet has experienced eighteen of the warmest years ever recorded.

Not only do temperatures rise. The last couple of years, European Commission state different types of extreme weather have occurred more frequently. Europe has experienced both drought and floods, America has been hit by multiple hurricanes that have led to death and devastation. Lastly, huge forest fires in the US, Europe and Australia have caused the death of many animals and people. Survivors have often had to flee their homes. Mostly, these climate changes are caused by human activity. It is estimated that humans have caused global warming to rise 1.0°C above pre-industrial levels, defined by Hawkins as the point in history where humans significantly began influencing the climate. As a result of humans burning fossil fuels, mainly from industrial activities and transportation, the levels of carbon dioxide in the atmosphere has seen a dramatic increase. Green forests provide natural carbon storage and prevent it from emitting to the atmosphere. Poor forest management allow deforestation reducing an important carbon depot, increasing carbon levels in the atmosphere [19]. Forecasts predicts the global warming to maintain its current temperature increase rate of 0.2°C per decade [17], reaching 1.5°C sometime between 2030 and 2050. [20]. Without taking preemptive action it is likely that by 2060 the global temperature increase will have reached 2.0°C. Temperature change will effectively make the Earth a "greenhouse", allowing for even more severe and potentially irreversible, climate impact [17].

Irreversible changes impacted by the global temperature increase will have its effect on different global industrial sectors by 2050. Areas experiencing flooding of rivers is expected to increase by 10-40%. Areas exposed to drought will grow. Ecosystems are likely to be exceeded due to flooding, drought, wildfire and acidification [20]. Sea-level might end up rising seven meters, affecting coastal areas and also cities near-shore [17]. The rise of sea-level will greatly affect industries located nearby coasts and the one using climate-sensitive resources [20].

Adger et al. defines the adaption to climate change as different systems adjustment to observed or expected climate change impacts to prevent adverse changes. As mentioned by Adger et al. societies, organizations and individuals have previously adjusted their behavior responding to past climate changes. Similarly, humans are now adapting to the ongoing and future climate conditions [16, 20]. One adaption to prevent and reduce climate change is to ensure sustainable development [20]. Sustainability contributes to improving adaptive capacity, increasing group's or individual's ability to deal with changes [16]. Sustainability is therefore a key concept in most discussions on future development and economic growth [21].

1.2 Sustainability

Today's concept of sustainability has appeared and gained importance only over the last few decades. It is therefore considered to be a relatively new idea [2]. However, the term is originally adopted from forestry, where sustainability since long, has meant that one is never to harvest more forest than what new growth adds [22]. Sustainability does not only focus on the environment and natural resources. Social and economic resources are also needed in order to establish sustainability. These two terms are always embedded in most definitions of sustainability [2]. The Office of Sustainability states that the sustainable movement has roots in past movements as social justice, conservationism and internationalism. Ideas from movements like these have clearly contributed to what sustainable development encompass today.

As with sustainability, many authors have their own definitions of sustainable development. Spence and Mulligan expresses that sustainable development is needed to avoid impoverishing our future generations by depleting resources and destroying biological systems on the planet. Zabihi and Habib says that sustainable development is needed to ensure better life quality for everyone today and generations to come. Few words or many, the message mainly remains the same. Both of them have been inspired by the famous definition given in the report "Our Common Future" by the Brundtland Commission [2]. The former Norwegian prime minister Gro Harlem Brundtland and her team, the World Commission on Environment and Development, defined sustainable development as:

> *"Development that meets the need of the present without compromising the ability of future generations to meet their own needs" [24]*

Figure 1: United Nations Sustainable Development Goals [1]

To ensure sustainable development, all members of the United Nations adopted an agenda for sustainable development in 2015. With 17 sustainable development goals, the agenda provide current and future peace and prosperity actions for people and the planet. Health and education improvement, inequity reduction and economical growth strategies must be harmonized with ending poverty and other deprivations. Simultaneously, climate change must be handled preserving oceans and forests [1]. The 17 goals are presented in figure 1. These goals unite the environmental focus with both social and economic aspects to achieve sustainable development. These three are therefore presented by the Office of Sustainability as the pillars of sustainability in figure 2.

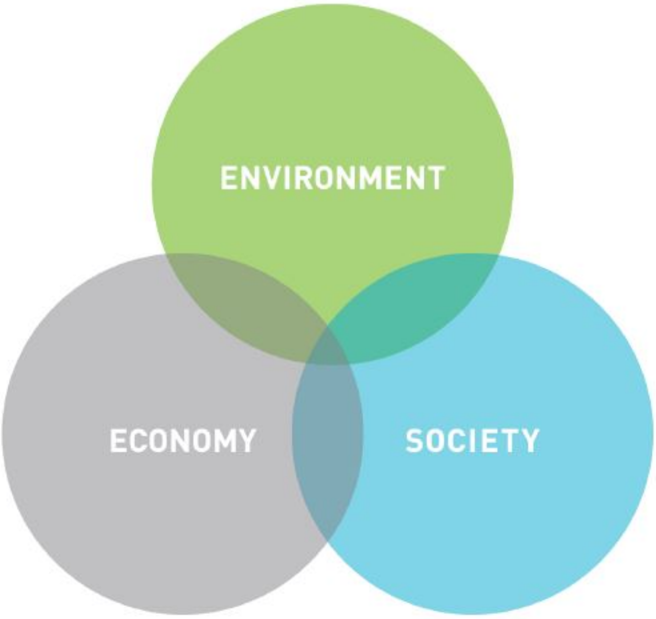


Figure 2: Three pillars of sustainability [2]

The environmental sustainability is present when the environment is kept in balance. It is maintained using natural resources at a rate that allow regrowth before they are consumed. If independent communities have access to their required financial resources, or other, to meet their needs, then the economic sustainability exists. Lastly, it is essential for all humans to keep their families healthy and safe, have access to enough resources and be protected by human rights [2]. With all three pillars present and in harmony development is made sustainable according to Kuhlman and Farrington.

Then main goal of sustainable development can be stated as maintaining welfare over time. To achieve this, it is important to take care of the environment and ensure preservation of resources for future generations [22]. The building and construction sector is one of the biggest global sectors in the world. Not only does it account for a large percentage of the global greenhouse gas emissions, it is also of great economic and social significance [25]. Therefore, the sector plays a key role in developing global sustainability.

1.3 Environmental impact of buildings and constructions

Estimates show that by 2056, the activity from the global economy will expand five times, the human population will increase by 50%. In addition, energy use and manufacturing activity considerably increases. World energy use increase linear to the population growth. The link between these are presented in figure 3, illustrating how population growth impacts the environment [3].

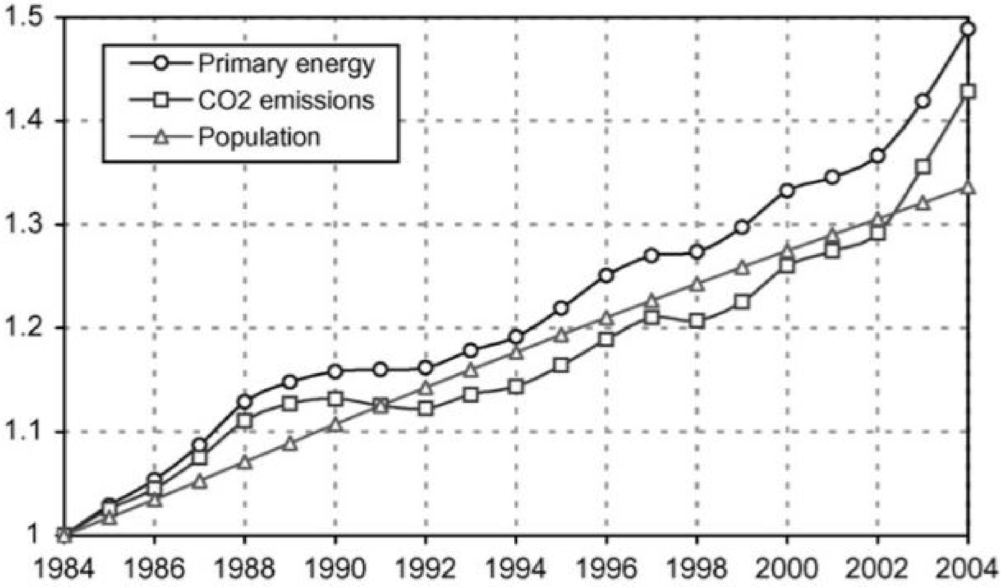


Figure 3: Global primary energy use, CO_2 emissions and world population from 1984-2004 [3]

The global building and construction industries grow rapidly compared to others, especially those using energy and fossil fuel [26]. The growth has raised global concerns. Challenges with supply management and energy resource exhaustion, make the sector contribute heavily to negative environmental impacts [3]. Hurmekoski announced that the sector alone accounts for more than 40% of global energy use and 35% of the greenhouse gas emissions. Being able to address these challenges, will be an important part of becoming a more climate-friendly sector [27].

The up-going trend is however predicted to continue. For many decades the industry's fuel and energy demand has been rising [27]. During a period from 1984-2004, showed in the figure, global primary energy use, energy harvested from natural resources [28], increased by 49% and the CO_2 emissions grew by 43%. This is an annual average increase of respectively 2% and 1.8% [3]. It was also discovered that the greenhouse gas emissions caused by the industry accounted for around 8.6 billion tons of CO_2-eqv in 2004 [29, 30]. CO_2-eqv is defined by OECD and is a measure used for comparing the global warming potential of different greenhouse gases. Pérez-Lombard et al. states that all current predictions show no signs of stopping. This is confirmed by Hurmekoski referring to numbers from the European Union expressing that the construction volume this century is significantly high.

Increased built volume is caused by population growth. Building standards are frequently updated to improve the indoor environment. To meet these updates buildings are constantly enhanced. Besides, humans do tend to spend much more time indoors [32]. More time indoors rises the comfort demand [27] Increased comfort demand and time indoors have raised the level of energy use in the building. The Building and construction industry has reached similar energy usage as transport and industry [3].

1.4 Energy use in buildings

One of the most important tasks in order to achieve environmental sustainability is being able to manage energy need. This is especially a key factor in buildings since they are huge energy consumers [26]. In 2004 buildings accounted for the highest consumption percentages in the European Union with 37% [3]. It has also been estimated by Pérez-Lombard et al. that the energy use in buildings in the next 20 years will increase by 34%, showing no indications that buildings will consume less energy in the near future. Only from 2004 the annual increase have been 1,5% [3]. In the same article, Pérez-Lombard et al. state that the building sector is expanding in Europe due to economic growth, and thereby creates and energy demand increase. However, possibly the biggest contributors to an annual increase are the growing use of building energy services such as heating, ventilation and air conditioning systems (HVAC).

The building sector and industries' significant contribution to climate change due to energy use and emissions. Energy policies therefore prioritize efficiency and strategies for savings. Akadiri et al. argues that 85-95% of climate change contribution is caused by energy demand used to comfort the building's occupants. HVAC has become an unavoidable asset with the increased comfort demand[3]. In addition, the HVAC manage indoor humidity to maintain acceptable levels [33]. Climate change concerns has forced the sector to discover alternative solutions with better environmental potential. Global governments now promoting energy efficiency and reducing of energy use. It is considered an important step to make the building sector and industry more sustainable [3]. Along other environmental issues, energy efficiency and energy use reduction plead the rise of the green building concept, known as sustainable building design [34].

1.5 Sustainable buildings

The necessary adaption to sustainable buildings is considered to be the construction industry's most valuable contribution to sustainable development [3]. John et al. points to a building practice that strives for better economic, social and environmental quality. This is achieved through a collection of building project process methods aiming to harm the environment as little as possible [3]. By a healthy use of natural resources and a building stock that is managed appropriately, sustainable buildings can reduce energy use and improve environmental quality. Harmonizing with the environment, the buildings will be more resource and energy-efficient which again will prevent pollution and reduce greenhouse gas emissions [35]. It has been claimed that it is possible to reduce energy use up to 50% and one third of the CO_2 emissions for sustainable buildings [36].

Adaption to sustainable building is complex and not done overnight. Hurmekoski tell that the sector has to confront slow-changing standards, rules and norms, perceptions and building culture. Also, it is necessary to consider the building's whole life cycle [35]. Hill and Bowen expresses that a sustainable construction process needs to start long before the construction of the building. This means that as early as in the planning and design process sustainability is to be addressed and thought of. Hill and Bowen also states that the process will carry on even after the construction work is finished and the construction workers have left the site. The building will be an energy consumer all the way until its destruction, coherent with the life cycle assessment's well-established concept of "cradle-to-grave" [5]. Due to the complexity, sustainable building must integrate architecture with environmental electrical, mechanical and structural resources [35]. Spence and Mulligan claims that *"the construction industry has to find ways to build more with less"* and propose strategies for the industry. Constructing buildings with longer service life that can be recycled. Substitute fossil fuels and other non-renewable energy sources. Reduce the usage of materials with limited availability, and improve buildings total life-cycle energy efficiency. These are a few of the proposed strategies [21].

More knowledge about sustainable buildings and their role in sustainable development is quickly evolving. The evolution is now becoming appreciated by the industry [3]. World Green Building Council express that sustainable buildings have the ability to contribute towards meeting United Nation's 17 sustainable development goals, shown in figure 4. According to Hydes and Creech, clients are more and more rightfully demanding buildings increased energy efficiency and less material intensive. A common misunderstanding is that sustainable buildings naturally must be more costly than conventional buildings. This is not the case, especially in a full life cycle perspective. By combining high-tech and not so high-tech solutions it is possible not only to build a building that cost the same as a regular building, but also a building far less expensive to operate [38]. A big part of conventional buildings is energy usage during operation. As mentioned in chapter 1.4 operational energy account for around 90% of a buildings' total energy use. Use of more efficient systems and better building technologies will make possible a reduction in the consumption of operational energy [26, 21]. A big reason for this positive effect is that we now have technology that enable us to produce more effective and advanced insulation materials [39]. Lately, more focus has been on reducing the energy required to produce or manufacture these energy efficient materials. Required energy is the energy needed to apply the material with embodied energy [26].

Figure 4: Green buildings contribution to sustainable development [4]

1.6 Embodied energy and emissions

Sartori and Hestnes defines embodied energy as the total energy needed to manufacture a good. This energy is non-renewable, excluding renewable energy sources. Material's embodied energy is the energy demanded during the material's process from extraction to manufacturing. In addition, deconstruction and decomposition of the material also consume energy. A building is the sum of many different building blocks and can, in a sense, be said to embody the total energy of all its parts [41]. Akadiri et al. expresses this energy as the energy required to create a building. This includes both energy used during construction and assembly. Also, embodied energy in the building materials is already implemented. Embodied energy has, through its impact on a building's total energy use, been adopted as a key in the construction of buildings and materials. To begin with, the energy used during operation was the only energy use considered to have environmental impact. Mainly due to it owning the largest share of energy during a building's life cycle [39]. In a inefficient building the embodied energy only account for 10-15% of the operational energy. However, with the increase of sustainable thinking buildings have become more energy efficient. With this reduction, the significance of the embodied energy becomes more prominent as shown in figure 5 [42]. That is why Akadiri et al. addresses that it is necessary to include both operational and embodied energy in a building's energy life, hence its energy use.

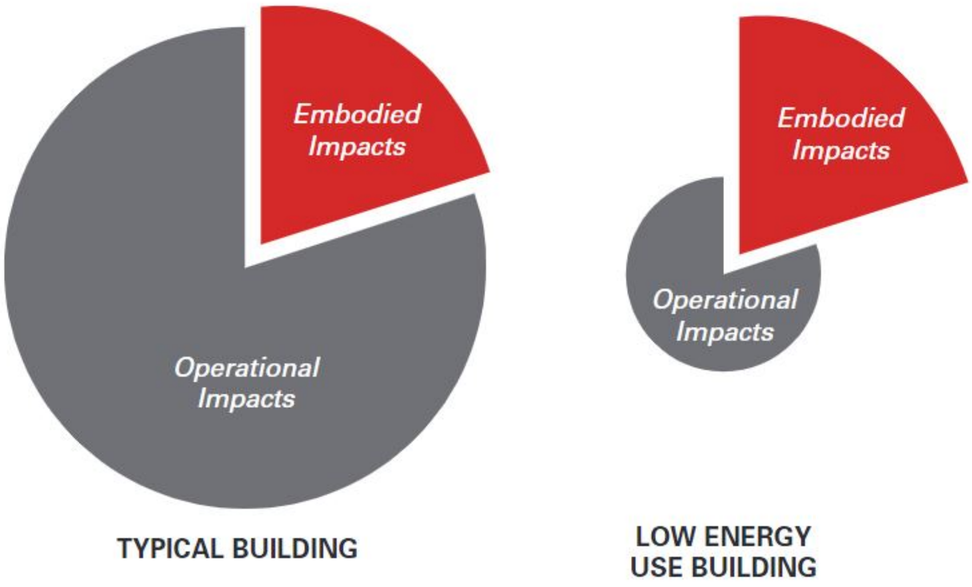


Figure 5: Traditional vs. sustainable buildings operational and embodied impacts [5]

In order to save energy and reduce emissions of CO_2, correct selection of materials and products is essential [43]. Akadiri et al. amplifies that materials with low embodied energy are a key to reduce energy use. High embodied materials, on the other hand, is by González and Navarro said to increase the possibility for more emissions. It is also concluded in the same article that careful selection of low environmental impact building materials can mean as much as a CO_2 saving of 28%. Common types of buildings found in the large parts of Europa are found to be heavy masonry or concrete constructions [43]. Substitution of these structures with wooden ones can significantly earn energy use and emission savings. It is in fact stated that the use of wood in buildings would enable a reduction of almost 50% of the CO_2 emissions [44]. It suggests wood to have a distinct environmental advantage when compared to other structural materials [34].

In a study performed on two cases calculated the GHGs emissions for two buildings from extraction to finished manufacturing (creadle to gate), it was found that reinforced concrete story building emitted significantly more CO_2 than a timber building with reinforced concrete used for foundations, basement and ground floor and solid timber products for walls and floors. The timber building emitted 2871 tons less [6]. Since the timber building is a combination of timber and concrete, Sandanayake et al. investigated the emissions from both materials as seen in figure 6. Even with approximately the same amount of distribution, it was discovered that the timber structures was accountable for 7% of the buildings total material GHGs emissions. The last 93% was caused by the concrete structures, suggesting timber to hold significant emission reduction abilities [6].

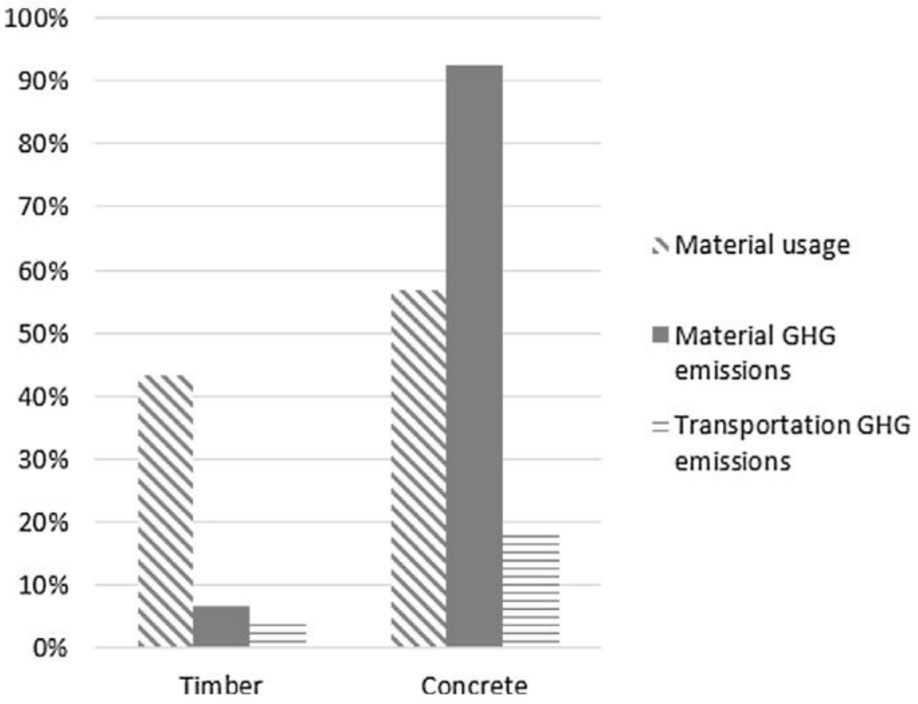


Figure 6: Distribution of material greenhouse gas emissions from timber and concrete [6]

A huge part of why wood is considered a preferred material in buildings is its sustainability. Being a renewable resource it has several advantages when compared to other materials used for construction. Due to its natural properties, like the capabilities to store carbon and produce oxygen, wood is more or less considered a CO_2-neutral material. It is also a material that requires minimal primary energy when manufactured [45]. Ross et al. addresses that this minimal requirement for energy during processing provides the wood with low embodied energy. In addition, there is more to wood than its sustainability and function as a structural material. Wood also has great heat capacity and low conductivity. The low conductivity of wood allows for less heat to pass through the material. This is of key importance when trying to maintain the indoor temperature at an accepted level [34]. Lastly, wood does also has good hygroscopic characteristics, which is explained later in this thesis.

2 Background theory

Wood has been used as a building material for millennia [46]. The main reason for wood's long tradition in building is that it always have been a material that is easily accessible [47]. Due to its renewability it has always been an available and cheap material. It is also easy to work with and can if needed easily take many different shapes and forms. Today wood is traditionally used mostly in single-family houses both in the United States and in the European Union. The most common technique utilises a wooden frame or "stick frame" of wood where wooden studs carries the vertical load and the airspace between them is filled with insulation [25, 46]. However, structures of solid wood also have traditions way back in time, and is now considered a pioneer for sustainable buildings.

This chapter will consist of more in depth theory about wood, its history, the transition to new solid wooden structures and the favourable characteristics that make it applicable to improve the indoor environment.

2.1 Evolution of timber building methods

Ten thousand year old findings show that timber has been used as building materials for a long time. The Neolitich longhouse, dating back to 6000 BC, is one example [48]. In Norway, there are found wooden buildings that were constructed in the 10th century [49]. Both the Neolitich longhouse and the Norwegian churches, figure 7, are stave constructions, using vertical wooden log or half-logs, embedded into the ground, to distribute the loads. Stave constructions are divided into three different types, palisade wall and two types of corner-post construction, embedded and not embedded into the ground. Embedding the logs was a popular building method in northern Europe until the eleventh century [9]. In the beginning of the 12th century, however, a significant change in construction of buildings occurred. Instead of embedding logs into the ground, logs were jointed into a sill beam laid horizontally on the ground or even on top of stones. This change revolutionized timber construction leading to better durability compared to the previous method [10]. Proof of this durability improvement can still be seen today, as some of these buildings have been preserved and still stands [49]. University of the West of England express that the horizontal log framed the wall gave birth to the "framed wall".

Figure 7: A) Neolithic longhouse [7], B) Norwegian stave church [8]

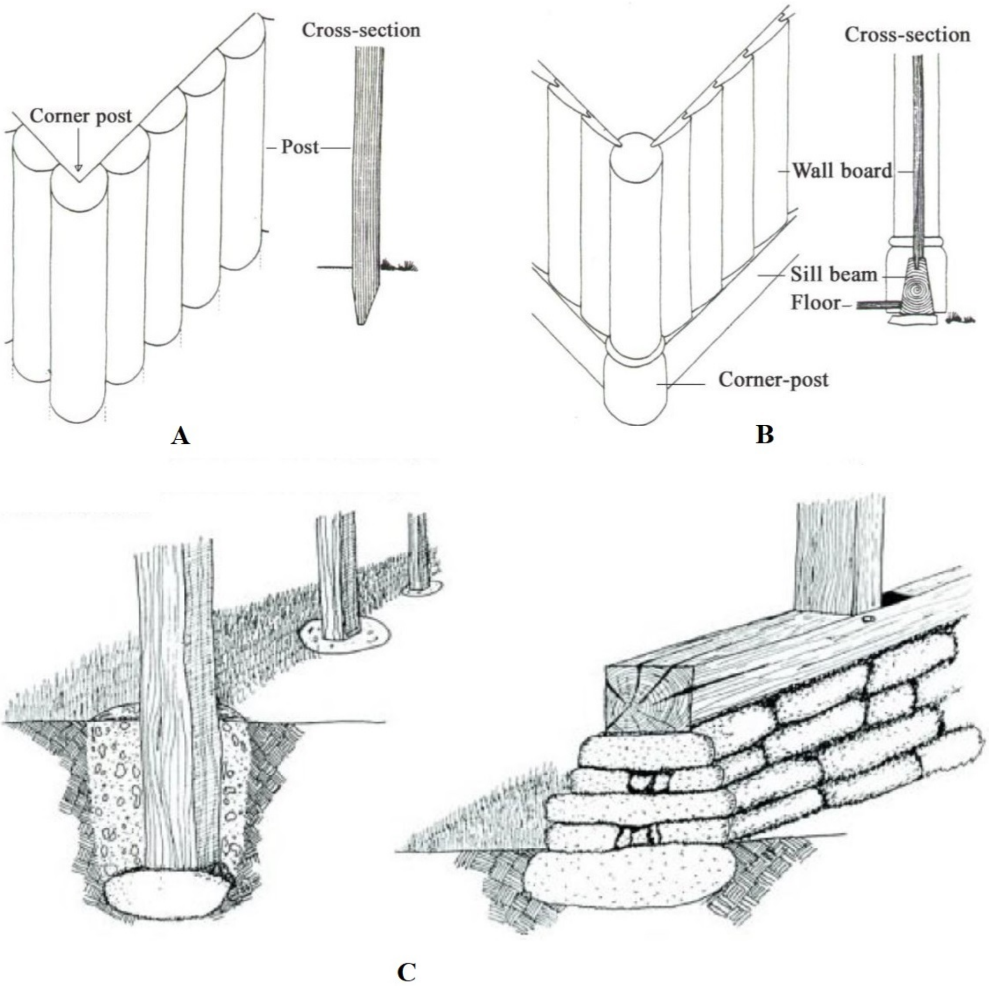


Figure 8: Stave constructions: A) Palisade wall, B) Corner-post with sill beam [9], C) Evolution from embedding to sill beam [10]

As stave constructions grew in popularity, so also did log and bole buildings. Sigurdardottir state that it is likely to believe that these methods was introduced around the 10th century. Wooden logs were placed on top of each other horizontally [14] and assembled together in the corners to make the wall sturdy [9]. The log-building is by Hameury announced to be the most well known solid timber structure. However, bole houses are also common from these ancient times. These constructions combines techniques from both stave constructions and the log house. Along a wall vertical studs became jointed into sill beam. To fill the gap, half-logs was slotted between the studs. For both these methods, accurate assembly is by Sigurdardottir said to be vital. The log dries in place. The drying process shrinks the wood, making the building tight and insulated [47]. As with the stave method, the log and bole method developed through the years, and were said to reach their peak in the middle ages. In Iceland the method was used until the 19th century and in Norway log houses was continuously built until the second world war [9].

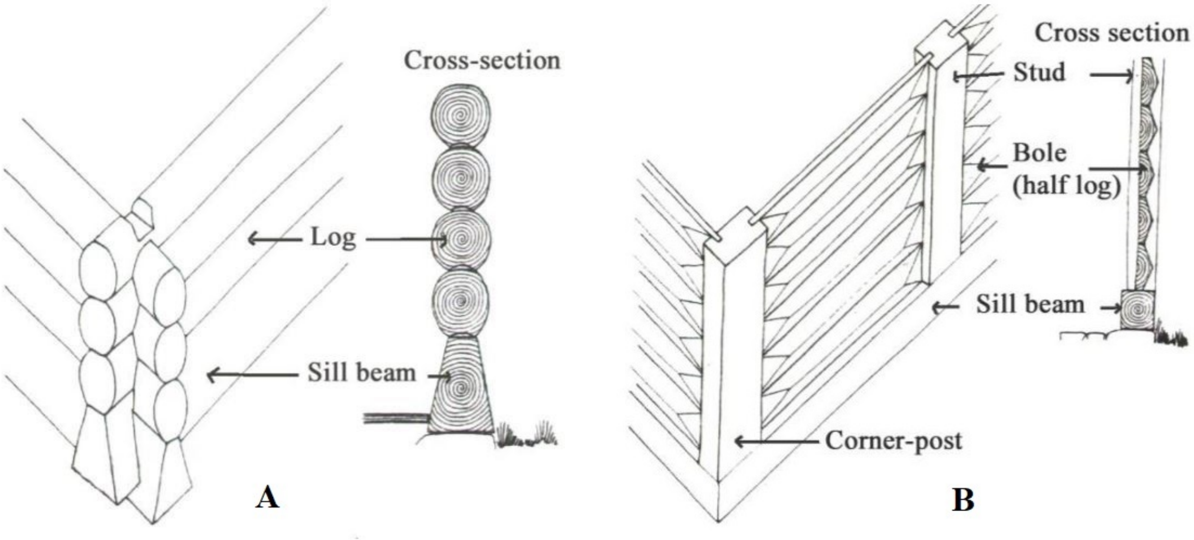


Figure 9: Horizontally laid log-structures: A) Log structure, B) Bole structure [9]

Timber-frame construction is more recent that both stave constructions and log and bole buildings. In Norway, it is commonly seen in the 17th century, after having spread rapidly [9]. However, the concept of building with a frame was already introduced in the 12th century, according to the University of the West of England. The article divide timber frame buildings into four types [10]:

- Box frame (figure 10A)
- Post and Truss (figure 10B)
- Aisled construction (figure 11A)
- Cruck (figure 11B)

Frames in box frame construction are connected by cross tie beams to form a box. The roof is a separate structure carried by the external walls, acting as the box's lid. It does not have rafters supporting at mid span. Collars were added to the rafters in order to help the tie beams prevent the walls from spreading outwards. Post and Truss framing method has much in common with the box frame. However, difference is that here the frame consist of both a roof and wall element. As with box frame these frames are connected with tie beams. Thus, there are also tie beams connecting the frames rafters, providing better carrying abilities. This is expressed to be the most usual timber frame method [10].

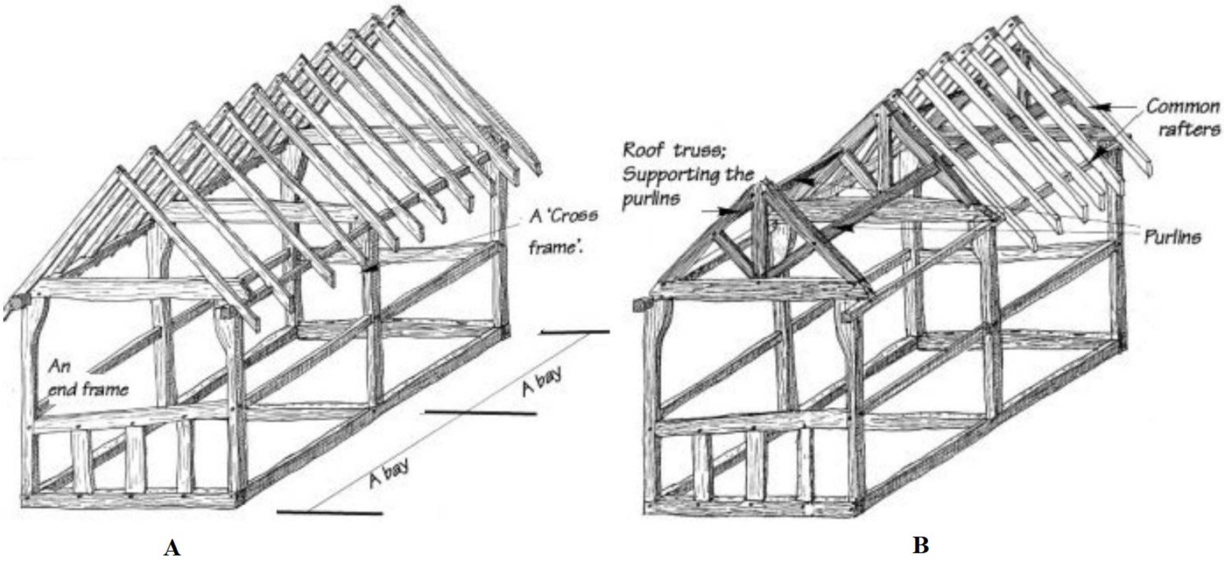


Figure 10: A) Box Frame construction, B) Post and Truss construction [10]

In order to increase internal space to the box frame construction, two side aisles were added to form the Aisled construction. This made the once external wall post internal, arcade posts. The roof is brought over the two aisles maintaining the roof original angle. Lastly, and structurally different from the other three constructions, is the Cruck construction. Each frame is made up of incline timbers assembled together, with the ridge beam at the top to form an bent "A" shape. Just like the other three methods, tie beams connect the frames [10].

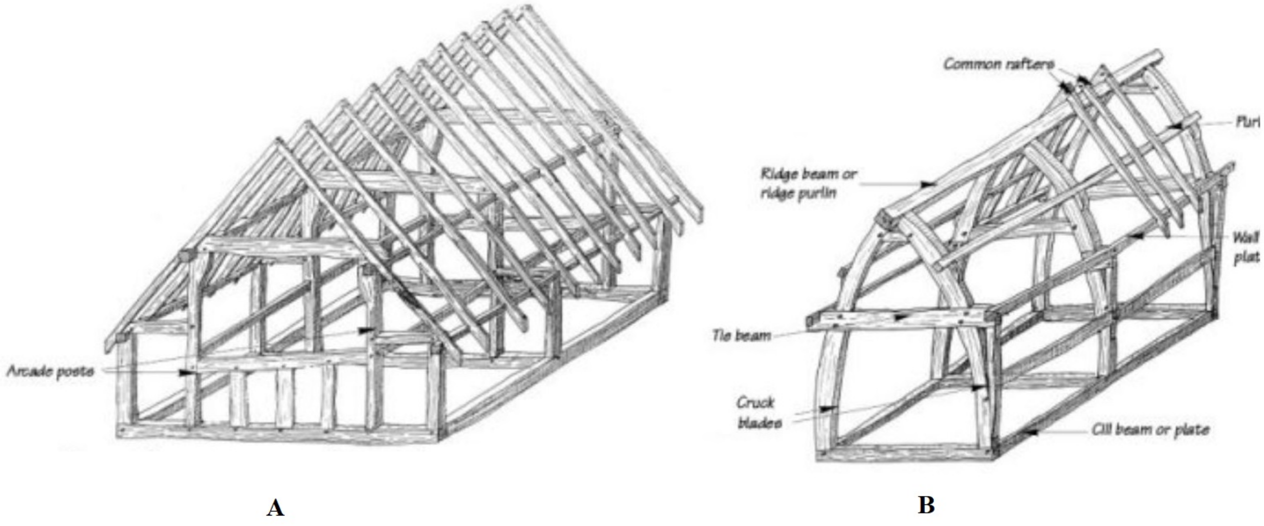


Figure 11: A) Aisled construction, B) Cruck construction [10]

Just like stavework and log buildings, the timber-frame method has evolved through time. The frames dating back to the 12th century have much in common with the once from the 17th century, though evolution has improved frame construction and made frames more stable and robust. Where the previously mentioned frame examples had their short ends constructed as one frame, more recent methods apply several frames in one wall. This indicates less distance between studs connected by horizontal noggin-pieces. Braces used diagonally brings even better stability of each frame, making each individually rigid [9].

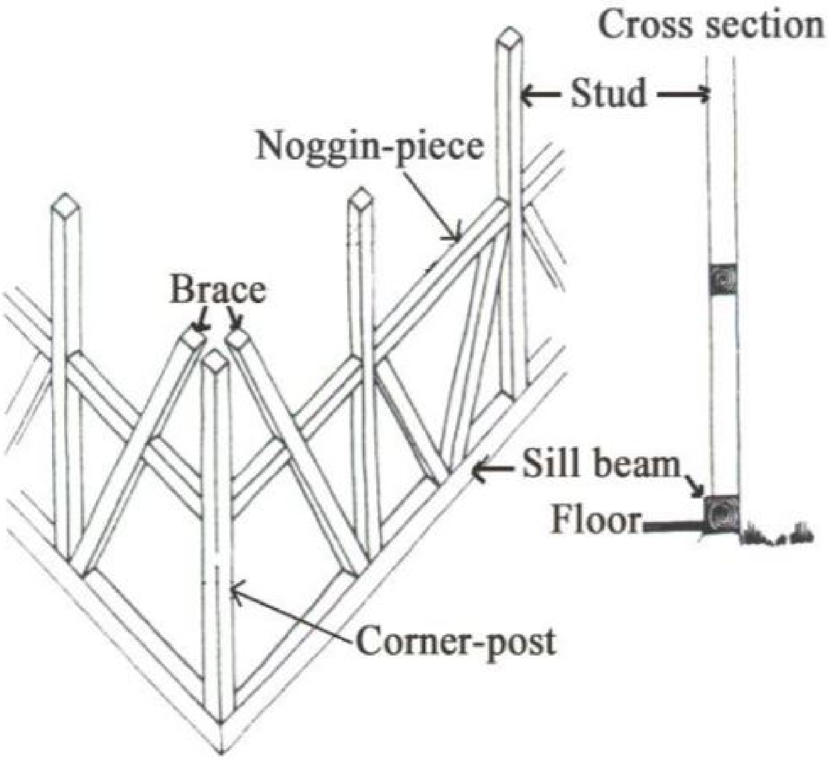


Figure 12: 17th century timber frame method [9]

Wood is stated to be the most used material in existence [48]. The most well known solid wooden structures are the log houses [14]. In the beginning of the 20th century development made it possible to reinforce concrete, making it a more economical alternative. Wood went out of fashion, solid wooden resources were getting harder to get hold of, and lastly other materials enabled faster building. Log houses and other wooden structures where replaced by more solid construction materials like concrete and brick [12]. In the early 90s, wood made a comeback.

2.2 Solid timber

Hameury expresses that several projects were conducted in central Europe following the development of different industrial timber products. These so called solid wooden products introduce new structural concepts that utilizes more of the wooden volume in in an attempt to innovate the industry. However, compared to the solid timber in log houses, much have changed. Traditionally the term solid timber is applied wooden products that is used in its natural structural form, being sawed out directly from the log [45]. McKeever mention that much have changed with the timber resources the last century. The grown timber in the United States has been harvested making timber more unavailable and lowering the quality. Nevertheless, the demand for timber increases, causing a considerably rapid increase in price. In response to the decreasing availability, reduced quality and increasing price, the solution has been to replace traditional sawn solid timber with Engineered Wood Products (EWP).

Hans Joachim Blass define EWP as products that are manufactured by reassembling already disassembled timber products. Product like these are more efficient since they are able to be produced by the timber resources that are available [50]. EWP are still solid timber structures, but are built up by pre-manufactured systems defined by Hameury as plate-like. These system are timber products provided by layers of wood. The layers are assembled with glue or pressed along the fibers or cross-wise [14]. Jakes et al. address solid timber as a class of composites. The class includes glue-laminated timber (glulam), structural composite timber and cross-laminated timber (CLT). These are showed in figure 13. Glulam is a solid beam consisting of lumber stacked along the grain. Structural composite lumber is used as a term to describe wooden composites made of flakes with their grain parallel. Lastly, cross-laminated timber elements are assembled in perpendicular layers [46]. CLT is by Mallo and Espinoza known as the most recent innovation of EWPs, and has the potential to increase the amount of wood used in buildings considerable and therefore revolutionise the industry.

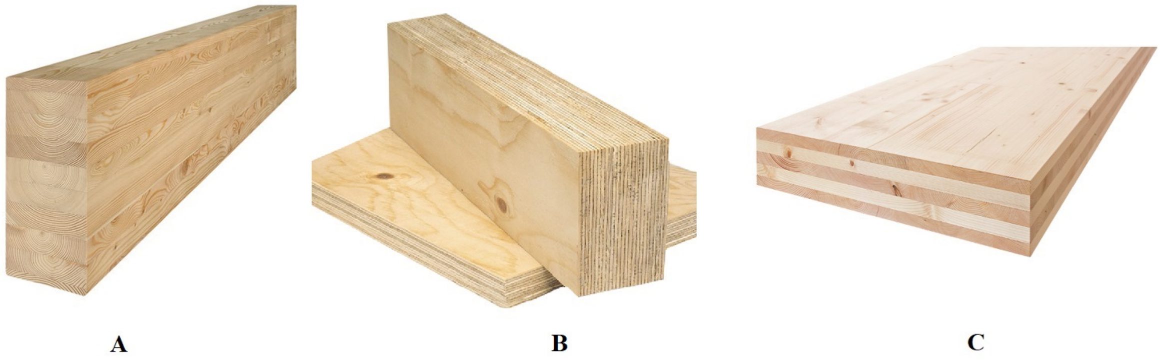


Figure 13: Different solid timber structures:
A) Glulam, B) Structural composite timber, C) CLT

2.3 Cross-laminated timber

Cross-laminated timber mostly consist of an uneven number of layers, generally three, five, seven or more as illustrated in figure 14. The layer arrangement is, as mentioned before, cross-wise to each other composed with an angle of 90°. Brandner et al. calls it as X-lam. Each layer is connected by adhesive binding, glue [11]. There are also cases where nails and screws may be used [45]. Like other common carpenter products, CLT has high in-plane stability. However, the thickness of the product also make it stable out-of-plane, giving it the potential to be a stand-alone structural element [12]. This is why Brandner et al. states that CLT is optimized for bearing loads both in and out of plane. CLT's properties has made it possible to improve timber engineering and allowing design and realization of buildings that previously have been restricted to other building materials [11].

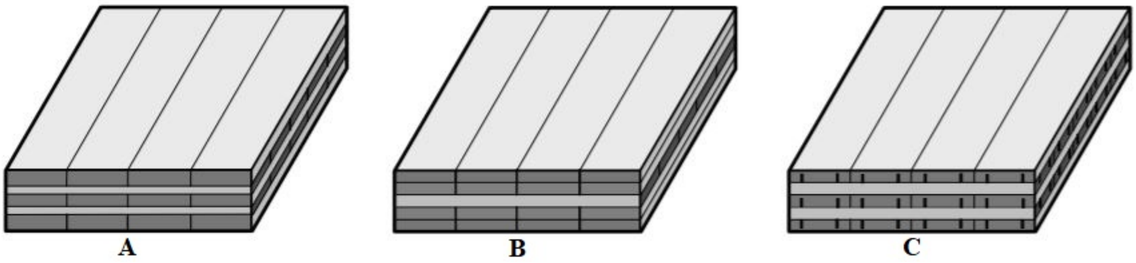


Figure 14: Example of five-layer CLT element in different arrangements:
A) Common layup, B) Double layer outside, C) Layers with gaps to relieve stresses [11]

CLT originates from Europe and was developed in the 90's [51]. Mallo and Espinoza suggest that CLT building systems might be used as walls, floor slabs and roofs. Brandner et al. states that these wooden systems are the reason why timber has regained its market shares the last 10 years, mostly inn residential buildings, office buildings and schools. Its low mass, high stiffness and significant bearing capacity make CLT ideal for these types of buildings [11]. Additionally, CLT is currently gaining popularity in other fields of construction, like building of bridges and rehabilitation of existing buildings. The last decades CLT volumes has shown significant growth, given in thousand (TSD) m^3. Figure 15 illustrate worldwide production of CLT since it was introduced, until 2015. The current adaption worldwide will contribute to a continuous growth for decades to come, expecting CLT to become as relevant as glulam [12].

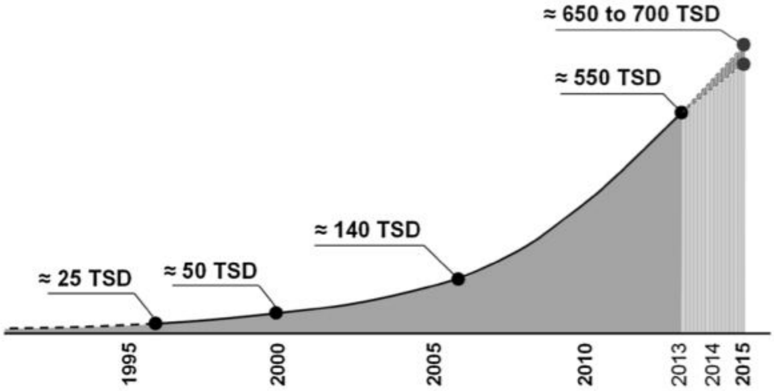


Figure 15: Worldwide production volume of CLT until 2013 with a 2015 forecast in thousand (TSD) m^3 [12]

CLT has many advantages and is becoming increasingly popular building material. Advancements in manufacturing have made large solid timber construction elements easy to pre-fabricate and use [11]. Pre-fabrication allows for high precision at the factory before its delivered to site [46]. The manufactoring process is characterized by clearly separating the layers for bearing, insulation, installation and cladding, which is of great help if any repair is necessary in one of the layers [12]. Pre-fabrication is by Brandner et al. expressed as a dry and clean construction process, Jakes et al. agrees and adds that constant control of the relative humidity is necessary due to wooden dimensions ability to change with alterations in moisture content. Being pre-fabricated makes CLT elements assembly fast. Family homes constructed with CLT is assembled in one or two days, making the on site erection time short. CLT is sustainable [11] and also has considerable benefits regarding building physics. CLT has low air permeability. Air permeability is by Kiron defined as the rate of air that passes perpendicularly through a material. The migration of air occur under a known air pressure that is different for the material's two surfaces. CLT also has specific storage capacity features both for thermal energy and humidity due to its hygroscopic characteristics. [12, 34].

2.4 Hygroscopic materials

Since the beginning of the 80's, hygrothermal building materials ability to moderate the indoor environment has been increasingly researched. Key to a good indoor environment is indoor air quality and temperature. Occupants perception of these two is determined by the indoor humidity [13]. Rode et al. states that humidity is known to impact occupant's productivity and health. The difficult thing about indoor humidity is that depends on load variation, the number of occupants and time of year. The humidity varies from day to day and from season to season. Materials with the ability to absorb and release moisture are presumably useful in reducing these day to day relative humidity fluctuations. The assumption is that it is possible to improve indoor air environment in all climate zones by applying building materials that are hygroscopic [13].

The hygroscopic statement made by Rode et al. has later been confirmed by different studies. However, the hygroscopic material's potential depend on multiple factors. It have more impact the larger the exposed surface is. That being said, Asphaug et al. states that all internal surfaces, interior and textile contribute to moisture buffering, to some degree. When surfaces are treated, they loose their ability to buffer. The outdoor climate, dependent on ventilation rate and moisture content, also has its affects the indoor temperature and humidity [54]. Like other natural materials, wood is hygroscopic. It is able to absorb and release moisture from and to the environment surrounding it. This exchange depends on the amount of water in the wood itself and the temperature and relative humidity in the air [34]. Wood's thickness, its permeability and capacity for storing moisture are features that influence its ability to buffer daily changes in indoor humidity [54].

To establish a definition of the moisture buffering capacity of materials used in the indoor environment Rode et al. started the NORDTEST project in 2013. Buffering capacity need to be considered within its indoor environment. The test define the phenomena and a new material property. The phenomena is divided into three levels, room, system and material. On the room level the moisture buffer capacity relates to the exposed area of the present material's surface, the room's moisture load, ventilation rate and indoor climate. On the system level the moisture buffer value is dependent upon the surface area and thickness. This is also know to be the practical moisture buffering value. Lastly, on the material level the moisture buffer capacity refers to the heat transfer rate over a material's surface as the surface changes temperature. These are all different levels of moisture buffering, and are illustrated in figure 16 [13].

In the tests carried out by the NORDTEST project, different types of building materials were exposed to changes in relative humidity. The purpose was to calculate the practical moisture buffering value ($\mathrm{MBV}_{\mathrm{practical}}$). This is a practical approach often used in experimental methods. $\mathrm{MBV}_{\mathrm{practical}}$ is an indication of the amount of water that is transported both in and out of a materials exposed surface. simultaneously, the relative humidity of the air is varying, over a certain time period. The tests showed that wood's moisture buffering value is three times the value for concrete and brick, and twice the value for gypsum. Greater buffering value indicate better buffering capacity [13]. Wood's buffering effect was proven by Nore et al. to reduce indoor relative humidity fluctuations. It was also found that absorption of moisture increased the wooden surface temperature, connecting moisture buffering with heat transfer [56].

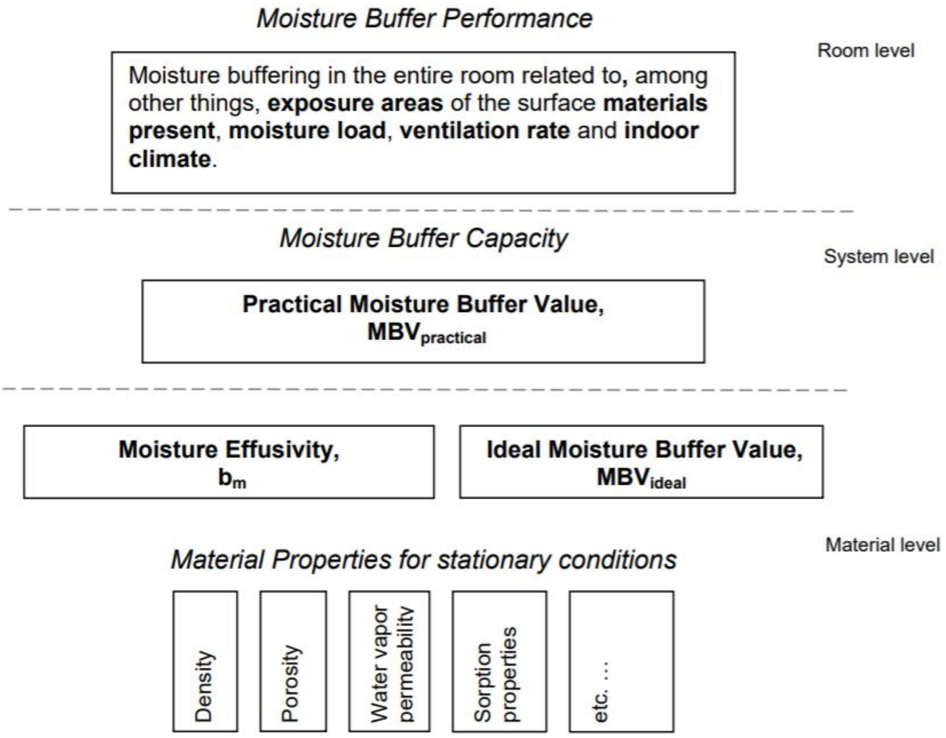


Figure 16: Indoor environment moisture buffering phenomena [13]

Variation in a building or rooms temperature and relative humidity is essential in order to take advantage of the hygrothermal mass. If these conditions are constant, equilibrium will occur between the air and material making the hygrothermal mass insignificant. Hygrothermal mass combines the effects of heat capacity (thermal mass) and moisture capacity (hygroscopic mass). However, with varying indoor conditions, exchanges of moisture and energy take place between the air and materials. A hygrothermal material exposed to increasing indoor air temperature absorb some of the heat. The absorbed amount depend on the materials thermal conductivity and heat capacity. It is necessary to address that heat capacity is a product of the materials density and specific heat capacity. High thermal conductivity allow more heat absorption. Higher heat capacity provides the material better abilities to store the heat. When the temperature decrease the material release the heat back to the room. This is know to be thermal buffering. As for heat and moisture capacity is moisture buffering identical to heat or thermal buffering. Changes in air moisture content exchange water vapor absorbed and released by the material. Water vapor absorption is initiated due to diffusion trough the material surface. The materials water vapor permeability and moisture capacity are crucial in order to measure the moisture transport. Higher permeability improve moisture penetration while high moisture capacity will indicate how good the material store it [53]. compared to concrete wood have higher heat capacity but lower thermal conductivity. Therefore not implying as good thermal properties. However, when comparing hygroscopic properties wood provide both better moisture permeability and moisture capacity than concrete [57].

2.5 Interaction between hygroscopic materials and HVAC systems

Heating, ventilating and air conditioning systems (HVAC) are used in modern buildings to provide acceptable indoor climate and thus maintain good indoor air quality. One of the most important tasks a HVAC system has, is to keep the indoor temperature and humidity at a tolerable level. It is stated that the indoor relative humidity both directly and indirectly may affect human occupants' health ability to perform. A high level of relative humidity, above 70%, initiate mould growth. It also release spores that might deteriorate the building materials. If the relative humidity decrease below 30% the materials ozone production increase. It might also dry out indoor air causing irritations for the occupants. Maintaining the indoor climate somewhat acceptable is energy demanding, which is one of HVAC systems major drawbacks, mentioned in chapter 1.4. Therefore, the desire to develop more energy efficient and passive systems rises as the industry is aiming at sustainability [14]. That is why Osanyintola and Simonson addresses that HVAC has the potential to save energy if it is controlled optimally and used in integration with hygroscopic materials.

Normally HVAC's are used with temperature controlled ventilation. The system govern the temperature with the purpose to keep the indoor conditions constant, hence less relative humidity fluctuations. When constant conditions are achieved, equilibrium between the air and the exposed materials occur. The equilibrium prevent exploitation of hygrothermal mass [53]. Hameury state that moisture buffering demand humidity fluctuations. With balanced fluctuations moisture buffering materials does not initiate. Moisture buffering demand interaction between the indoor environment it is found in, and the building envelope. The interaction needed to fully exploit moisture buffering is illustrated in figure 17 [14].

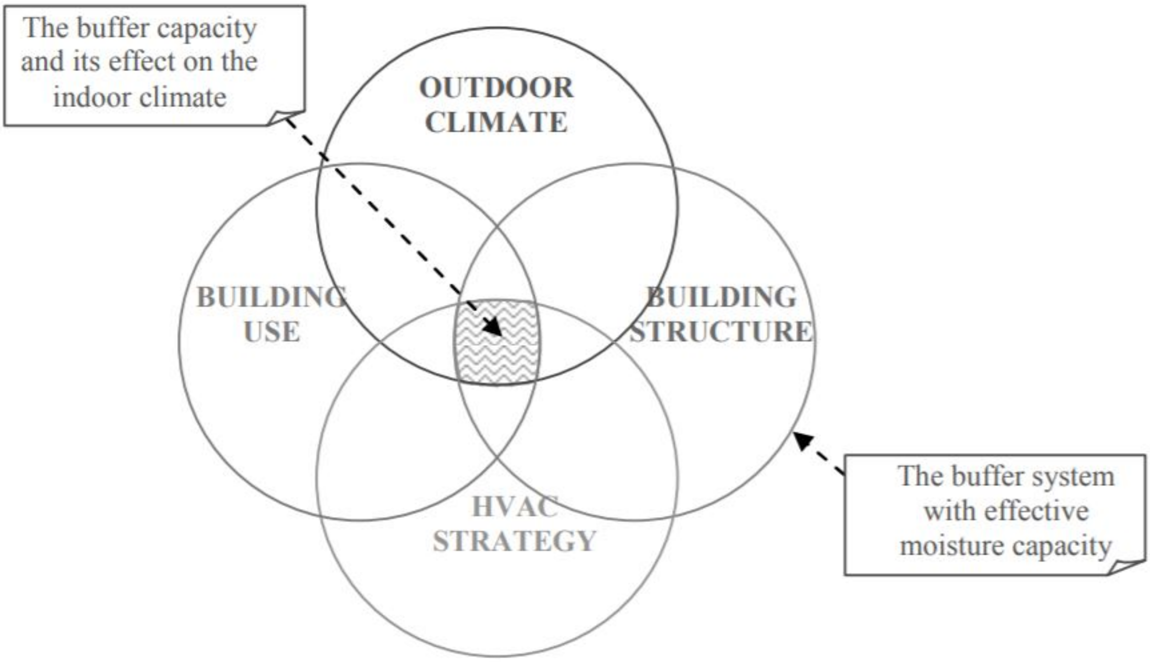


Figure 17: Demanded interaction between building systems in order to make full use of moisture buffering [14]

Osanyintola and Simonson found that moisture transfer hold the potential to reduce buildings energy use, both directly and indirectly. An HVAC system's energy use is not just dependent of its performance. Heating and cooling in cooperation with the buildings thermodynamic also affect the energy use [58]. The direct approach used an optimized controlled HVAC system that allow the hygroscopic materials to buffer moisture. Therefore, less energy is needed for heating and cooling. The indirect approach adjusted the ventilation rate and temperature, allowing the hygroscopic materials to maintain the air quality and comfort. Both methods showed considerable energy savings, mostly for cooling, but also for heating [54]. The results indicate that buffering materials might provide significant contribution to reduce energy use, if the HVAC system allows it.

2.6 Research question

There is no question that a lot can be done by the building and construction industry to adapt to climate change and reduce emissions. Sustainable buildings have shown to have a positive contribution with careful selection of materials with low embodied energy. However, the industry is not known to evolve rapidly and significant technical progress and conviction is necessary for the industry to meet the 2050 climate requirements. Luckily, there are still processes that can be further optimized to reduce energy use and prevent emissions. A wise choice of materials holds the opportunity to reduce a building's climate footprint both in manufacturing and during the operation of the building. Wood is such a material.

A hygroscopic material has the capability to absorb and release moisture from the surrounding environment [34], so-called moisture buffering. Wood holds excellent hygroscopic characteristics. Combination of hygrothermal properties allows the wood to potentially save energy, thus lower the ventilation rates. The purpose of this thesis is to evaluate the hygroscopic characteristics of wood and its effect when exposed to an indoor environment. Through laboratory experiments of solid timber elements and numerical simulations of a school building built in solid timber, the interaction between solid timber and the indoor environment will be investigated. The research attempt to bring answers to the following research questions:

- How does thermal transmittance of solid timber vary under different indoor environments?
- How does hygroscopic properties of solid timber affect the HVAC system and how the latter might be optimized?

3 Methodology

In order to examine wood's hygrothermal properties and its affect on the indoor environment, a quantitative research method has been conducted. Quantitative research method measure a quantity or an amount [59]. It is commonly used to study larger groups of people or equipment, by assuming that a smaller sample is representative for a larger group [60]. The method is by Kothari expressed to be a typical technique implemented for engineering research. It is therefore relevant when evaluating different hygrothermal phenomenons.

A quantitative method is one of two basic research approaches according to Kothari. It is also said to be the foundation of modern science. Being a popular method, its traditions has been a key to improve humans knowledge on resource development [60]. Quantitative research is often divided into three sub-categories, research designs. These designs are inferential, experimental or simulation based. Inferential design involve observing a small part of a population. The result is then assumed to apply for the whole population. A more controlled research design is the experimental one. An experiment make it possible to manipulate wanted variables and observe their manipulation effect on the other variables. Last design is the simulation. A simulation is an artificial model of a realistic case. The model permit observation of a system's behavior under controlled conditions [59]. With three different research designs, the research objective decide which one to use [61].

3.1 Research design

A research design is expressed by Akhtar to be the "glue" holding different elements of a research together [62]. It is also expressed to be the research's structure. It also includes an overview of the research objective and how it will be conducted [59]. To establish the significant contribution hygroscopic characteristics have on the indoor environmental contribution, more than just an observation is needed. Therefore, a laboratory experiments of solid timber elements are carried out. In addition, a cross-laminated timber building simulation is developed.

3.1.1 Experimental design

The experimental design strive to control experimental conditions to evaluate the significance of the changed variable. Controlled surroundings prevent unexpected disturbance. The manipulated variable effect is observed. Then, what, why, when and how the change happened is investigated. The simplest experiment example is to change an independent variable and detect how that change influenced a dependent variable. An experiment could be conducted to examine a specific cause. However, Walliman mention that experiments usually demand a pre-formulated prediction about what is going to happen. It is necessary to know which variables that needs to be tested and how to control them for accurate results. Experiments are common in many subject areas. Some might concern how people interact with each other, how people interact with other people or how things interact with other things. Experiments are normally done in controlled surroundings and therefore mostly associated with laboratories [61]. The conducted laboratory experiment for this research is performed in a controlled climate chamber.

The degree of environmental control is important for experimental design. A laboratory makes it possible to create a realistic environment with know parameters. With familiar external parameters one is able to identify the variable that caused the event. If the same experiment was conducted in a uncontrolled space, the complexity would make it difficult to address the variable and its influence. Laboratory experiments are therefore ideal when performing material experiments [61].

3.1.2 Numerical simulation design

Similar to an experiment, does a model attempt to simplify a situation to investigate it. A model is a representation of a real life structure, event or case. The representation is called a simulation. The purpose is to imitate a phenomena and manipulate it. After the manipulation, recorded data is obtained and inspected. A model could be used for many different occasions. Not only does it control a phenomena, it might also be used to organize and analyse data or test hypothesis. Walliman mention the importance of understanding the system used to perform the simulation. The benefit of a quantitative model is that it describe the entities relationship in addition to measure it accurately. To evaluate the precision, results are compared to the real-life structure [61].

Models can be divided into three types, diagramatic, physical and mathematical. The mathematical, by Walliman called simulation, is used to predict a material's performance in known conditions. It is therefore ideal to simulating hygrothermal inertia. The quality that make a model an essential research design is that it is built to suit a particular purpose. In addition, reduction of the real situations complexity is permitted. The importance of addressing and explaining the purpose of the model is necessary [61]. Also, considered assumptions is stated. Both the experiment and the simulation conducted for this thesis is further disclosed in the following sections.

3.2 Laboratory experiment

The research aim to conduct laboratory experiments on two solid timber elements, in a climate chamber. The solid timber elements are delivered from different manufacturers, hence assembled differently. Their thermal conductivity is obtained using a advanced heat flow meter. The experiment also seek to investigate thermal transmittance (U-value) variations when exposed to varying moisture content. For accurate and realistic results is correct laboratory setup invaluable.

3.2.1 Climate chamber

Measurements are executed in a climate chamber to ensure a controlled environment. The climate chamber is constructed of pre-fabricated elements made by Fresvik. Fresvik produce sandwich elements with a polyurethane foam core covered with hot-galvanised steel sheet skins. Floor, walls and roof are put together to establish a tight envelope. The floor element consist of three layers with a base of aluminium, polyurethane foam and finished with a layer of parquet. Polyurethane foam is used due to its great thermal conductivity. Walls and roof layout are originally the same. Both have the same base as the floor element with aluminum and polyurethane foam. What separates them is the aluminum finish on the indoor side [15]. An illustration of the wall and roof element is presented in figure 18. Prior to this experiment was the climate chamber used for another experiment, changing the original wall structure. An additional layer of gypsum with PCM finish was added to the already existing structure. To attach the gypsum board, an extra air layer is also built in. The current element structures are expressed in table 19.

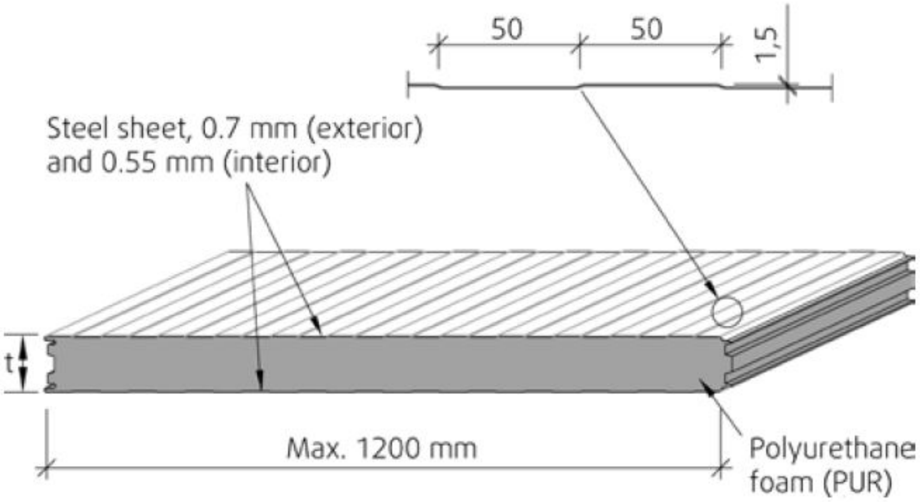


Figure 18: Fresvik element used to construct the climate chamber [15]

Table 1: Climate chamber element structure

Element type	Structure	Thickness [mm]
Roof	Steel sheet Polyurethane foam Steel sheet	0,7 100 0,55
Floor	Steel sheet Polyurethane foam Parquet	0,7 150 0.55
Walls	Steel sheet Polyurethane foam Steel sheet Air layer Gypsum board PCM finish	0,7 100 0,55 48 13 4

The climate chambers is meant to replicate a real life situation. It is facilitated to test different types of building element, and consist of both an indoor space and a cold storage. The cold storage is operated by a cooler, able to achieve a room temperature of -20°C. Such temperature are applicable simulating Norwegian conditions. The indoor space is heated by a ventilation system to maintain level temperature. The room is able to obtain temperatures from 10-30°C. It is not provided with any cooling abilities. The two rooms both have external doors. 1 x 2 meter for the internal room and 0,9 x 2 meter for the cold storage. In addition, the internal room also has a 2 x 2 m window used for smoke tests. It is not of any significance for this experiment. Indoor room height is 2,45 m, with an area of 15,05 m^2. The volume is 36,87 m^2. These measures are also found in table 2. A total overview of the climate chamber is illustrated in figure 19. The part of the inner wall marked with red is a replaceable part. This 1,2 x 1,2 m opening is removed and replaced by the solid timber elements that are tested.

Table 2: Indoor space measurements

Room	Area [m^2]	Height [m]	Volume [m^3]
Indoor space	15,05	2,45	36,87

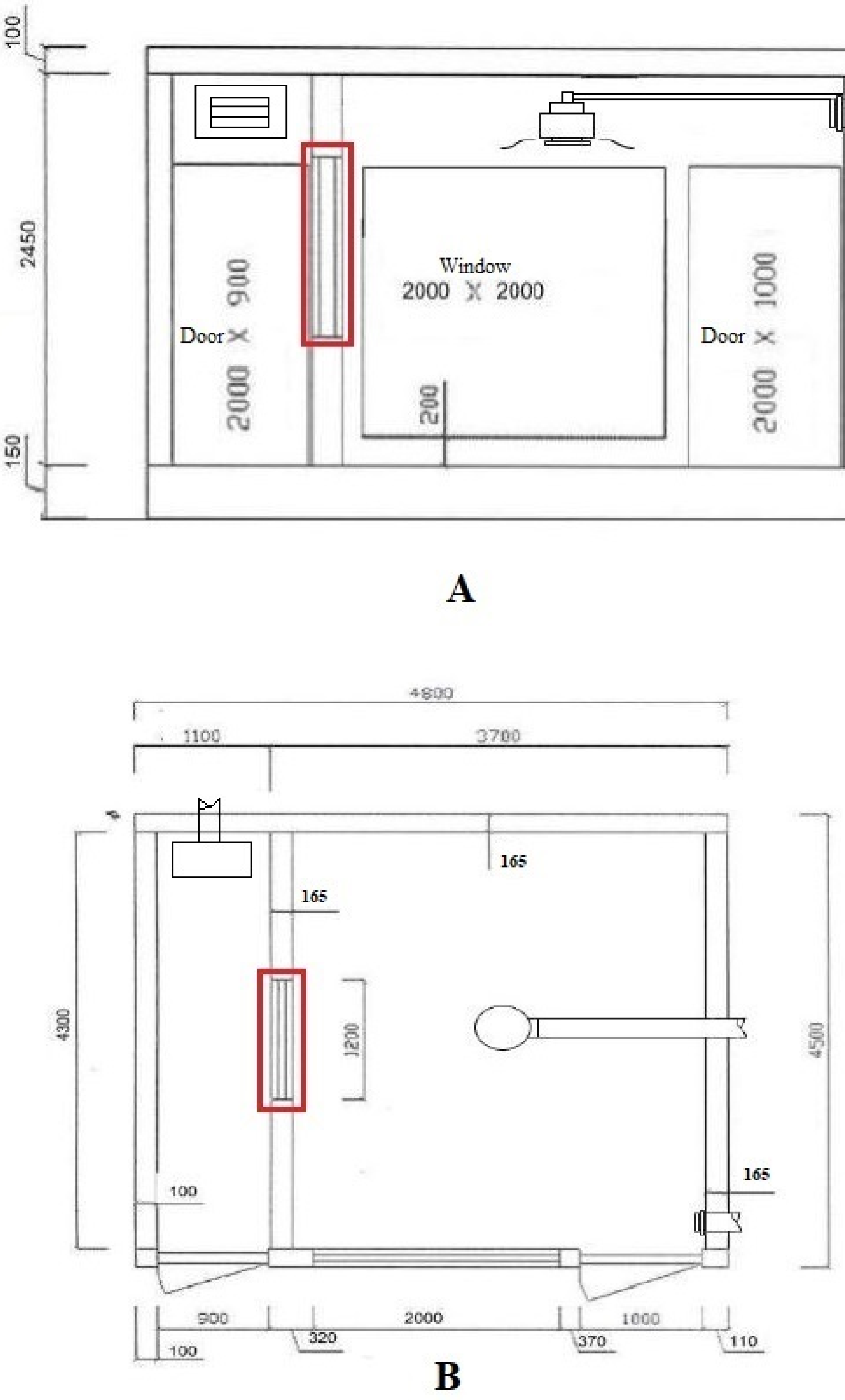


Figure 19: Climate chamber measurements, cold storage left and indoor zone right: A) Sideways, B) From above

As mentioned is the indoor space heated by the ventilation system. The system has the ability to operate at three different modes, low, normal and max. The "low" mode supply less air than it withdraw, making the ventilation unbalanced. An unbalanced ventilation system is not favourable for this experiment. The "normal" and "high" are separated by their ventilation rate. The rate for the "normal" mode was calculated to be 57,9 m^3/h using the formula 1. Section 3.2.9 express the importance of the correct ventilation rate for accurate results, hence why the "normal" mode is chosen.

$$Q = \pi \cdot r^2 \cdot v \cdot 3600 s/h \tag{1}$$

The equation express r as the radius of the ventilation pipes, both supply and exhaust. It is measured to be 0,08 m v is the measured air speed in the middle of both pipes and found to be 0,8 m/s, and 3600 is the conversion from cubic per seconds to hours. Knowing the ventilation rate inn and out of the room is useful when investigating the solid timbers moisture uptake. The ventilation rate express air changes. Air changes remove moisture. The moisture not removed by the system is available to be buffered by the solid timber element.

3.2.2 Solid timber elements

The laboratory experiment seek to investigate solid timber elements and their hygrothermal characteristics. More and more manufacturers produce solid timber elements implying different structures and specification from manufacturer to manufacturer. To broader evaluate how moisture content in the indoor space influence the elements are different solid timber elements from to manufacturers tested. Comparing these elements makes it necessary to state their assembly and structure.

The first tested element is a solid timber element manufactured by Norsk Massivtre. Norsk Massivtre deliver two types of solid timber elements, overlapping elements and edge assembled elements. An overlapped element is tested in this experiment, since it is commonly used as wall structures. The element consist of layers of spruce planks assembled together by screws. Each layer is added parallel to the previous one, covering the underlying joints. The overlapping element is normally manufactured with three to five layers, but is easily customized depending on it's use [63]. A three layer element, shown in figure 20, is tested.

Figure 20: Solid timber element from Norsk Massivtre

The other element is manufactured by Splitkon. Splitkon manufacture cross-laminated elements whit perpendicular assembled layers. Unlike the screws used by Norsk Massivtre, Splitkon glue their spruce planks together with a special glue. An element normally consist of three to nine layers adding up to thickness ranging from 60-300 mm. Each delivery is however manufactured specific for the client and purpose. The structure of Splitkon's CLT element make it appropriate for all kinds of support structures. In addition, it provides high fire resistance. The Splitkon element tested is a four layer CLT element illustrated in figure 21.

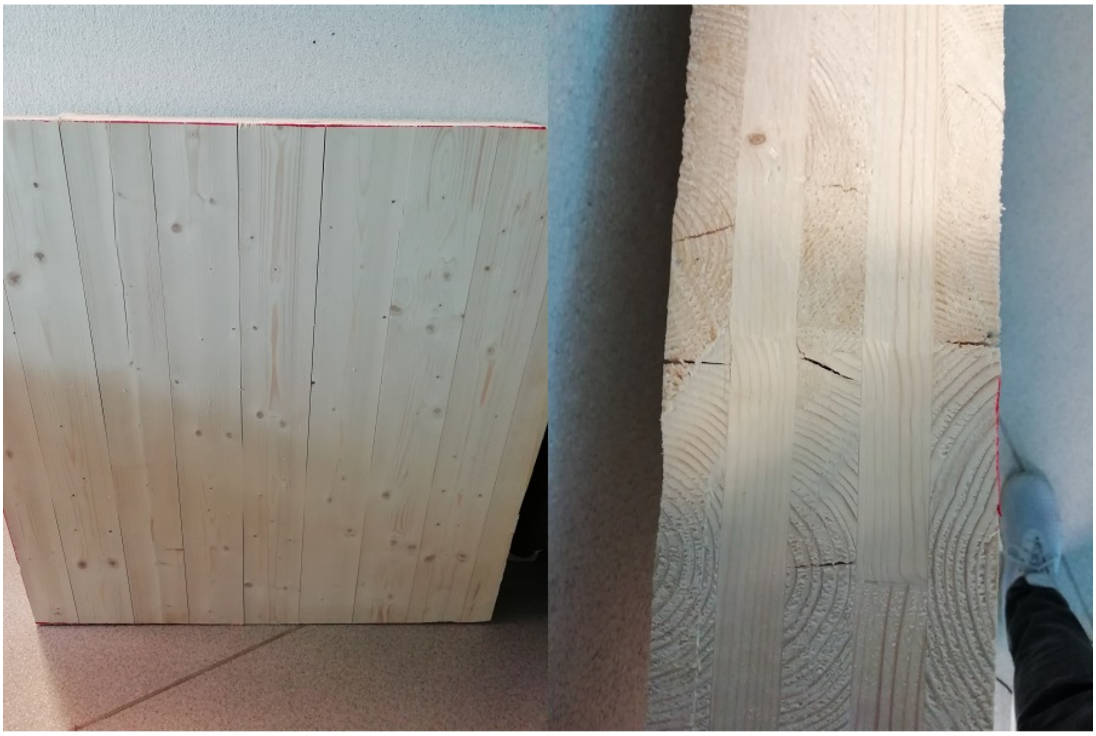


Figure 21: Cross-laminated timber element from Splitkon

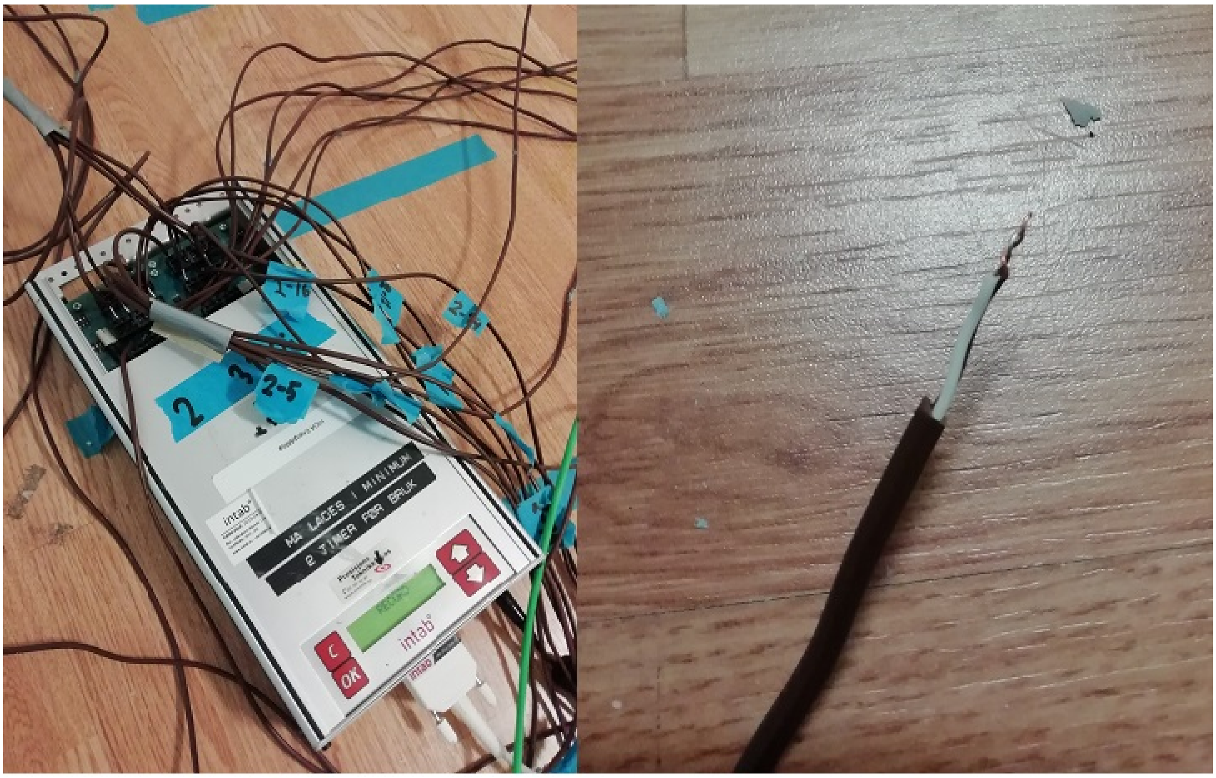
To examine the solid timber elements are three different measuring methods used. These three are stated to be necessary apparatus when performing an in-situ measurement of thermal resistance and transmittance [64]. The experiment therefore utilize thermocouples, huksefluks, a heat flow meter, and an infrared camera. During the experiment are Celsicom meters attached. They monitor hygrothermal properties, humidity and temperature, on both the cold and warm surfaces. Different measuring methods ensure distinct temperature measurements. Comparing the temperatures provide validation.

3.2.3 Thermocouples and Intab PC-logger

Thermocouples are sensors are wires from different metals. Welding the two metals create a junction recording temperature. Change of temperature is detected by the thermocouples creating voltage issued to a logger. The logger receive the voltage and transform it into equivalent degrees Celsius [65]. The thermoucouples used in this experiment are connected to an Intab PC-logger 3100i. Intab PC-logger is commonly used to recording long term temperatures. 3100i constitute a solid recording system. Especially due to its excellent accuracy (±400ppm). It is possible to achieve great results despite tough conditions [66]. The recorded temperatures are presented in Intab Easyview. Easyview is also used to set up the measurement.

Intab PC-logger has the ability to connect 24 thermocouples. For these experiments are twelve operative. Ten measures the timber elements surface temperature, at different locations. Five on the internal side and five on the cold surface. The remaining two will record the indoor and outdoor temperature exposed to the sample. Both the cold storage and indoor temperatures might change during the experiments, influencing the results. Recording the air temperature is therefore considered crucial to evaluate the results.

The thermocouple measurement setup is as mentioned performed in Intab Easyview. The active channels are selected. 12 thermocouples are chosen, and configured. Each channel is given a label that suits their purpose. After labeling, are their input selected. 50 mV for thermocouples type K is used to display temperatures ranging from −100-1200°C [66]. All twelve channels are given the same input. Signal transformation units are Celsius and high and low values are set to be respectively 100 and 0. Lastly the sampling interval is decided to be every tenth minute, corresponding to the other measuring methods.



A **B**

Figure 22: PC-logger and thermocouples used for measurment:
A) Intab PC-logger, B) Thermocouple

3.2.4 Heat flux measure system

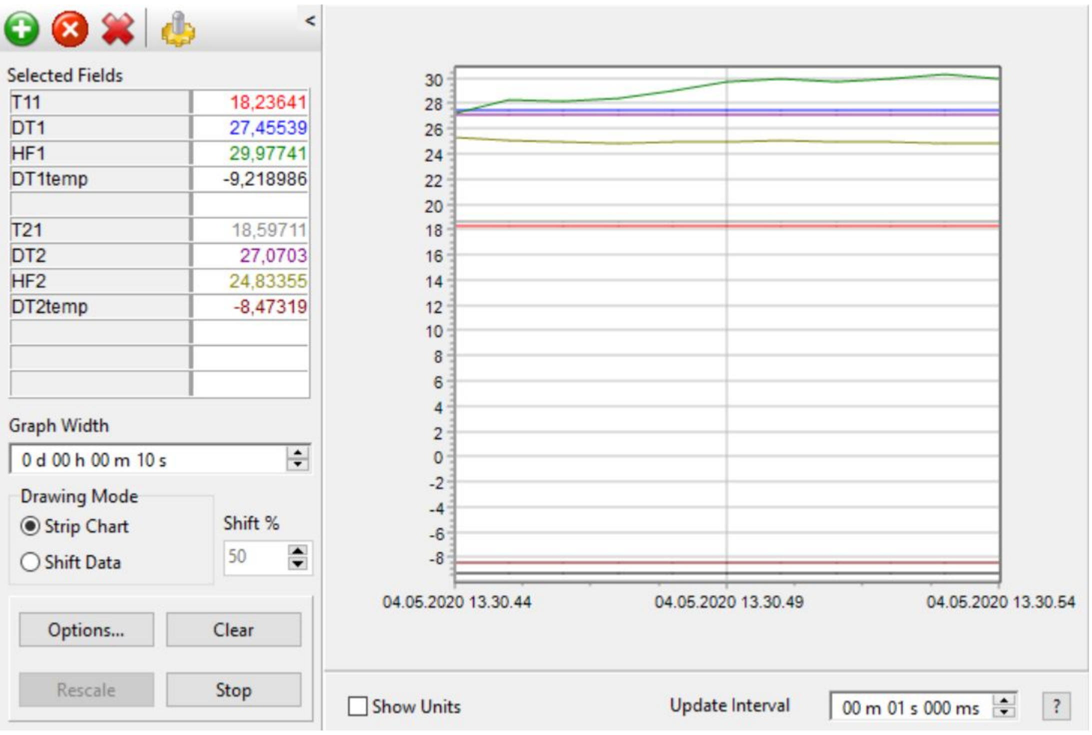
A building material's thermal transmittance is dependent of heat flow, area and the indoor and outdoor temperature differences. The U-value is obtained measuring the heat flow through the element surface and surface temperatures. A heat flux meter measures such flow. The meter also have the ability to measure surface temperatures with additional thermocouples [67]. The heat flow meter used for the experiment is the TRSYS01 measuring system.

TRSYS01 is used for on-site measurements of different thermal properties, wanting high accuracy. Measured thermal properties are thermal resistance, thermal conductance and thermal transmittance. These are respectively the element's R-value, λ-value and U-value. The system have two sensors measuring heat flux (HFP01) and two pairs of thermocouples. Two heat flux sensors provide the system with the ability to measure an element at two different locations simultaneously. Two measurement locations assign the system with a high level of accuracy. For building studies are HFP01 plates the most popular heat flux sensor to use. TRSYS01's precision heat flux sensors and thermocouples continue to measure even in difficult conditions. Small temperature differences between the element's two sides is an example of such conditions. To evaluate the element's thermal transmittance is the heat conductivity calculated. Thermal resistance, R, is dependent on the average heat flux and the difference surface temperature of the sample sides. Since R equal the thickness, t, above the heat conductivity, is λ easily estimated using equation 2. The obtained λ-value is transformed to R, then equation 3 converts the it into thermal transmittance [68].

$$R = \frac{t}{\lambda} = \frac{\Delta T}{\phi} \tag{2}$$

$$U = \frac{1}{R_{\text{tot}}} \tag{3}$$

The procedure of setting up the heat flux meter is done according to the system manual [69]. Similar to the Intab thermocouples are TRSYS01 measurements displayed and stored with a logger, LoggerNet. The software sets up and control the measurements. When the connection between LoggerNet and TRSYS01 is established, logging begins. TRSYS stores result every 10th minute and every 24 hours by default. The manual recommend using values from T11, DT1, HF1, T21, DT2 and HF2 when performing a heat flux measurement. These essentially signify indoor surface temperature, surface temperature differences and the heat flux through the element. With the meter's two heat flux plates, are these placed on either side of the element. HF1 is placed on the outside surface, while HF2 on the inside. An illustration of how LoggerNet display the different values through the experiment is shown in figure 23.



Selected Fields

T11	18,23641
DT1	27,45539
HF1	29,97741
DT1temp	-9,218986
T21	18,59711
DT2	27,0703
HF2	24,83355
DT2temp	-8,47319

Graph Width: 0 d 00 h 00 m 10 s

Drawing Mode: ● Strip Chart ○ Shift Data

Shift %: 50

☐ Show Units

Update Interval: 00 m 01 s 000 ms

Figure 23: Graphic preparation of recommended parameters for hukseflux, heat flux, measurement (LoggerNet)

3.2.5 Thermography

In addition to thermocouples and heat flux measurement are thermography used. Temperatures received from the camera is used for a surface temperature comparison with the other measuring methods. Thermography is performed with an infrared camera. Infrared radiation on the objects surface is detected by the camera which display the intensity as a thermal image. The radiation is dependent on the surface temperature, the elements total heat transfer coefficient and environmental temperature. The camera use for this measurement is the FLIR T640.

FLIR T640 is designed for high performance and include the latest of available technology. It provide great image quality for infrared resolution capturing. Including high accuracy the camera also has high sensitivity. The combination of theses two make FLIR T640 able to measure temperature differences exact. It also has the ability to record real-time video. The camera is used to experiment the solid timber elements with its variety of functions for measuring and analyzing [70].

When measuring surface temperature of an object with FLIR T640, it allow distinct measurement tools. The experiment uses different measuring methods to investigate the wooden element. To not interact with the other methods, FLIR provide measurement boxes. Four boxes are made to cover the part of the element where no other measuring method record. These four boxes are sized and move to fit as much experimental surface as possible inside them. Each box record max, min and average temperatures. The four are divided into two smaller, and two bigger boxes. The two smaller ones are placed on the lower end of the element, while the big ones, one the middle and one on the top. The placement and size of the boxes are shown in the figure 24 and marked with numbers from 1-4.

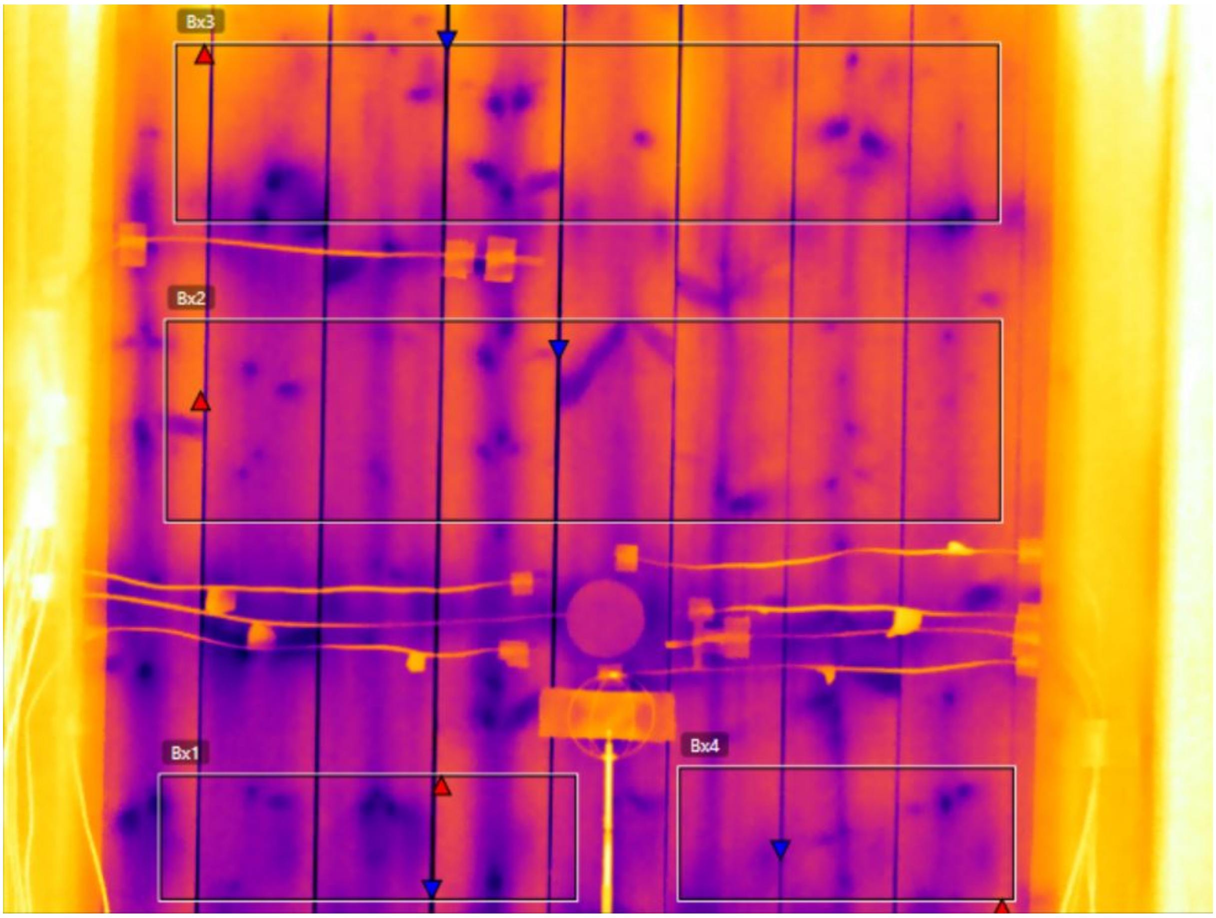


Figure 24: Box measurement setup and location (FLIR T640)

With the boxes in place, object parameters are assessed the camera for accurate measurement. It introduces six different parameters that might influence the measurement. These six are External IR window compensation, objective distance, atmospheric temperature, relative humidity, reflective temperature and emissivity. Of the six are emissivity the important parameter to set correctly. The element emissivity is decided to be $\varepsilon = 0{,}90$ for both, based on measurement performed by Kraniotis et al.. The remaining five are change from recommended values to suit the experiment [70]. Notice that the camera's relative humidity parameter changes during the experiment. During the experiment is the indoor relative humidity changed. To ensure accurate results is the parameter changed with the relative humidity. Section 3.2.9 further explain how this is performed. Parameters used for the experiment are listed in table 3.

Table 3: Thermography parameters for the experiment

Parameters	Values
Object distance	3.0 m
Atmospheric temperature	22°C
Relative humidity	30-60%
Reflected temperature	22°C
Emissivity	0,9

3.2.6 Indoor environment monitoring

Celsicom is a monitoring system that are flexible for measurement of different applications. It is usually used to measure temperature and humidity, but is also capable of CO_2 and energy use measurements. Besides, it is user friendly. Being cloud based, are recorded values directly sent to the cloud live monitoring [72].

For the experiment are six Celsicom recorders in use. They measure temperature and influence humidity has on the element. One recorder is placed 1 cm into the element, measuring the wooden temperature. Two recorders are attached on either side of the surface to measure the element's moisture content. This is performed by connecting the with two screws screwed into the element. The last three censors measure the air temperature and relative humidity (RH). One is placed in the middle of the indoor space and one on either sides surfaces. Their number and measuring content is listed in table 4 and figure 25 illustrate how they are attached. The measurements is significant when evaluating the influence moisture has on the thermal transmittance. In addition, measuring surface temperature are the values compared to the other measuring methods.

Table 4: Indoor environment monitoring measurement

Number	Placement	Measuring
1	Indoor surface	Temperature θ, RH
2	Inside the element	Wood temperature θ_{Wood}
5	Indoor room	Temperature θ, RH
8	External surface	Temperature θ, RH
12	Internal surface	Wood moisture content
13	Externals surface	Wood moisture content

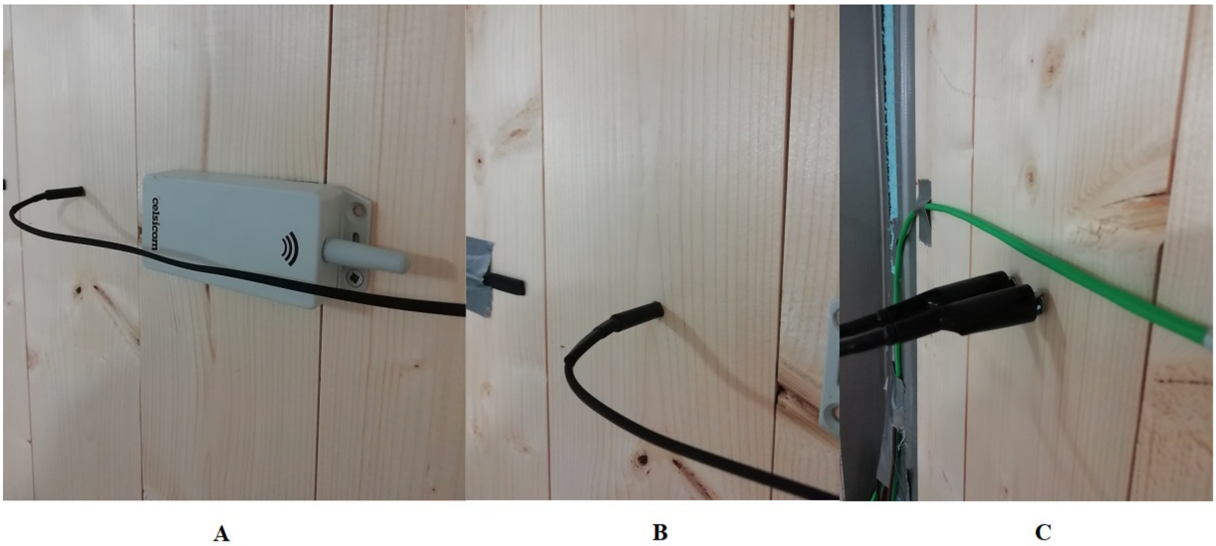


Figure 25: Installation of Celsicom meters:
A) Surface temperature and RH, B) Wood temperature, C) Wood moisture content

3.2.7 Additional equipment

In addition to the measuring and monitoring equipment are other equipment used to execute the experiments as planned. Their contribution might be smaller, but their significance as important to ensure properly and accurate experiments. The additional equipment used are:

- Swema 3000 - wind speed meter
- Cotech humidifier - ultrasonic humidifier
- Adapter countdown

The wind speed meter is used to measure the ventilation rate. The humidifier have a maximum efficiency. Frequent air changes require increased humidity productivity. Therefore, to ensure level humidity in the room during the experiments, ventilation rate is measured. The humidifier is only active for a certain period of time during the humidification experiment. Therefore, an countdown turn the humidifier off automatically when the humidification period ends. The equipment implementation and their importance is further described in section 3.2.9, later in this chapter.

3.2.8 Experimental setup of element measurements

Before initiating the first the experiment, were all measurement recorders placed. The element was divided into sections to correctly place all measurement sensors. Element height was split into three sections, each 330 mm, and the width was halved. The heat flux manual recommend using both heat flux plates, which were placed according to the standard. Attachment was performed with double-sided tape to prevent inaccurate measurements, hence the use of TESA 4939 [69]. To make sure the plates not covered the same area, the indoor heat flux plate was attached on the bottom. The out-facing plate placed on the upper part. Both was attached in the middle of the element, avoiding the cracks between the planks. Intab thermocouples surrounds the heat flux plates. These were taped to the surface to evaluate the surface temperature during the experiments. In addition, heat flux thermocouples were placed in the same area to compare results with the other measured surface temperatures. All thermocouples were placed to avoid cracks. Underneath the plates was a wind meter attached, logging air speed onto the surface. Remaining areas was recorded by the infrared camera measurement boxes. The set up is illustrated with both a drawing, figure 27, and images from the laboratory, figure 28. Notice that the color representation in the illustration reflects the image measuring methods. In addition is the placement of the humidifier and sensor recording humidity in the middle of the room shown in figure 26.

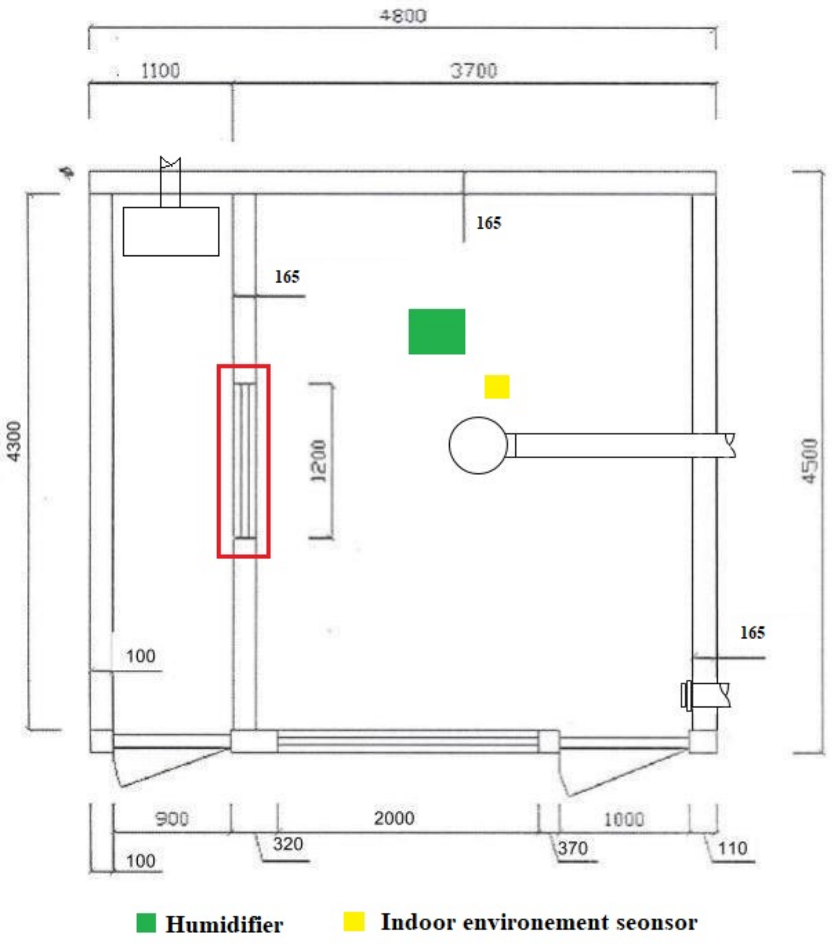


Figure 26: Placement of humidifier and indoor room monitoring sensor

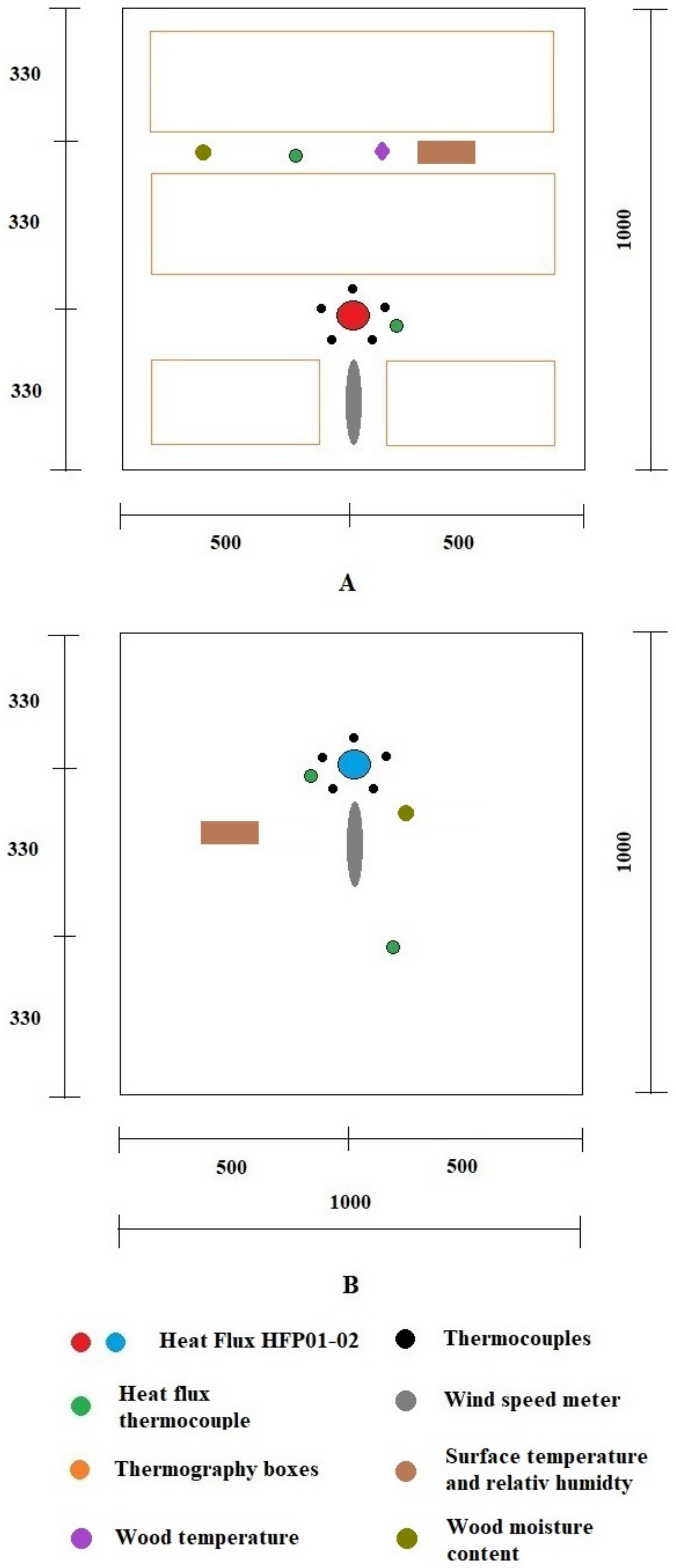
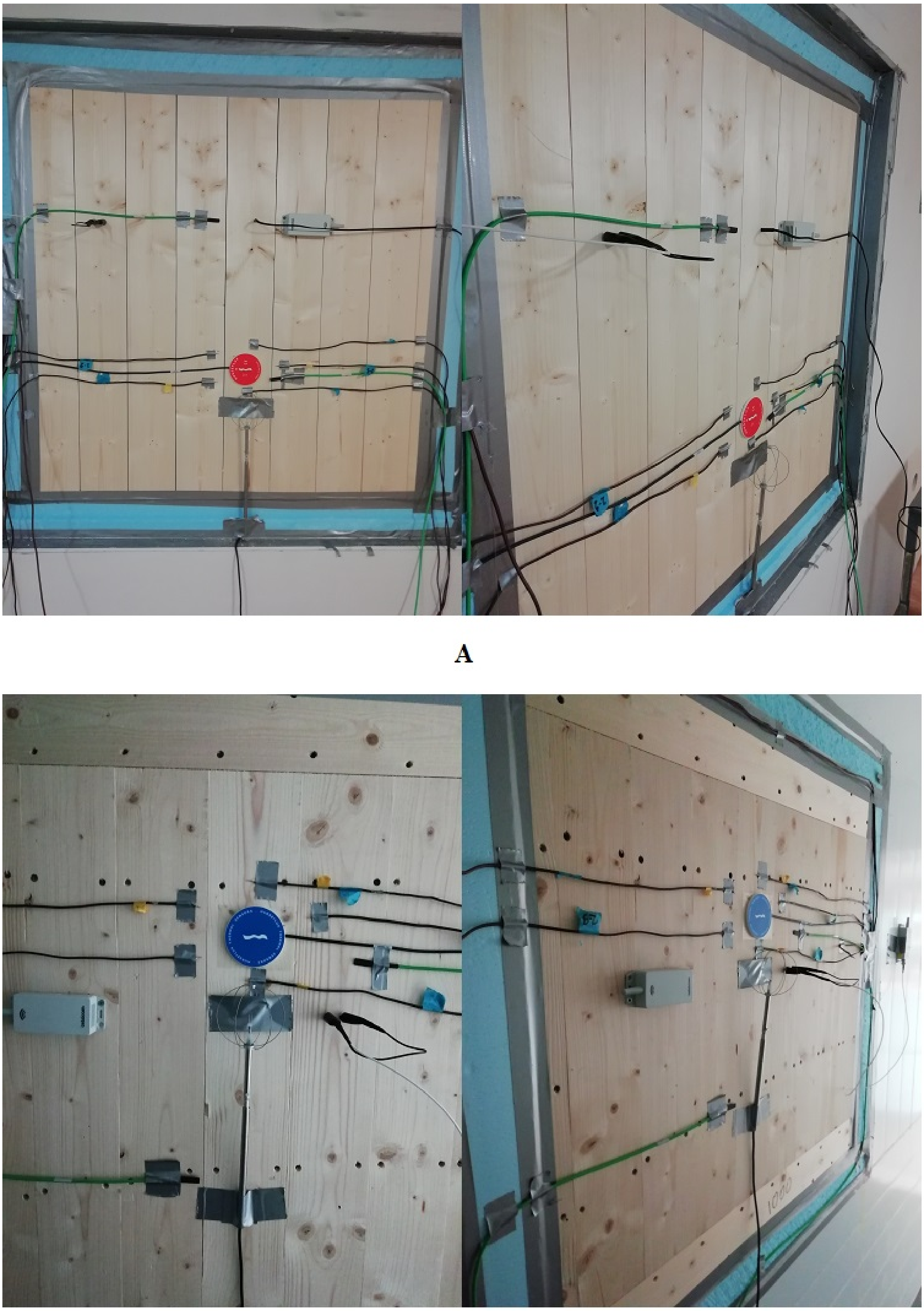


Figure 27: Drawn illustration of the elements measurement setup: A) Side facing indoor area, B) Side facing the cold storage



A

B

Figure 28: Image of climate chamber setup (thermography boxes not shown):
A) Inside , B) Cold storage (outside)

3.2.9 Experimental process

The experiment divided the process into two parts. Part one concerned the element's λ-value. Later used to decide the steady state U-value. The second part of the experiment consist of a humidification and dehumidification period. How the humidifying and drying of the room influence the dynamic U-value and surface temperature are inspected.

3.2.9.1 Steady state experiment

Part one of the experiment determine the element's λ-value. Heat conductivity for a material is described as the heat quantity transferred through the material over a given time period. Temperature differences on either side of the material and the thickness also impact the conductivity. Therefore, a low λ-value signify better insulation abilities than a high one, allowing less migration of heat [73]. A λ measurement is dependent of the element's surface temperature. For a period of 72 hours, the element is exposed to an inside temperature of 22°C and an outside temperature of -10°C. Winter condition apply the wooden element Norwegian situation. In addition, for accurate measurement, the thermography required temperature differences greater than 10°C between the inside and outside [64]. The experiment's three day duration is decided by the heat flux measurement standard [67]. Referring to the thermography standard, camera store images every 30th minute. The heat flux meter log results every 10th minutes by default. For accurate surface comparison was therefore the Intab PC-Loggers assigned the same ten minute interval. Although the infrared standard expresses a six hour measurement period during the night to avoid sunshine, it followed same three days as the other measuring methods. This was approved due to the test being performed in a closed climate chamber without exposure of sunlight at any time.

If the measurements after 72 hours approved standard requirements, the experiment is ended and analysed. Results from the different measure methods and the obtained heat fluxes are used to estimate the element's λ-value with equation 4. The equation present the heat flux through the element, ϕ, the internal and external surface temperature differences, ΔT and the element thickness, t. Calculated λ-value provide the element with a U-value, acting as a initial base. The U-value is compared the obtained dynamic U-values from the second part of the experiment. Thermal transmittance estimation demand knowledge of heat transfer resistance. NS-EN ISO 6946 address common heat transfer values for measured building elements. Experimenting a wall structure make the horizontal R-values appropriate to use. It is therefore decided that the indoor heat transfer resistance is 0,13 and the outdoor 0,04 [74]. The same process is performed for both elements.

$$\phi = \lambda \cdot \frac{\Delta T}{t} \tag{4}$$

Table 5: Experiment part one parameters and measurement purpose

Duration	Interval	Internal temperature	External temperature	Measuring
72 h (3 days)	10-30 min	22°C	-10°C	λ

3.2.9.2 Dynamic U-value measurement with moisture load

When initial λ-value is obtained, part two of the is experiment started. As mentioned, part two seek to investigate how humid and drying periods influence the thermal transmittance. Periodically increase and reduction of humidity is inspired by the NORDTEST performed by Rode et al.. Similar to the NORDTEST is the element exposed to specific relative humidity for eight hours. The humidity is provided by a humidifier. After eight hours is it turned off and the dehumidification period begins. Drying bring the room back to initial relative humidity. The period last 16 hours before a new cycle is initiated. Unlike the NORDTEST is the solid timber elements in these experiments exposed to three cycles, all at different relative humidity levels. The first cycle provide 40% humidity, the next 50%, before ending with a 60% humidity cycle. The duration of the second experimental part is equal to the first part. Maintaining a stable relative humidity throughout eight hours is critical for the experiment. The maximum productivity of the humidifier is 350 ml/h. High ventilation air flow withdraw more moisture, demanding increased humidifier productivity. Therefore, the ventilation system is used at its "normal" mode, producing an ventilation rate of 57,9 m^3/h. Higher ventilation rate would prevent the humidifier maintaining 40%, 50% and 60% relative humidity for eight straight hours. Unlike the first part of the experiment are some additional sensors attached to the element. These measure different wooden parameters to monitor moisture influence. The process is performed for both elements.

Table 6: Humidification and dehumidification process and time

Duration	Humidification	dehumidification	Relative humidity	Measuring
24h (72h)	8h	16h	40% 50% 60%	U-value

3.2.10 Sources of error

Even though performing experiments in a laboratory are known to be controlled and accurate, does errors still occur. Errors could be system irregularities, equipment difficulties or structural inaccuracy. It is therefore considered important to address the experiments sources of error.

The first source of error is related to the cold storage. It is intended to keep a stable outdoor temperature at -10°C at all time during the experiment. However, the cooling system does not allow the temperature to stay even. When the system reach -10°C, the system turn the cooling off. When the cold storage a few degrees warmer is it turned back on. Temperature increase causes an average cooling temperature much lower than wanted. Therefore, to make sure the cold temperature average -10°C, the set point temperature for the system was adjusted to -12,7°C. The figure 29 below show the temperature fluctuations related to the cooling system. It illustrate frequently changes, not being able to maintain a stable temperature. The same figure also state an even higher temperature change happening every 6th hour. The cold storage initiate a defrost process ever six hours, shutting it down for a longer period of time. No cooling increase the cold storage temperature considerably.

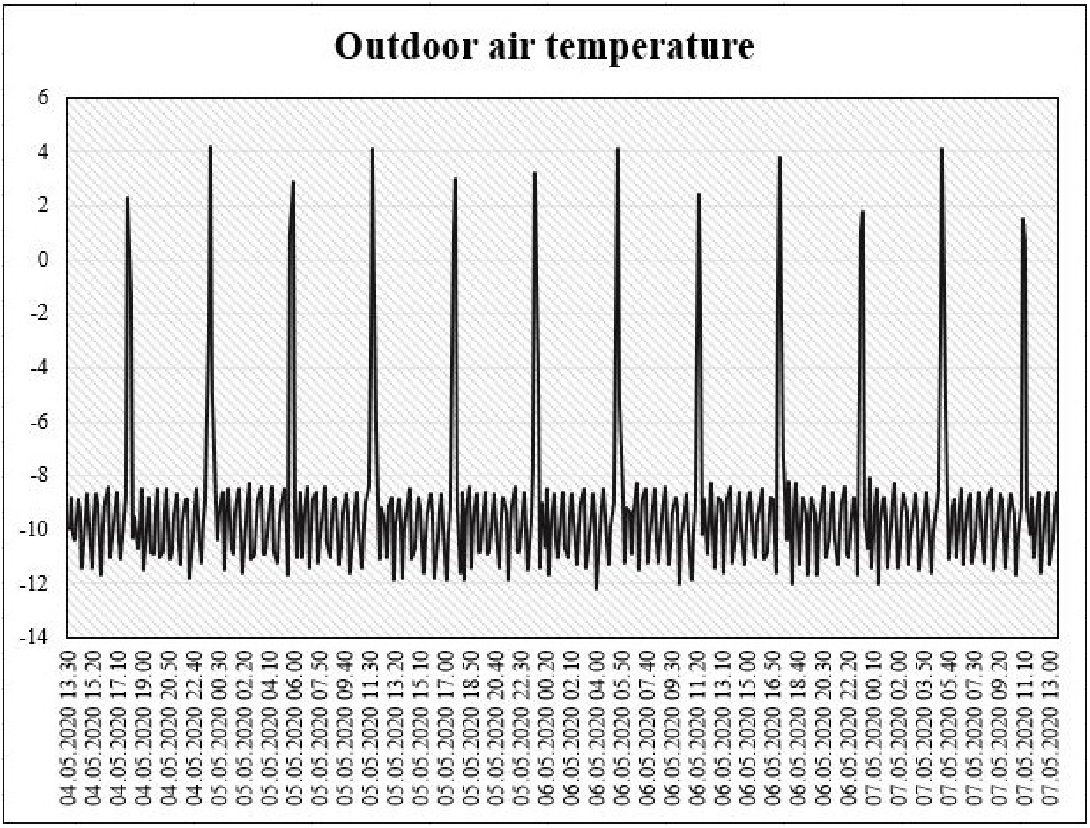


Figure 29: Cold storage temperature fluctuations

Fitting the element into the opening in the wall could also cause irregularities. The opening is bigger than the element itself and the gaps are filled with EPS. If the element is poorly manufactured, unwanted gaps occur between the EPS and the element, shown in figure 30. Even though the gaps are sealed with additional EPS and duck tape, leaks take place. Leaks are not favourable when investigating the wooden element.

Figure 30: Unwanted gaps between the element and EPS due to poor manufacturing

Another source of error is related to the humidifier. The humidifier require assistance during the experimental period. As the humidifier is restricted to four liters of water, it need refill during the humidification cycles. Also, the countdown used to turn the humidifier off is restricted to a period six hours. In addition, increasing the relative humidity between each cycle demanded human interaction. All these actions might affect the indoor humidity. This is however, carefully planned so that eventual errors is noticed and explained subsequently.

There is also sources of error considering the attachment of some measuring methods.

Some of them are placed with duck tape. Duck tape could cause inaccurate attachment, measuring above the surface instead of on the surface. In addition, cold air dries the duck tape glue possibly leading to a less accurate attachment. This is however considered by having several measuring components and measuring methods recording the same area and parameter.

3.3 Building Energy and Hygrothermal Simulation

36 different simulations of a school building built in solid timber is carried out. The Norwegian school has increased its capacity by building an extension. It consisted of solid wood, except for the concrete ground floor and a few technical rooms. All remaining components are either cross-laminated timber elements or glulam. CLT is used to construct the floors and walls, exposing timber to the indoor environment. Structural columns securing vertical loads are made out of glulam. Being a wooden building make the school a pilot project for these type of buildings, and provides new challenges. However, the school is developed with robust solutions making it comparable to concrete and steel [75].

When performing a simulation is the computer stated by Walliman to be a highly valuable tool. The school's floor plans operated as a base for the model. Even though models are supposedly less complex than the real-life structure, is it necessary to ensure that the it is comparable to the school building. Therefore, the program SketchUp was used to develop a suitable model. SketchUp is a 3D modeling program for different drawing applications. It might suit architects, civil and mechanical engineering and interior designers. Another advantage with SketchUp is that it could be used to import a model to WUFI. So, instead of modeling in WUFI, all components and zones are defined in SketchUp before imported.

It has for a long time been necessary to account for a building's thermal response. However, since thermal and moisture conditions are coupled, it is essential to understand moisture conditions and humidity effects. Higher moisture levels contribute to increased heat losses, and the indoor temperature influence the transport of moisture. It is also know that exposure to high moisture conditions over a long time might cause damage to components and occupants [76]. To analyse a building's hygrothermal properties with a software like WUFI is therefore necessary.

3.3.1 WUFI Plus

WUFI is a software product that provides building engineers the possibility to perform realistic calculations of heat and moisture transport. One can perform both one- and twodimensional, through walls and other building components exposed to real conditions. WUFI is a German abbreviation translated to heat and moisture transiency. To ensure accurate calculations is the program been validated by comparing software measurements with laboratory and outdoor tests. The validation provides the software with the latest vapor diffusion and moisture transport findings in building materials [76].

The WUFI software's most complete tool to simulate heat and moisture is WUFI Plus. Not only does WUFI Plus simulate building components hygrothermal conditions, it also simulate the indoor environment. This makes it suitable to address buildings energy use and comfort. To make the simulations as realistic as possible are all parameters user-specified. Users might specify both out- and indoor climate, define ventilation rates, design conditions and internal loads relevant to their project. Simulating the interaction between building usage and technology systems is necessary in building physics. Their interaction allows for a review of indoor climate and air quality, hygienic conditions, thermal comfort and component damage based on heating and cooling loads and the need for humidification and dehumidification. WUFi Plus has abilities that makes it able to analyse the dynamics of 3D bodies, thermal bridges, and how different conditioned zones and the outside exchanges air [77].

The capabilities and advantages of WUFI Plus makes it the ideal software to analyse the model of the Norwegian school extension built as a passive house and constructed after TEK10 claims. Both have guidelines and requirements for minimal execution to meet their requirements and ensure safe and precise construction.

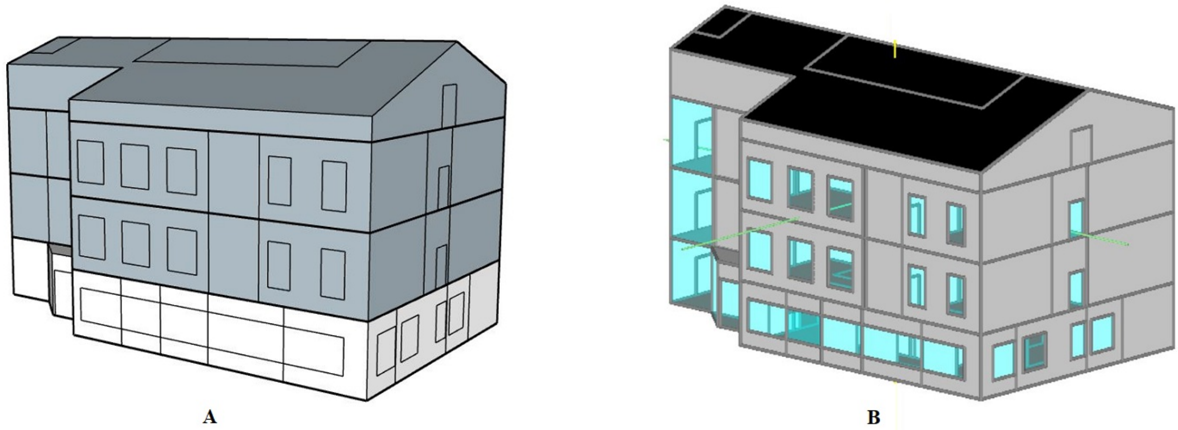


Figure 31: The model used for the simulation:
A) SketchUp B) WUFI Plus

3.3.2 TEK10, NS 3031 and NS 3701

TEK10 is the former Norwegian regulations on technical requirements for construction works. The updated version is now TEK17. The intention of these regulations and technical requirements is to ensure that project planning, designing and execution are done according to universal design. This ensures good visual aesthetics, but most importantly make the project comply with safety, energy and environmental health standards [78]. TEK specify functional claims and referrers to Norwegian standards to achieve these claims. By doing so is the regulations fulfilled and documented. However, it is necessary to address that the use of NS 3031 and NS 3701 are voluntary [79]. With a building being constructed as a passive house, TEK10 referrers to the Norwegian standard NS 3701:2012 for embodiment.

In 2012 did the committee of Standard Norge establish the standard NS 3701:2012 for planning, execution and evaluation of energy efficient commercial buildings. The standard divides these buildings into two groups, passive houses and low-energy buildings. NS 3701 is used for three main purposes. It could be used to valuate whether a building satisfies energy efficient building requirements. The standard demands specific products and building elements. Lastly, it also pose execution claims concerning technical construction works for these buildings. NS 3701 is based on calculations of energy demands after another standard, NS 3031 [80]. NS 3031:2014 is compiled to document energy claims given by the technical requirements in TEK. It is also customized to calculate buildings energy efficiency. A building's energy efficiency is dependent on the interaction between the buildings technical systems and the building envelope. The standard compliment the Building Energy Directives European standards by adding national aspects to the European requirements, suiting Norwegian purposes and climate. Definitions, requirements for heat losses, heating and cooling demands, energy needed for lights and energy supply and minimum requirements for building elements is in the standard. In addition does the standard demand minimal values for leakage, measuring methods and the building energy performance when finished [81]. The same goes for NS 3701, however, the requirements and claims are more strict than the ones found in NS 3031.

3.3.3 Evaluation criteria of thermal environment and indoor air quality

The design conditions employed for the simulation's design conditions are based on standard prEn 15251:2006. prEn 15251 is the standard for indoor environmental input parameters for design and assessment of energy performance of buildings. It addresses indoor air quality, thermal environment, lighting and acoustics and establishes design criteria used to dimension systems. The standard uses different categories to define acceptable design values for calculations [82]. These categories are defined as follows:

- Category I - High level of expectation (recommended for spaces occupying sensitive and fragile people)
- Category II - Normal level of expectation (used for new buildings)
- Category III - An acceptable, moderate level of expectation (used for existing buildings)
- Category IV - Values outside the criteria above (only acceptable for a limited part of the year)

The building is simulated with different types of ventilation controlling systems. Depending on each ventilating method the standard address design values that correspond to each of the mentioned four categories. Table 7 express design values for minimum and maximum temperature, relative humidity and CO_2 concentration.

Table 7: prEn 15251:2006 recommended design values for energy calculations

Category	Heating	Cooling	Humidification	Dehumidification	CO_2 concentration
I	21-23	23,5-25,5	50	30	350
II	20-24	23-26	60	25	500
III	19-25	22-27	70	20	800
IV	-	-	>70	<20	<800

3.3.4 Building envelope

A key to construct a passive house is the building envelope. External walls, ground floor, roofs, windows and doors must all be built to suit a purpose that make the building as tight as possible. This requires components composed of materials that contribute to the tightness. If done properly, the building envelope prevent inside air to leak outside through thermal bridges. The simulated building envelope is based on values and components obtained from building contractor's documents. Their structure are illustrated in figure 32 obtained from WUFI Plus.

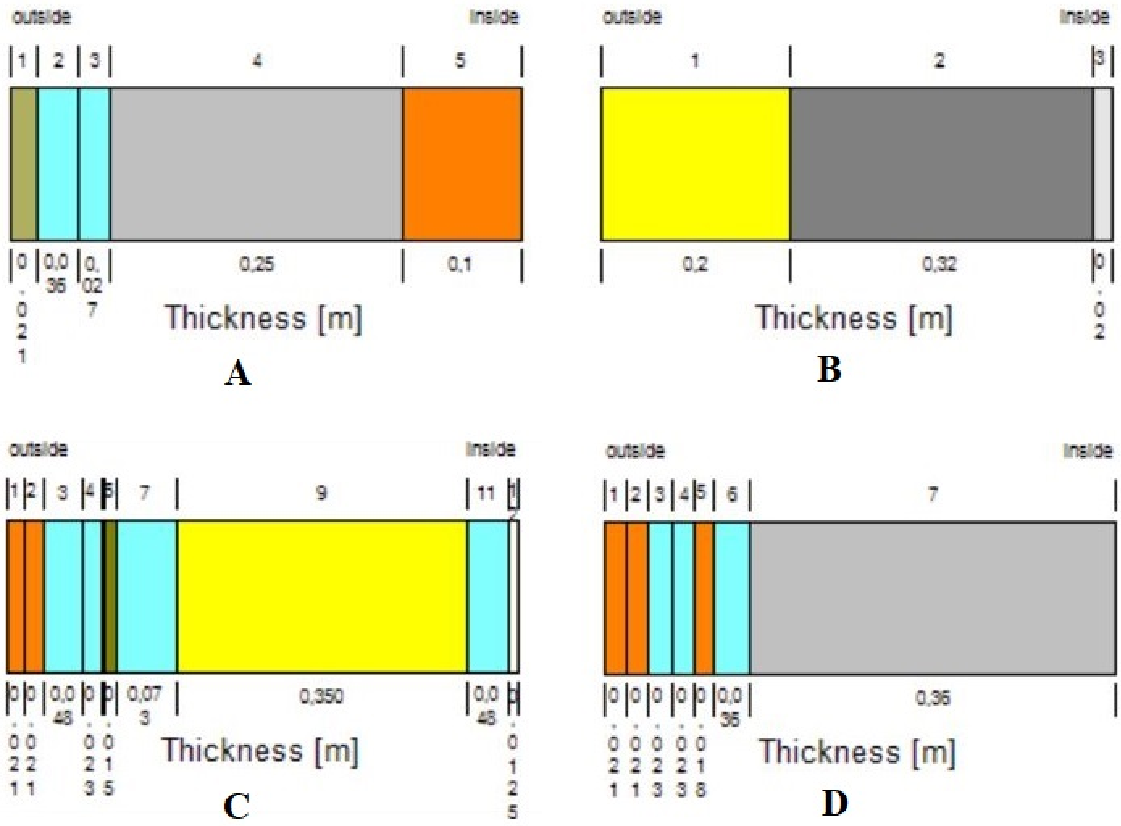


Figure 32: Building envelope structure based of WUFI Plus:
A) External wall, B) Concrete slab, C) Roof, D) Entrance Roof

Understanding the structure of each component is necessary to accurate calculate its thermal transmittance. The chosen materials to pose the component are therefore expressed in table 8 with each materials thickness.

Table 8: Building envelope structure from WUFI Plus with material choices and thickness

Building component	Material (outside to inside)	Thickness [m]
External Wall	Spruce	0.021
	Air Layer	0.036
	Air Layer	0.027
	Rockwool	0.25
	KLH Massivholz	0.1
Concrete Slab	EPS	0.2
	Concrete, w/c 0.5	0.32
	Aerated Concrete	0.02
Roof	Spruce	0.021
	Spruce	0.021
	Air Layer	0.048
	Air Layer	0.023
	PVC membrane	0.002
	OSB plate	0.015
	Air Layer	0.073
	Vapor retarder (sd=10)	0.001
	Mineral Wool (0.035 W/mK)	0.35
	Laminated polypropylen membrane	0.001
	Air Layer	0.048
	Gypsum Board	0.013
Entrance Roof	Scandinavian spruce	0.021
	Scandinavian spruce	0.021
	Air Layer	0.023
	Air Layer	0.023
	Woodfibre board, hard	0.018
	Air Layer	0.036
	Rockwool	0.36

The building envelope not only consist of built components. Windows and doors also contribute to prevent loss of heat. The building have windows in different shape and with distinct properties depending of their placement. In addition is the whole entrance made out of a glass, made up mostly of windows and some opaque panels. The main entrance also has the only external door made out of glass. The last two external doors are hidden by the external stairwell on the south side of the building. When preforming a simulation model, material choices would be different from the real situation due to WUFI's material base. Therefore, thermal transmittance values and other building envelope assumptions vary somewhat from the real case. U-values and other component attributes are shown in table 9. These are also compared to minimum requirements from TEK10 and NS 3701.

Table 9: Building envelope assumptions

Description	WUFI Plus value	Claims TEK10	Claims NS 3701
U-value external wall [W/m^{2}K]	0,12	$\leq$0,22	-
U-value roof [W/m^{2}K]	0,08	$\leq$0,18	-
U-value ground floor [W/m^{2}K]	0,17	$\leq$0,18	-
U-value windows/glass facade/external doors [W/m^{2}K]	0,8	$\leq$1,2	$\leq 0,8$
U-value opaque panels glass facade [W/m^{2}K]	0,20	-	-
Normalized thermal bridge-value [W/m^{2}K]	0,03	-	$\leq$0,03

Regarding windows, all have zip screens to protect the indoor environment from the sun. The zip screen provide them with a total g-value of 0,06 when activated. The exception are two south-facing windows. Since the external stairwell cover these windows it also works as a sun protector. That being said, most windows have a general g-value of 0,42 to begin with. However, since the sun transmittance is higher for windows facing east, these have a g-value of 0,53. For the glass facade all windows have a g-value of 0,37. These values are assigned to their respectively windows under solar protection. Figure 33 illustrates all windows and their placement.

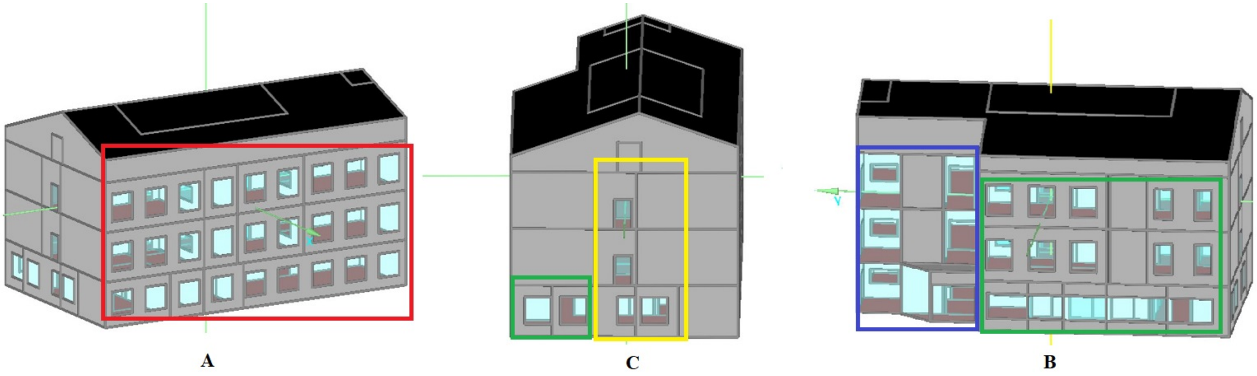


Figure 33: Buildings external window placement:
A) East, B) South, C) West

Windows facing east, marked with red, are the ones with high sun transmittance. On the south-facing side the yellow square mark the windows and doors protected by the external stairwell. The green square mark the once with regular g-value. Windows facing west have the same green square marking since the attributes are equal. Blue marker indicate the glass facade and main entrance.

3.3.5 Building zones

In order to examine the building as realistic as possible, is the model divided into zones depending of their occupancy, internal load and ventilation needs. The zones, and what they contains are expressed in table 10.

Table 10: Building zones

Zones	Content	Net volume
Zone 1	Offices and IT	185,95m^3
Zone 2	Meeting room, social, archive, copy room and group rooms	574,27m^3
Zone 3	WC, HCWC, technical rooms and sprinkler central	727,52m^3
Zone 4	Corridors	1338,91m^3
Zone 5	Classrooms	1505,64m^3
Zone 6	Elevator shaft (unheated)	218,79m^3

The building divided into zones improve the simulation's accurate. Some zones are occupied all day, others more occasionally. Rooms with continuous occupancy through entire day day are exposed to internal loads e.g. pupils and teachers. For instance are classrooms in use all day, while technical rooms are more or less never occupied. The internal loads for each zone is expressed in table 11. Dividing the building into zones also allow for more exact analyse. Each zone will display an indoor environment and air quality. If a zone needs improvement, its easily changed. Sectioning of zones and their building location are marked with colors in figure 34.

Table 11: Internal loads for each zone during operation

Zones	Activity	Specific ventilation rate	Time
1	Adult - Office - seated	6	7am to 17pm
2	Adult - middle activity	1	7am to 17pm
	Child - sitting	3	7am to 17pm
3	Child - standing, light activity	7	7am to 17pm
4	Adult - Walking	1	8am - 9am, 11am - 12am, 15pm - 17pm
	Child - Walking	30	8am - 9am, 11am 12am, 15pm - 17pm
5	Child - Sitting	75	7am to 17pm
	Adult - Standing	4	7am to 17pm

It is necessary to address that the load count renders people per hour. It is therefore estimated somewhat amount of adult or children present in that zone during the one hour. Zone one is as mentioned offices and therefore only houses seated adults throughout the whole day. The second zone is a mix of rooms with different occupation and activities, but they are all seated. Therefore are these given both adult and child activities. Zone three is mostly technical rooms where without any occupation. However, toilets and wardrobes are also included in this zone and it is therefore provided with light standing activity from children. Until now are all these zones frequently used during a day, hence the given period from 7am to 17pm. The exception is zone four. Being corridors and hallways does this zone only get used when the pupils transfer from one room to another or outside. This occurs often at the beginning of the day, around lunch and when the school day is finished. The fifth zone are the four classrooms where the pupils supposedly are to work seated or listen to their standing teacher, thus the activity given this zone. Notice that zone six is unheated and therefore left out. This indicates that the zone will not be simulate with any additional loads or ventilation rates, and contribute nothing to the environmental impact.

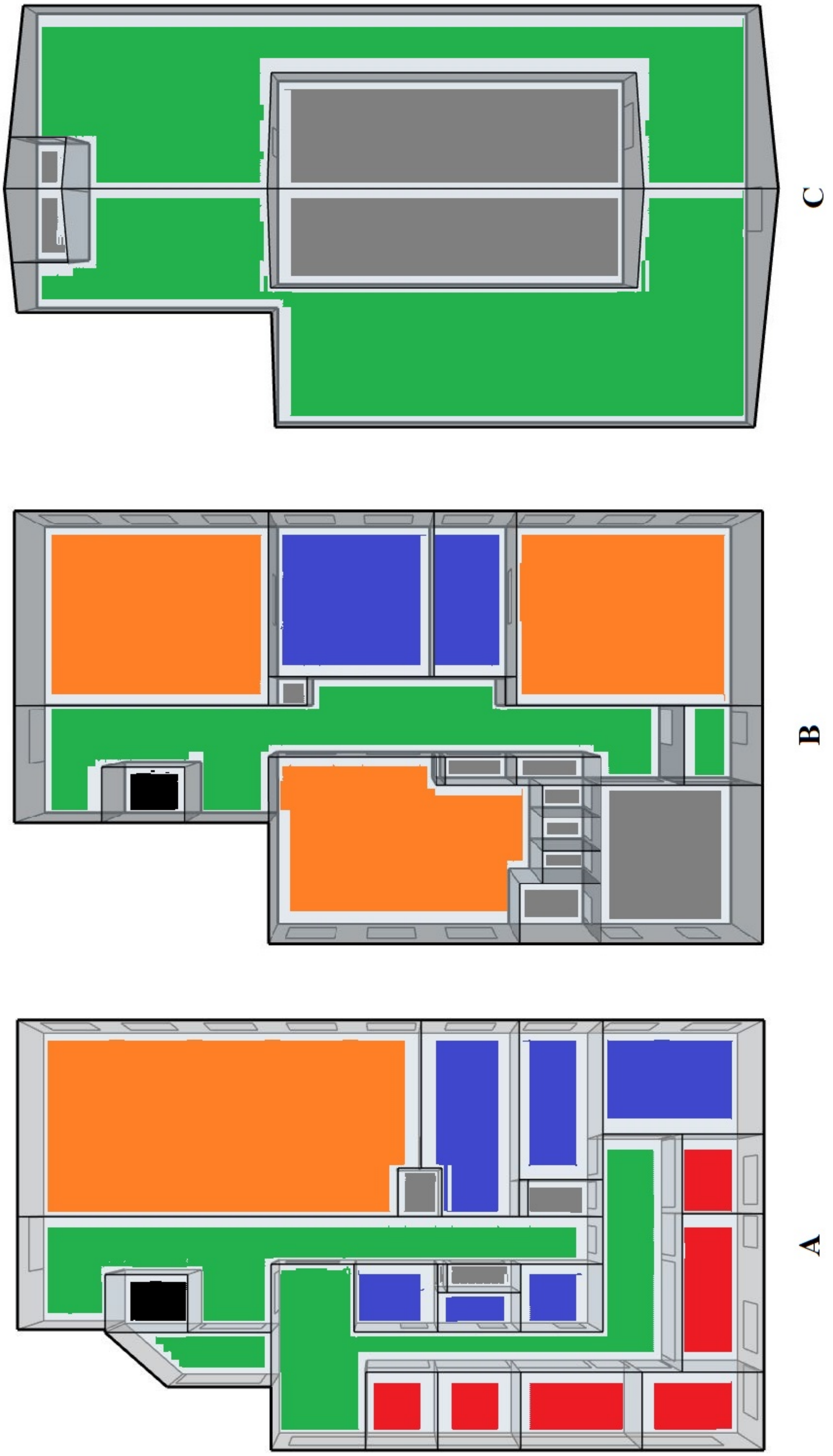


Figure 34: Floor plans with zones: A) Ground floor, B) second and third floor, C) Loft Red (zone 1), blue (zone 2), Gray (zone 3), Green (zone 4), Orange (zone 5) and black (zone 6)

3.3.6 Simulation period

Necessary standard values given by NS 3031 is key to perform an accurate simulation. Table A.3 in the standard addresses such values for a building's operation regarding heating, lights, equipment, occupants and ventilation. School buildings are by the standard said to be operational 44 weeks a year, five times a week and ten hour a day. During this operation the need for heating, lights, equipment, ventilation and people are all equal. Consequently, this also influence the simulation, relying on operation according to NS 3031. A simulation period of one school year is estimated, lasting from mid August to late June. Since NS 3031:2014 exclude week 52 and summer break, operational period is decided to be from August 17th to June 30th, securing 44 weeks of operation. During a week, the school is operational from 7am to 5pm, from Monday to Friday. The remaining weeks, days and hours makes up the outside operation period. Whole period is given in table 12 [81].

Table 12: Simulation period

Simulation period	Date	Weekday	Hours
Operation	17.08.2020 to 30.06 2021	Monday - Friday	7am to 5pm (10h)
Outside operation	17.08.2020 to 30.06.2021	Monday - Friday	5pm to 7am (14h)
	17.08.2020 to 17.08.2021	Saturday - Sunday	24h

3.3.7 Design conditions

As mentioned is the school building simulated with three different ventilation controlling methods. Each ventilation methods is assigned specific design values to suit prEN 15251:2006. Temperature control is assigned temperature design values. Relative humidity control specific humidifcation and dehumidification design levels, and CO_2 control concentration provisions. Each controlling methods design conditions are presented in this section.

3.3.7.1 Temperature control

The standard express design limit values for heating temperature for in different buildings. For a school building heating is initiated when temperature descend below 21°C during operation. During outside operation is the building allow temperature to drop below 19°C. This are standard values also found in NS 3031:2014. However, based on the building contractors preconditions, operation limit temperature is changed to 22°C. outside operation temperature remain equal as the standard value. The simulated minimum temperatures are addressed in table 13.

Table 13: Simulated minimum temperatures

Simulation period	Simulated minimum temperatures
Operation	22°C
Outside operation	19°C

3.3.7.2 Relative humidity control

The HVAC system is assigned humidification and dehumidification in addition to mechanical ventilation. HVAC prevent temperatures from dropping below a certain temperature by adjusting the mechanical ventilation. Humidification and dehumidification maintain the relative humidity in the room between given design values. If the relative humidity rises above a certain percentage, is dehumidification initiated and humidification starts if the humidity drops to a percentage lower than design value. The simulations that implement humidification and dehumidification are assigned prEN 15251 recommended design values. During occupation humidification and dehumidification design values for category two demanded, while during outside operation the building is allowed category III. Design values according to the two categories and when they are applied is shown in table 29.

Table 14: Recommended simulated design criteria for humidification and dehumidification

Simulated period	Relative humidity for humidification	Relative humidity for dehumidification
Operation	25%	60%
Outside operation	20%	70%

3.3.7.3 CO_2 control

The standard also address design values for allowed CO_2 concentration in the air. Based on these values are recommended CO_2 concentrations simulated. The standard suggest values that correspond to the outdoor concentration for demand control. All simulated scenarios have been added design values maintaining acceptable max CO_2 according to [82]. The values are given in table 15 underneath. Note that the initial assigned maximum CO_2 concentration are 50 ppvm higher than category two from section 3.3.3.

Table 15: Max CO_2 allowed for the initial simulations

Simulated period	Max CO_2 concentration
Operation	900 ppvm
Outside operation	1200 ppvm

3.3.8 Wall surface coating

In order to evaluate the significance of exposed wooden elements, different surface coating is assigned to the model's internal walls. As mentioned previously water vapor flow, due to diffusion, from a high vapor pressure area to the low. A material exposed to diffusion resist movement individually. How well a material resist vapor diffusion is dependent of their sd-value. The value state the material's ability to resist vapor movement compared to a resistance of one meter air. Lower sd-value indicate less resistance. Common vapor barriers have a sd-value of 10 m and wind barriers 0,5 m, forcing the moisture out of the building. It is also necessary to address that a material's sd-value is dependent of it's thickness. Two identical materials, with different thickness, have distinctive sd-values [83]. The sd-value of a material is a key investigating moisture buffering and latent heat. If the exposed material does not allow vapor flow, moisture buffering is not initiated.

WUFI Plus have the advantage that surface coating might be applied to components without implementing it to the assembly. Instead it simulate the component with and additional thin layer. The surface coating property allow the wanted diffusion resistance to the remain as the existing one. Since almost all internal walls expose solid timber, the first test evaluate how exposed material attracts moisture without any surface coating assigned. Examples of the used internal solid timber walls are show in figure 35. Two other surface coating examples are carried out. A gypsum board surface is simulated to compare the results. Gypsum walls has commonly a sd-value of 0,1 m. A third provide the exposed wood with a painted surface coating, assigning a sd-value of 5 m. The last surface allow less moisture to flow into the wall compare to the other two. The simulated surfaces therefore have a sd-value varying from 0,01 m to 5 m.

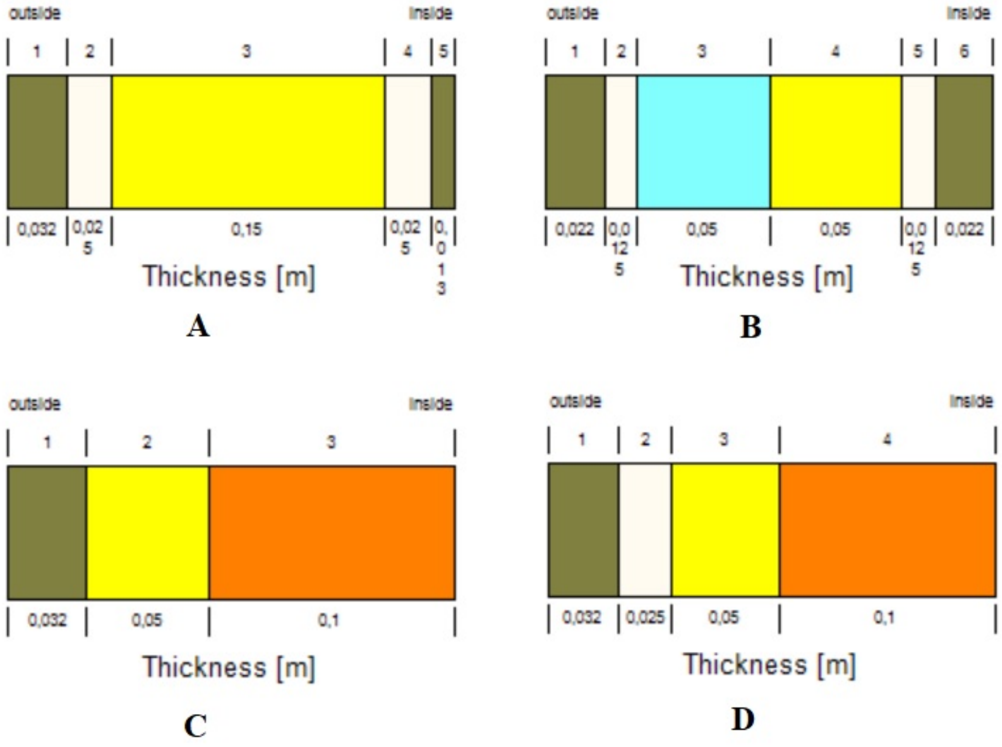


Figure 35: Most frequent examples of internal solid timber walls in the simulation

Table 16: Simulated exposed surfaces with WUFI Plus's surface coating

Simulated surfaces	Sd-value [m]
Exposed wood	No coating, <0,1
Gypsum board	0,1
Paint	5

3.3.9 Air flow and ventilation controlling systems

To possibly reduced with indoor environment with exposed CLT elements, knowing the ventilation air flow is necessary. The two standards provide useful minimum values for building ventilation air flow. Table A.6 in NS 3031:2014 address such values when comparing buildings with public claims in TEK. The table express that school buildings must allow a minimum air flow of 10 $m^3/(h\cdot m^2)$ during operation and at least 2 $m^3/(h\cdot m^2)$ outside operation [81]. However, since the school is constructed as a passive house, energy savings require lower air flow. Where NS 3031:2014 has a minimum value of 10 $m^3/(h\cdot m^2)$ during operation, NS 3701 demand for 8 $m^3/(h\cdot m^2)$. Reducing air flow outside operation is also possible with passive houses, requiring half of the air flow [80].

Even though the school is a passive house and built to suite NS 3701, minimum airflow from NS 3031:2014 is also included in the simulation. That being said, the school contractor utilize a higher air flow than minimum during operation. Their estimated value used for energy calculation is used. Instead of using 10 $m^3/(h \cdot m^2)$, the school contractor uses 10,2 $m^3/(h \cdot m^2)$ as their max allowed air flow. Values from both standards are used in order to evaluate the effect ventilation rates have on the indoor environment and the CLT elements. Frequent change of air at a high rate might prevent the moisture buffering in wooden elements. Therefore, simulations are done based on both NS 3031 and NS 3701, applying the following values for maximum air flow presented in table 17.

Table 17: Simulated airflows based on standards and building contractor provisions

Standard	Operation	Outside operation	Unit of measurement
NS 3031	10,2	2	$m^3/(h \cdot m^2)$
NS 3701	8	1	$m^3/(h \cdot m^2)$

It was earlier stated that common ventilation systems are controlled by temperature. This signify that system boundaries have been established for specific temperatures. If it rises above or falls under the limits, the ventilation system increase the supply or subtraction of air from the building to maintain stable temperature. That being said, other controlling methods might be used. To improve the indoor environment the ventilation system could be CO_2 controlled, or dependent of the relative humidity. The buffering capacity of wooden elements is influenced by the indoor relative humidity. RH-controlled ventilation therefore might allow full exploitation of the hygroscopic properties. To examine how the different controlling systems affect the buffering capacity, all three are simulated.

Table 18: Different ventilation control methods simulated

Controlling methods	Minimal difference allowed	Infiltration
Temperature control	3°[K]	0,028 [h^{-1}]
Max CO_2 control	0,1 [g/m^3]	0,028 [h^{-1}]
Relative humidity control	0,5 [g/m^3]	0,028 [h^{-1}]

3.3.10 HVAC capacity and distribution

The last thing done before beginning the is to make sure that the HVAC capacity for all the different systems is high enough to not be exceeded. To make sure this does not happen is their been estimated a buffer for each one. Space heating, mechanical ventilation and humidification and dehumidification are all given high enough capacity to cope with the buildings needs. The district heating is given a capacity of 100kW, the mechanical ventilation a capacity of 20000m^3/h. The mechanical ventilation also regain

84% of the heat withdrawn from the room, which is added to the system. Lastly both the humidification and dehumidification is provided with a capacity of 100kg/h.

When the system has been developed and the purposes its suppose to fulfill have been added, it has to be distributed to the building. The HVAC could cover only parts of the building, depending if there are more systems or areas that don't require assistance from the HVAC. HVAC distribution is based on the area of each zone. Smaller areas will be less affected than bigger areas, thereby given less distribution than the bigger ones. Distribution of the HVAC is shown in table 19, given as percentage.

Table 19: HVAC distribution to the zones depending on their area

Zone	Area [m^2]	Heating	Ventilation	Humidification	Dehumidification
1	66,41	0,04	0,04	0,04	0,04
2	191,72	0,13	0,13	0,13	0,13
3	231,23	0,17	0,17	0,17	0,17
4	522,37	0,31	0,31	0,31	0,31
5	477,98	0,35	0,35	0,35	0,35
6	18,78	0	0	0	0

3.3.11 Initial simulation process

As mentioned is 36 different situations simulated. These are further divided into more categories depending of which standards and ventilation controls that are used. The 36 simulations are divided into two groups based on supplied air flow. 18 simulations are performed with the modified NS 3031 air flow and the last 18 are simulated with the air flow value required for passive houses. One interest of this thesis is to investigate how different ventilation control systems affect solid timber elements hygroscopic characteristics. Therefore are the simulations further divided into three groups representing the different control methods in WUFI Plus. These control methods are temperature control, relative humidity control and CO_2 control. All of them are assigned 6 simulations to evaluate their affect. The hygroscopic characteristics will also be influenced by humidification and dehumidification. Therefore, three of the six simulations are performed with humidification and dehumidification. Lastly, to investigate if solid timber might be optimized with these ventilation methods are two other surface coatings also simulated. All conditions applied to the different simulations are expressed previously. The simulation distribution are shown in the tree-figure 36.

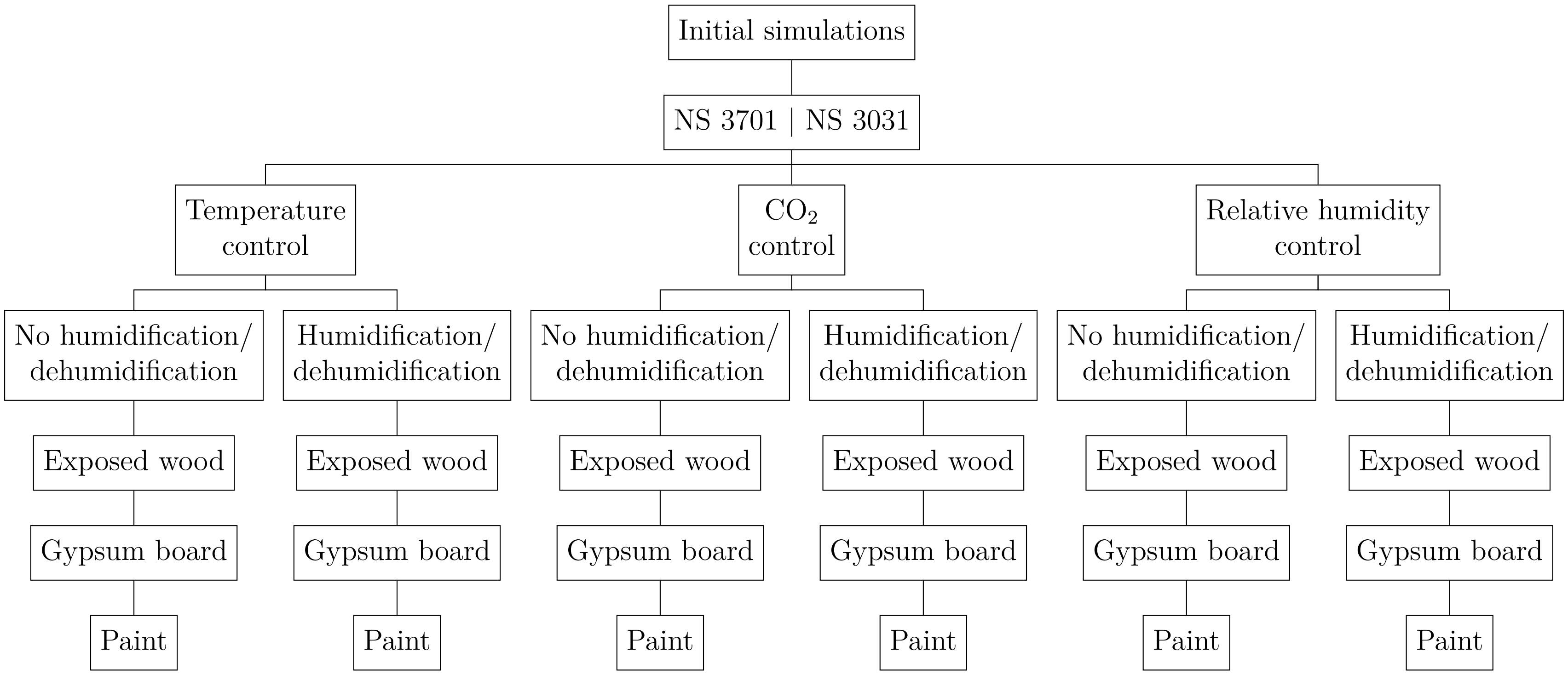


Figure 36: Initial simulation process distribution

3.3.12 Optimized simulation

The first 36 simulations signify the need for change to take more advantage of the exposed woods hygrothermal characteristics to improve the indoor environment. Therefore, based on the initial simulations are six additional simulations performed in order to optimize the buildings indoor environment. The first change was done to the minimum allowed indoor temperature during operation. Operation minimum temperature was increased from 22°C to 23°C. This change is performed for all simulations. If the indoor temperature dips below 23°C during operation, heating initiate to maintain temperature at acceptable levels. Change has also been made to the operation CO_2 concentration design level. It is lowered from 900 ppvm to 850 ppvm to express second category concentration levels. The indoor environment is dependent of the indoor CO_2 concentration, hence lower concentration pledge the indoor air quality. $CO2_2$ concentration change is done to all six simulations. However, it will mostly benefit the simulations where the building are controlled by CO_2 concentration levels. Operation temperature and CO_2 concentration changes are listed in table 20.

Table 20: Temperature and CO_2 concentration changes performed for optimization

Simulation	Minimum temperature	Max CO_2 concentration
Initial simulation	22°C	900 ppvm
Optimized simulation	23°C	850 ppvm

The biggest change from the initial to the optimized simulations is the introduction of cooling. Initially, indoor temperature was only within acceptable minimum temperature levels. To make sure the temperature do not rise to a level where the indoor temperature becomes too hot, is cooling added. Like with other design conditions, are cooling temperature obtained from prEN 15251:2006. The standard's table A.3 addresses cooling temperature range for different building purposes [82]. It is decided that a school building require a cooling temperature ranging from 23-26°C to obtain category two. In addition, NS 3701 require a cooling temperature of 24°C. Therefore, the cooling temperature, i.e the maximum temperature, during the buildings operation is adjusted to 24°C. When the building is not operated the cooling initiative temperature is 30°C. The implementation of cooling also need to be addresses in the buildings HVAC system. Just like heating capacity is cooling capacity 100 kW. The distributions are also same. All necessary changes associated with cooling implementation are listed in the table 21 below.

Table 21: Cooling temperature and zone distribution

Operation	Cooling temperature	Zone distribution
operation	24°C	Zone 1: 0.04 Zone 2: 0.13 Zone 3: 0.17 Zone 4: 0.31 Zone 5: 0.35 Zone 6: 0 (unheated)
outside operation	30°C	

In addition to cooling and adjust both the temperature and allowed CO_2 concentration, is the ventilation system assigned moisture recovery. It work the same way as with the heat recovery, reusing moisture from the building in order to save energy. The moisture recovery is decided to be the same percentage as the heating recovery, i.e 84%. These optimization changes are performed one at the time to investigate how each affect the building. A step by step implementation provide understanding about the optimization its advantage or drawback combined with exposed wood. The implementation of the optimized simulations are illustrated in figure 37. Notice that only the NS 3701 exposed wood simulations with humidification are optimized.

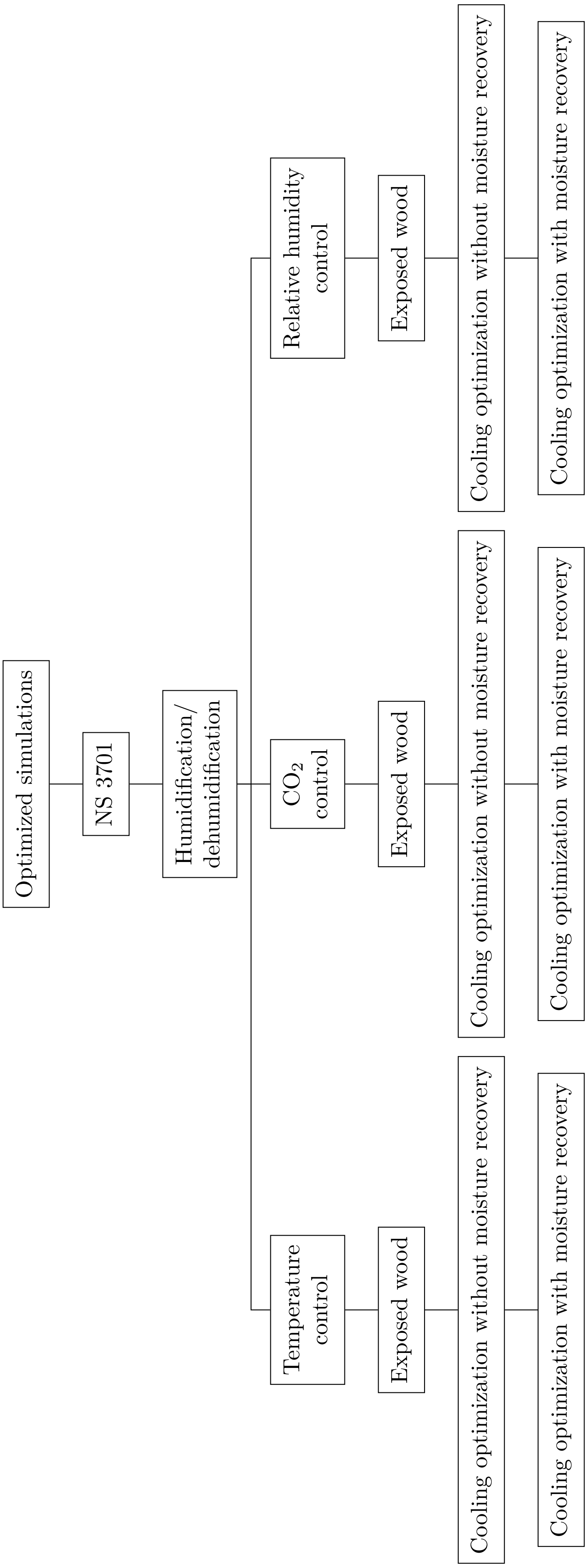


Figure 37: Optimized simulation process distribution

4 Results and discussion

Based on both the laboratory experiment and simulations, this chapter present results and discuss the findings. The presentation will be divided into the two research design approaches introduced in section 3. Only the findings that are important to answering the research question will be presented.

4.1 Laboratory experiment

The section will introduce the findings from the laboratory experiment conducted on the two solid timber elements. Initially, elements λ-value was obtained and a starting U-value calculated. Then dynamic U-values for each cycle was gathered. The effect moisture buffering on the U-values was then evaluated. Results for each element is individually presented and discussed, then compared.

4.1.1 Norsk Massivtre

4.1.1.1 Steady state λ-measurements

Surface temperatures are significant when investigating a material's λ-value. Inaccurate surface temperatures influence the λ-value, providing incorrect results. Several measuring methods was utilized to avoid inaccurate temperatures. Different measuring systems obtain different surface temperatures. Figure 38 provide an overview of the different measuring methods and their measured surface temperatures.

Figure 38 illustrate how the indoor surface temperature varied with different measuring systems during the experiment. Highest measured surface temperature was provided by Intab thermocouples. Heat flux thermocouple (TC11) was not far behind. Despite being attached at two different places, the two measure almost the same surface temperature. The other huksefluks thermocouple (TC21) was the one surrounded by Intab thermocouples. It provide distinct temperature difference compared to the Intab thermocouples. Uncovered, surrounding environment influenced the measurements causing inaccurate surface temperature. Thermocouples only measured surface temperature at the exact spot they are attached. Dealing with a inhomogeneous material therefore caused temperature differences based on there placement. The element from Norsk Massivtre not evenly distributed the surface temperature, best illustrated by the thermography in figure 41. Yellow areas indicate warm spots, blue cold ones. The camera obtained surface temperatures from

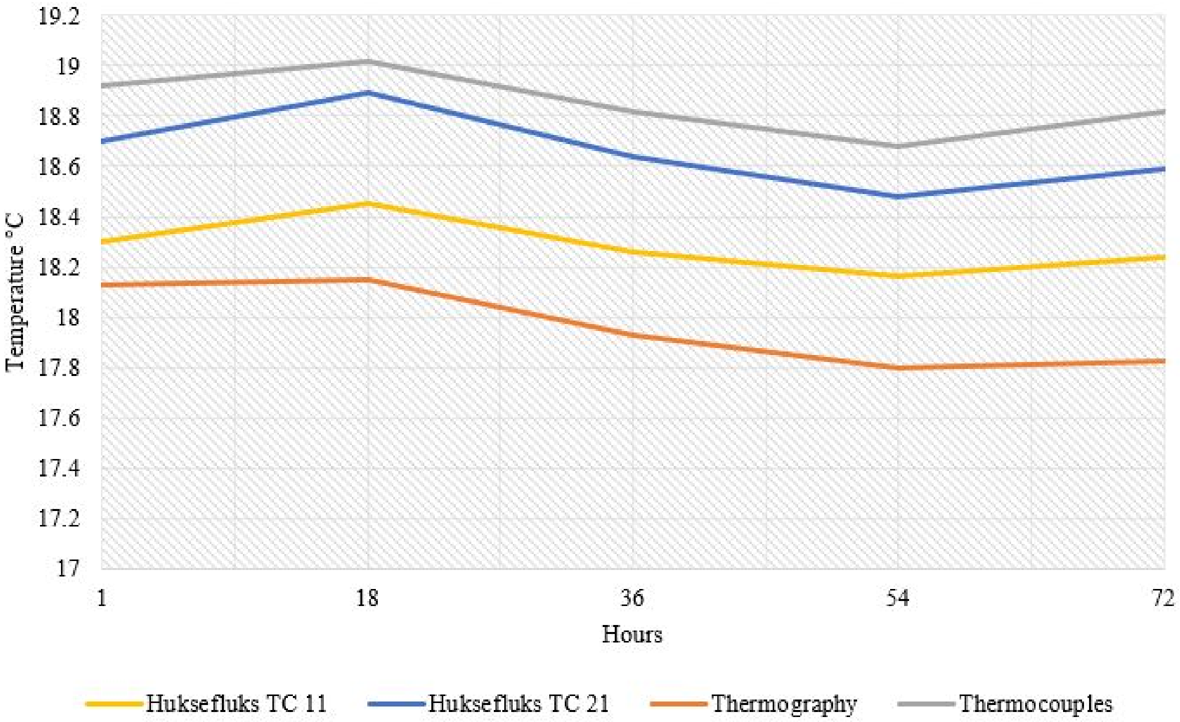


Figure 38: Indoor surface temperature comparison for λ-measurement of Norsk Massivtre

the four boxes, covering larger area than the thermocouples. Based on the highest and lowest temperature an average value was estimated. Instead of measuring one spot, bigger area coverage made the measurements more reliable. λ-value is dependent on the surface temperature and the heat flux. Heat flux thermocouples measured temperatures between the two other methods. Therefore, to avoid errors, their measured surface temperature values was made into an average temperature. Then, the obtained value was used to find the element's λ-value.

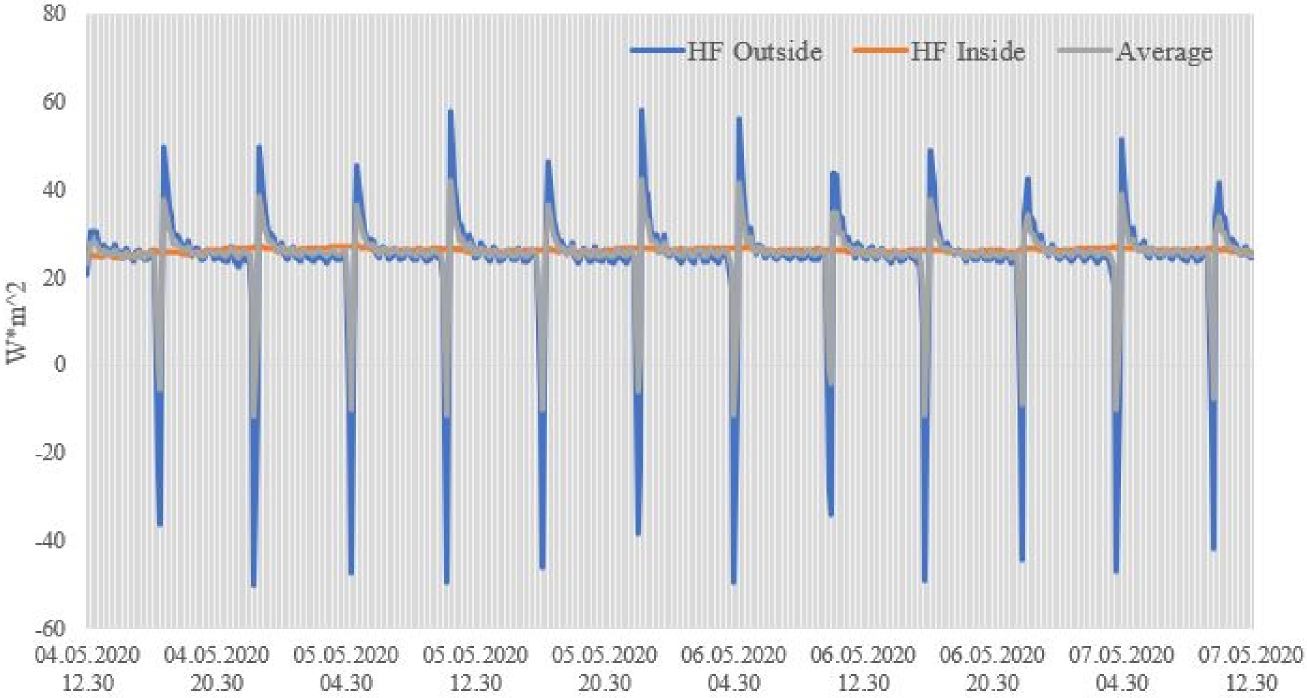


Figure 39: Measured average heat flux used for steady state λ-measurement Norsk Massivtre

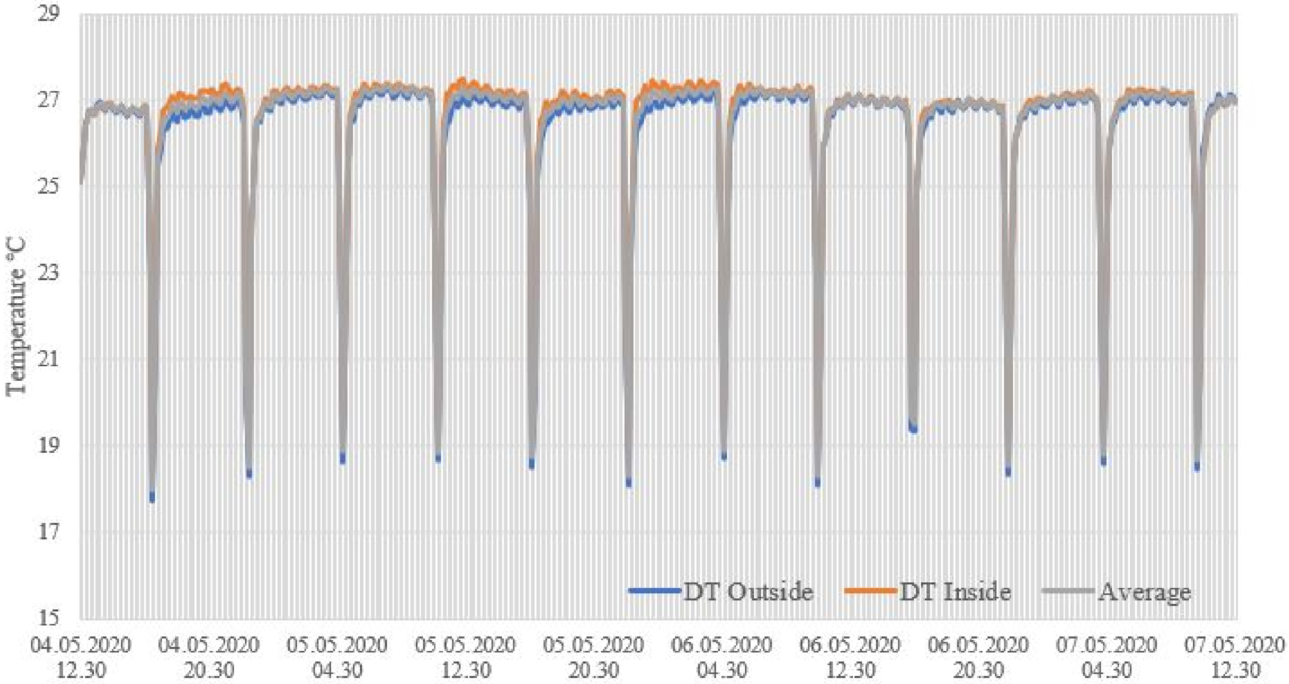


Figure 40: Average temperature differences used for steady state λ-measurement Norsk Massivtre

Measured λ-value was performed according to equation 4. Calculation parameters and the

λ-value is showed in table 22. The element thickness is 0,1 m, HF1 and HF2 correspond to the average heat flux obtained through the element. Average heat fluxes recorded outside and inside are expressed in figure 39. In addition the figure is an average heat flux displayed used in steady state λ-measurement. HF1 recorded the outside surface while HF2 the inside. DT1 and DT2 represented the surface temperature changes between the cold storage and the indoor space shown in figure 40. Similar to the heat flux figure, it also display their average temperature.

Table 22: Norsk Massivtre λ-value and corresponding U-value parameters

HF1	HF2	DT1	DT2	R_{Se}	R_{Si}	λ
24,4	26,7	26,8	26,9	0,04	0,13	0,095

With the calculated λ was a steady state U-value established using equation 3, shown below.

$$\lambda = 0,095 \rightarrow U - value = 0,819$$

It is noticed by both figure 39 and table 22 that the recorded heat flux through the to heat flux sensors differed. Distinctions are not abnormal with HF1 and HF2 located at separate surfaces. A higher indoor heat flux than outside indicated that some of the heat passing through the surface not exited on the outside. Instead, some heat is stored inside the element. In addition, figure 40 show that the heat flux thermocouples measured even indoor and outdoor surface temperature differences through the experiment. Figure 41 obtained thermography images of the surface during the experiment. Both indoor thermocouples measured colder spots of the element surface. If the thermocouples was placed somewhere else, the image show that it would influence the λ-value.

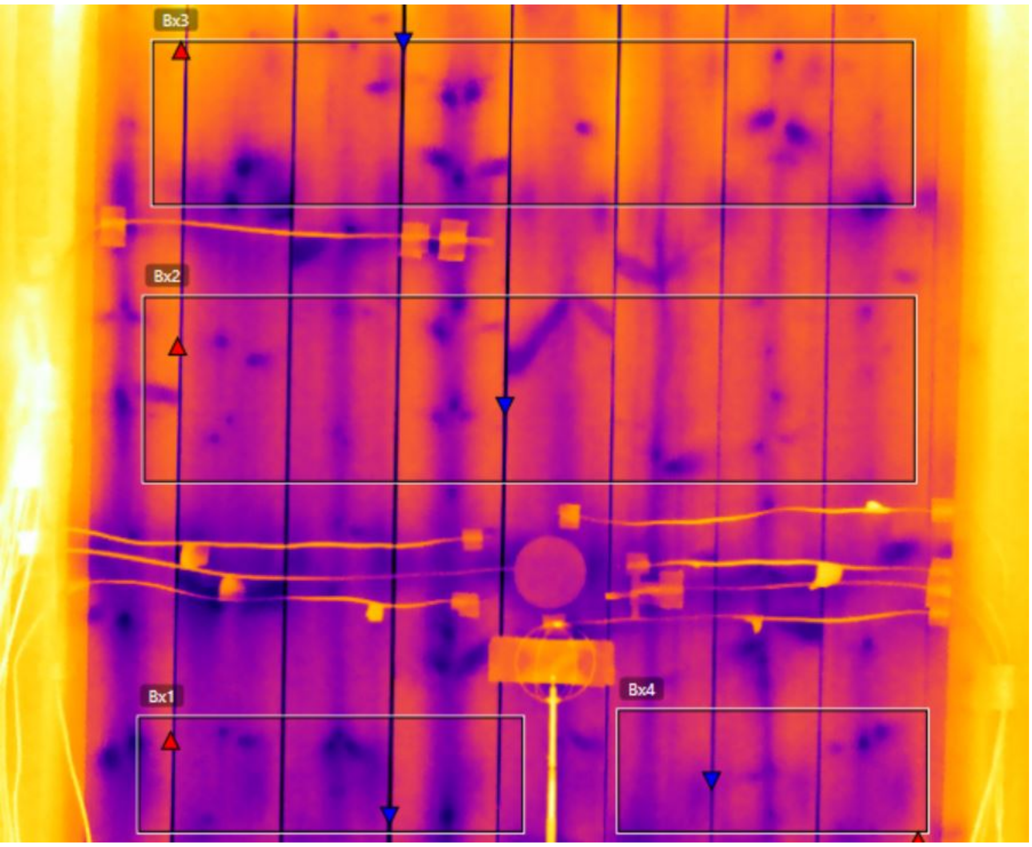


Figure 41: Thermography illustrating the inhomogeneous wooden element (FLIR)

4.1.1.2 Dynamic U-value

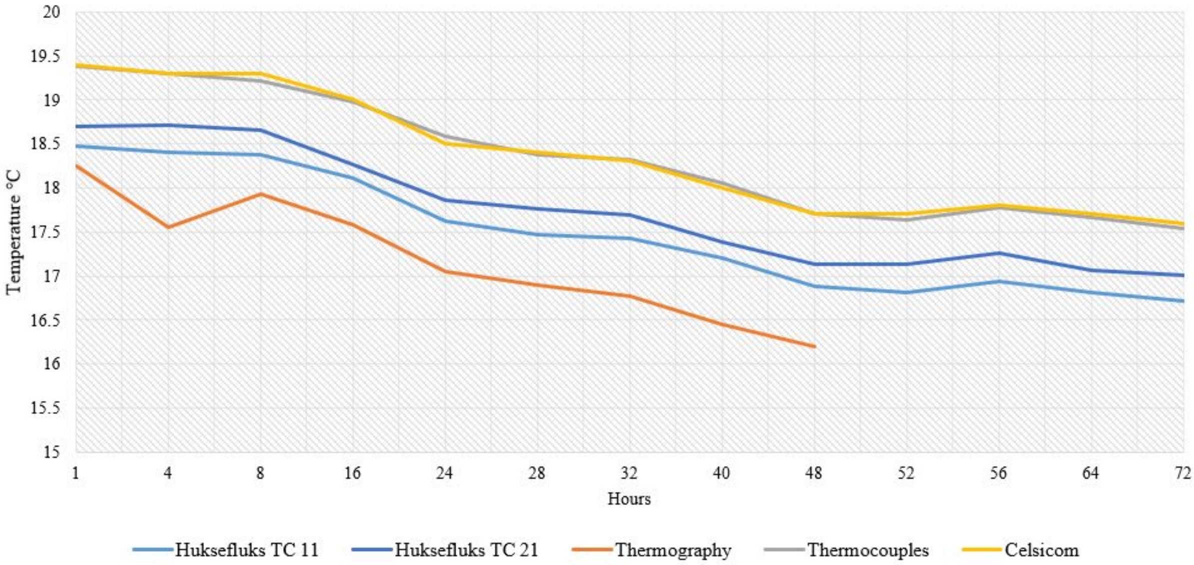


Figure 42: Indoor surface temperature variations during humidification process Norsk Massivtre

Similar to the steady state measurement, surface temperature comparison for the dynamic experiment is presented in figure 42. A fifth surface temperature is also presented. Surface temperature recorded by a Celsicom monitor is compared to the others. The dynamic experimental part included humidification and dehumidification periods. To better illustrate their impact the graph was divided into section. A four hour sections expressed the humidification period, while an eight hour one the dehumidifcation period. The pattern constructed in the previous surface temperature presentation repeated itself. Intab thermocouples reported the warmest surface temperature, while the camera the lowest. Between them, heat flux thermocouples measurements. Unlike the steady state experiment, heat flux thermocouples measured almost similar temperatures. TC 21 distanced itself from the Intab thermocouples. Celsicom surface temperatures followed identical path as Intab thermocouples. Notice that the thermography surface temperature values only recorded 48 hours of testing. During the third humidification cycle, indoor relative humidity exceeded the 60% humidity assigned to the camera. Relative humidity levels above the assigned value affected the camera focus. Instead, it took pictures excluding some of surface. These values was therefore found to be unreliable, and left out.

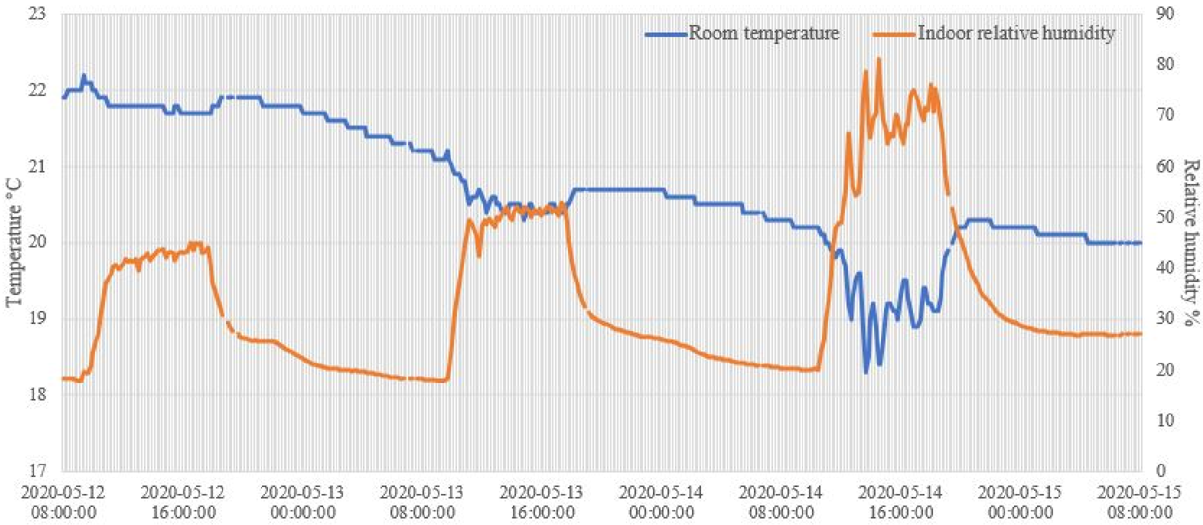


Figure 43: Room temperature and relative humidity relationship Norsk Massivtre (Celsicom)

During the experiment all measurement methods reported a down-facing temperature trend. Surface temperatures in the beginning and in the end indicated a reduction of 2°C. Negative temperature change occurred due to technical problems in the building locating the climate chamber. These technical problems also affected the laboratory temperature as shown in figure 43. Interestingly, all three humidification periods paused the trend. All cycles expresses the reverse propositional relationship between temperature and relative humidity. Drastically temperature drop increase the relative humidity. The same figure also show significant relative humidity alterations. Instead of maintaining 60%, it fluctuated between 65-75%, and even boosted above 80%. The relative humidity peaked when the temperature dropped to its lowest.

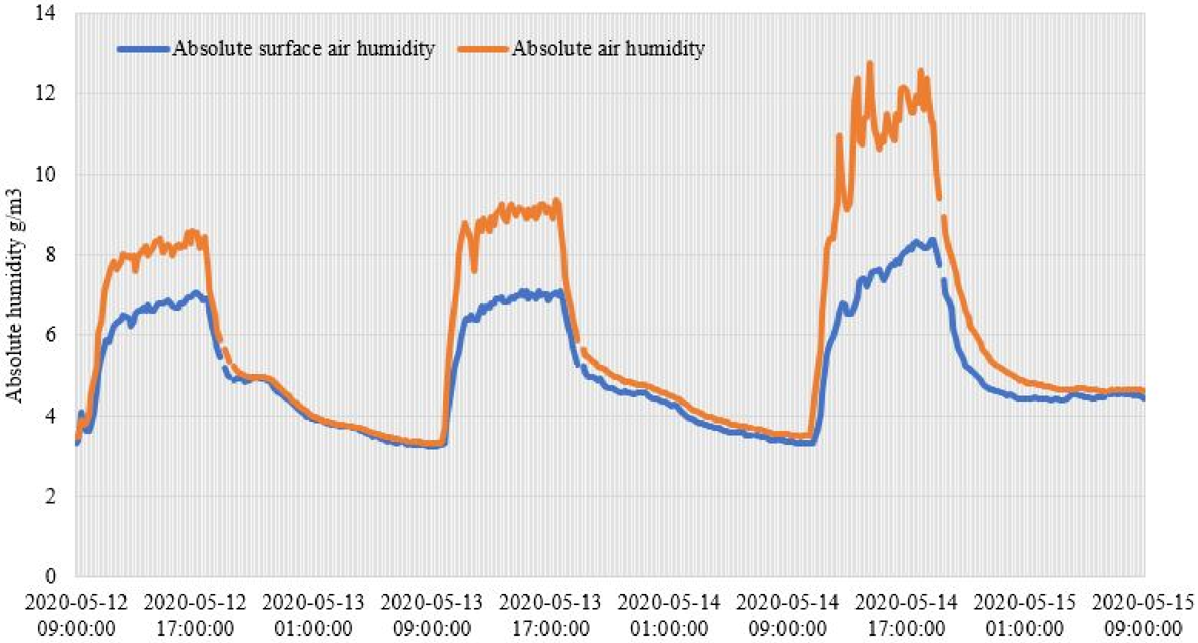


Figure 44: Absolute humidity comparison in the room and on the surface Norsk Massivtre (Celsicom)

Humidifying the room caused moisture alterations. Varying moisture content influenced the element. Figure 44 express the experimental periods absolute air and surface air humidity. Notice that a higher absolute humidity was recorded in the middle of the room than on the surface. Different absolute humidity occurred because the ventilation rate withdrew moisture during the humidification period. Increased moisture supply through the experiment also influenced ventilation removal. Cycle one and two recorded almost identical surface air humidity. Increased absolute humidity in cycle two indicate improved moisture removed by the ventilation. In addition, the temperature challenges influenced the room's humidity. Absolute air humidity in the last cycle show a low/high absolute humidity difference of 9,3 g/m^3. 9,3 g/m^3 at an indoor temperature of 19 °C imply a relative humidity of 70% using the Mollier diagram. However, with the instructed 22°C room temperature, it implies 60%. Without the temperature issue the absolute humidity would have been at humidifier assigned level.

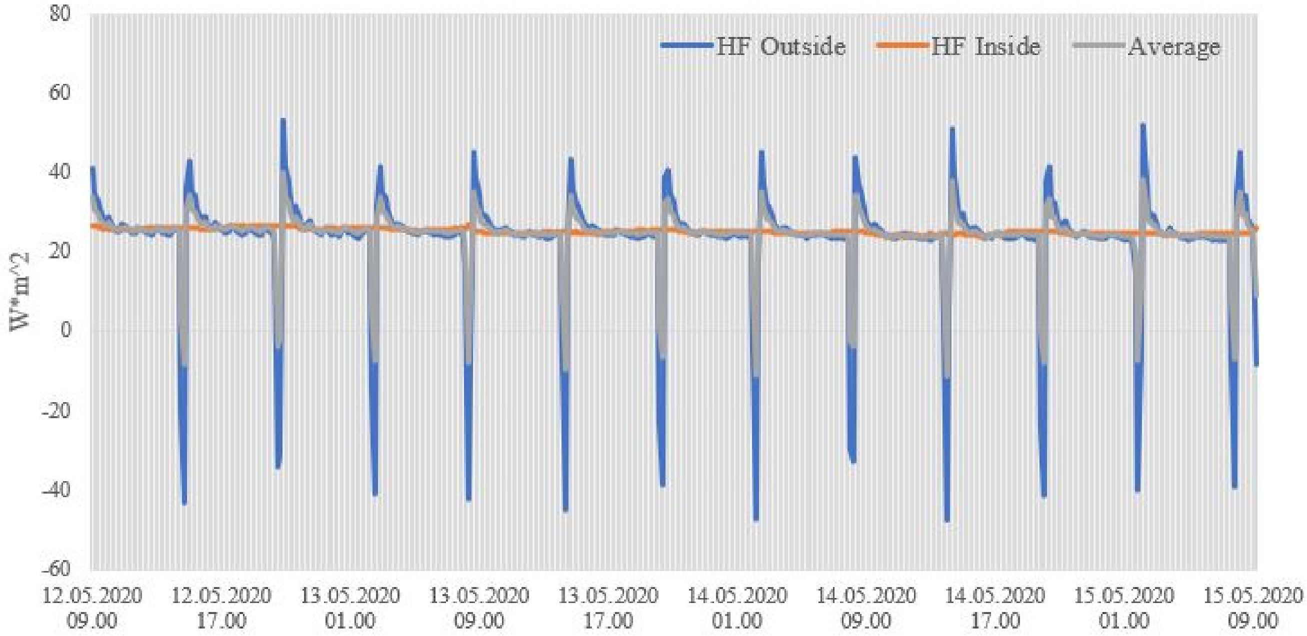


Figure 45: Measured average heat fluxes used for dynamic λ-measurements Norsk Massivtre

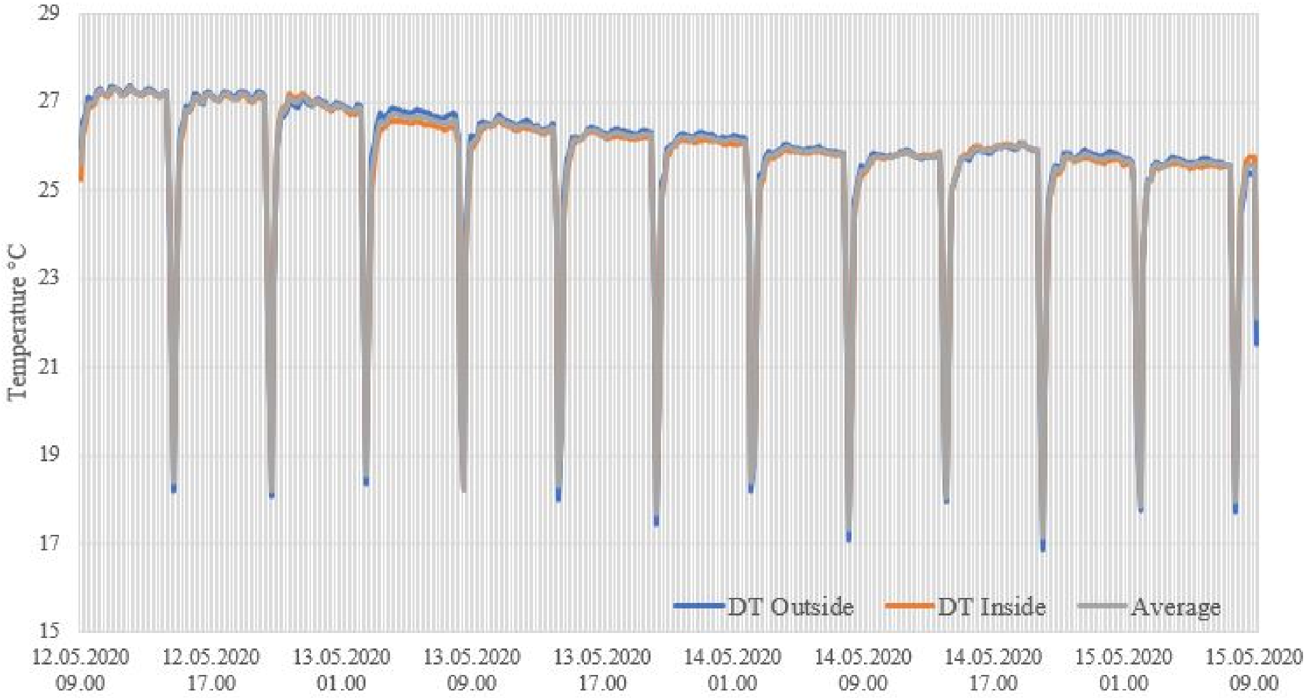


Figure 46: Average temperature differences for dynamic λ-measurements Norsk Massivtre

Investigating how different moisture levels influence the element's thermal transmittance is interesting. After each humidification and dehumidification cycle was a new heat conductivity obtained, used to calculate a dynamic U-value. Figure 46 show a surface temperature difference reduction throughout the experiment, influenced by the temperature issue. The heat flux also decrease. It is not easy to spot the reduction since the figure 45 express considerably alterations through the experiment. However, table 23 address flux reduction for each cycle. Differing moisture content for each cycle initiate the hygrothermal mass, buffering moisture in addition to heat. Decreasing trends for both heat flux and surface temperature differences is the heat conductivity affected. Figure 47 show the obtained dynamic U-values. It display a decreasing trend with growing moisture content. Lower U-value allow less heat to migrate through the element thereby propose an improvement.

Table 23: Dynamic U-value average calculation parameters

Cycle	HF1	HF2	DT1	DT2	R_{se}	R_{si}	λ
I	24,2	26	26,4	26,3	0,04	0,13	0.095
II	23,3	25,1	25,7	25,6			0,094
III	21,9	23,8	24,3	24,3			0,093

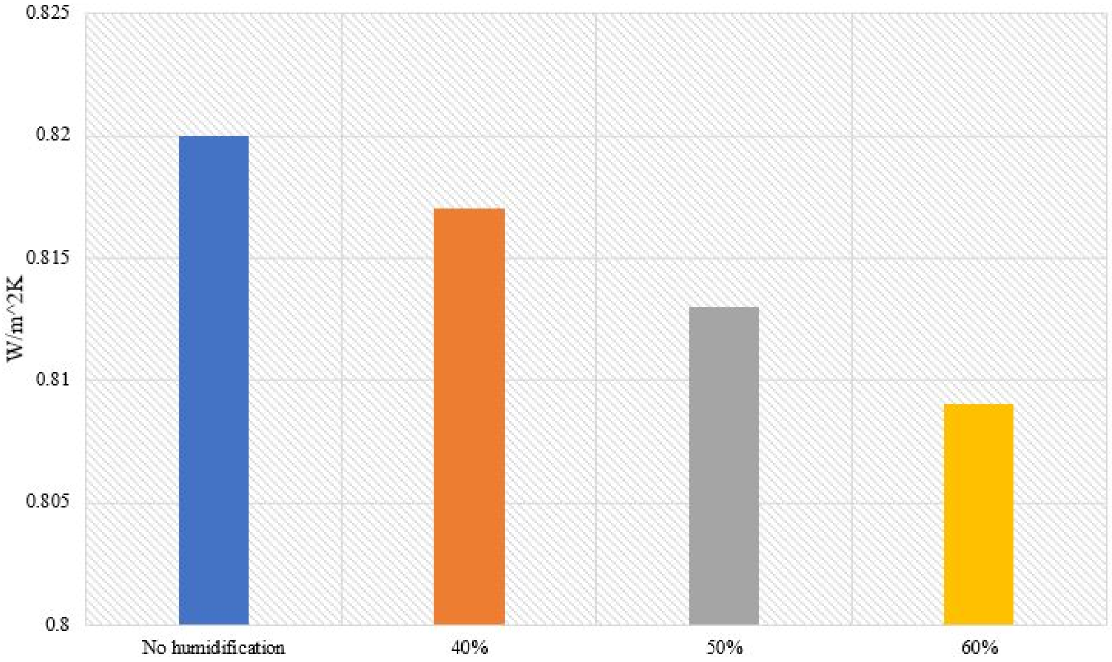


Figure 47: U-value comparison Norsk Massivtre

4.1.2 Splitkon

4.1.2.1 Steady state λ-measurements

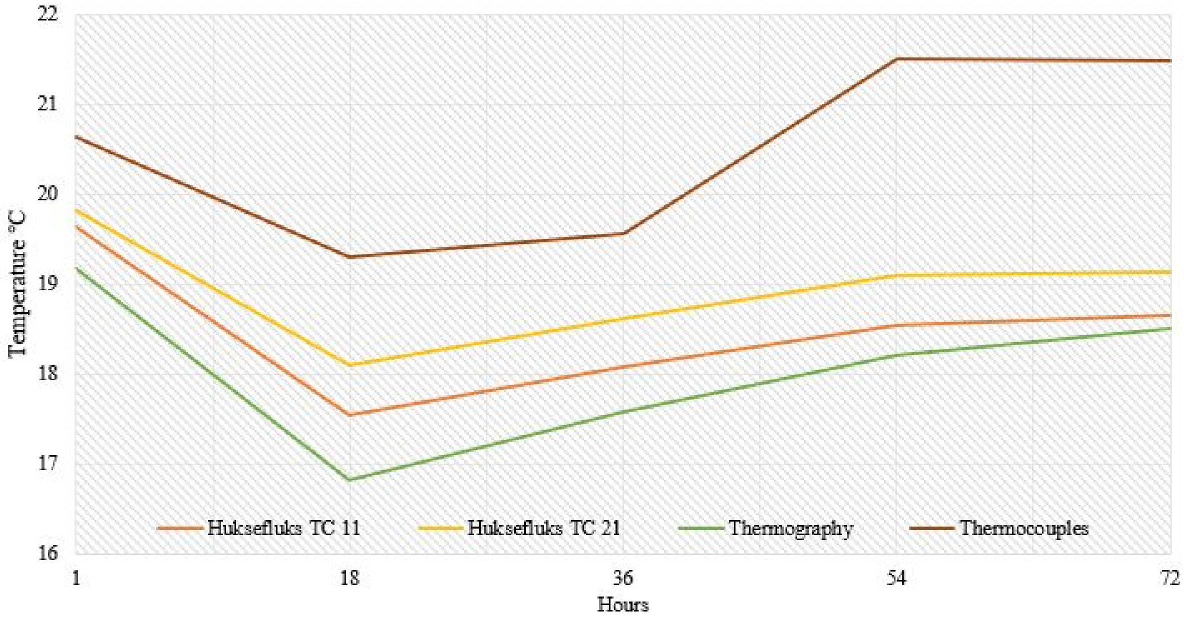


Figure 48: Surface temperature comparison Splitkon

Similar to Norsk Massivtre is the Splitkon element surface temperature measurements displayed in figure 48. Intab thermocouples still recorded the highest surface temperature and the camera the lowest. Equally for the heat flux thermocouples. Notice that the figure address a steep reduction in the beginning. The experiment was initiated as soon as the element was in place. The cold storage had to work its way up to -10°C, and the indoor space needed to re-adapt to the outdoor temperature decrease. In addition, uneven edges possibly leaked air inn and out of the room. These factors influenced the elements surface temperature, explaining the first 18 hour decrease. From there the temperature grew, finishing almost where it started. Intab thermocouples was the only exception. Around 36 hours, one of the thermocouples detached, recording above the surface. Therefore, the graph increase, almost recording room temperature levels. In addition, one of the heat flux thermocouple had some attachment issues. However, it stayed in place continuing to record the surface. Both these cases was captured by the thermography camera, showed in figure 49. As the same figure show, detaching also influenced two measurement boxes. Box one and two increased their highest recorded value, affecting the average value. However, since the graph show the average of all four boxes it is not considerably influenced by the detaching.

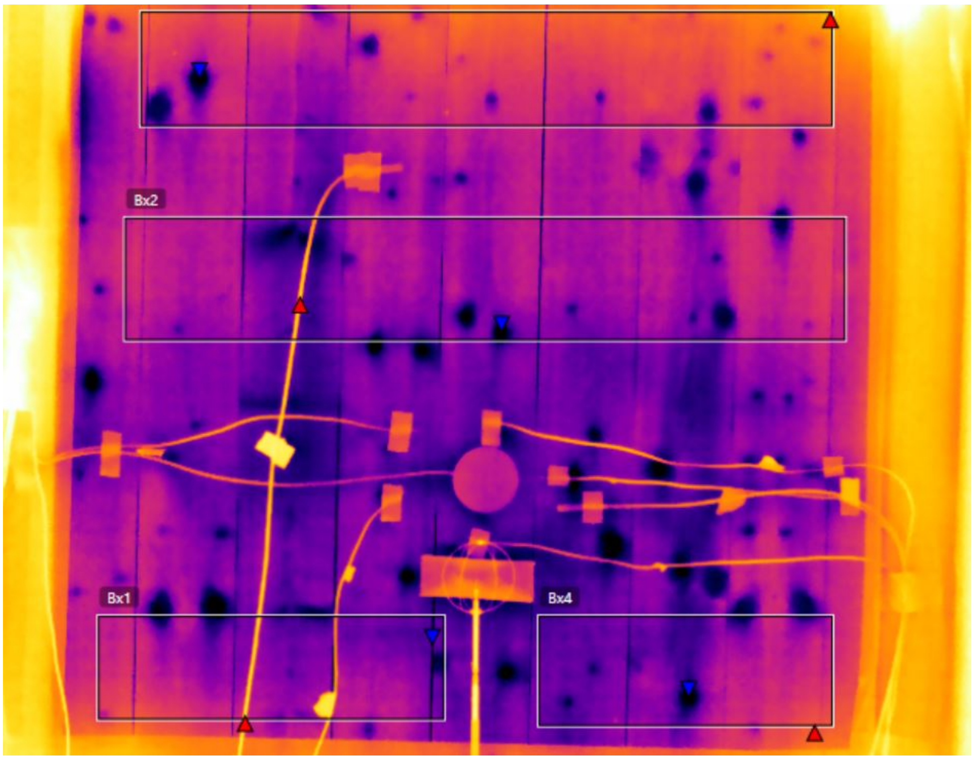


Figure 49: Thermography illustrating the detaching of thermocouples

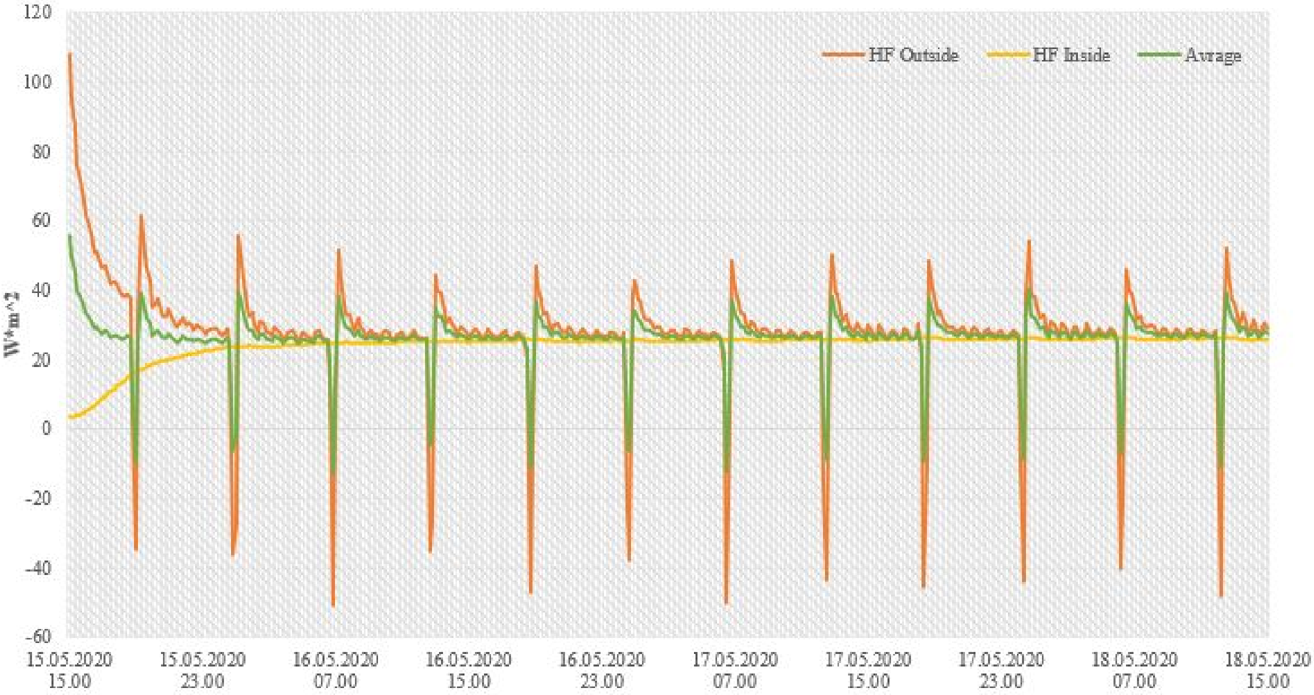


Figure 50: Measured average heat flux used for steady state λ-measurement Splitkon

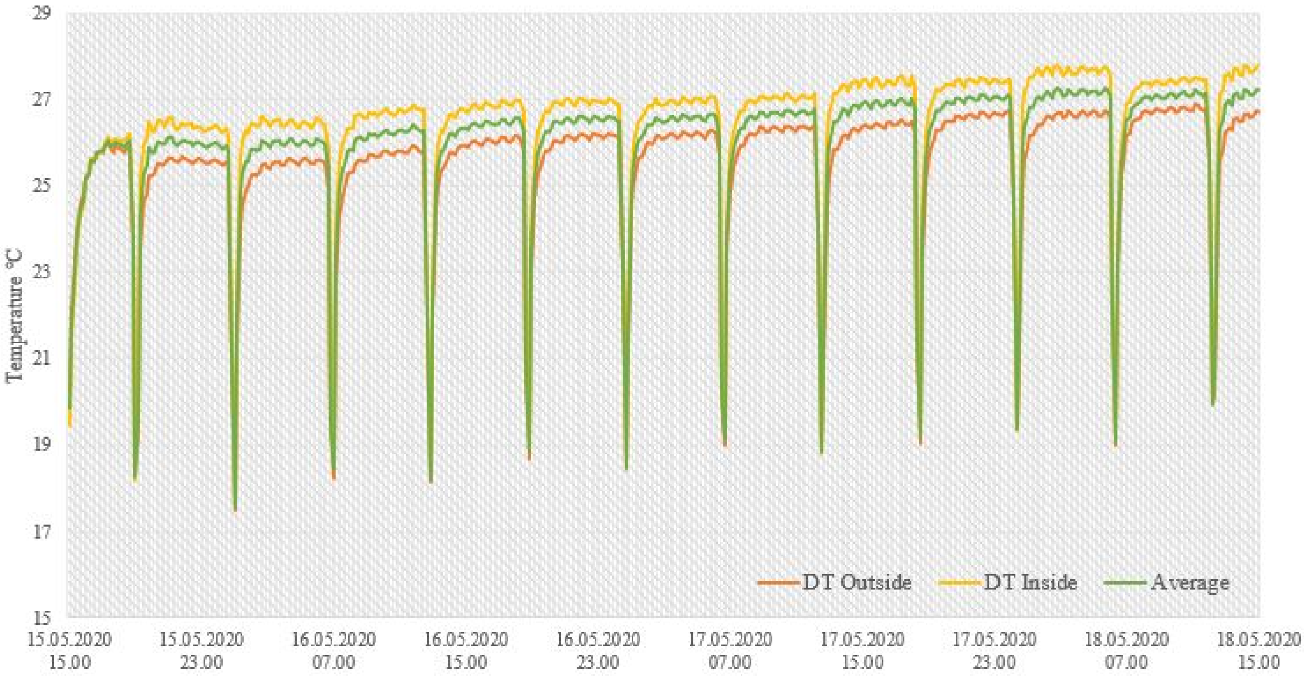


Figure 51: Average temperature differences used for steady state λ-measurement Splitkon

Calculation of the steady state λ-value was performed the same way as for the first element. The average values for the two heat flux meters, along with the surface temperature differences are presented in table 24. Note that figure 50 and figure 51 addresses the in- and outdoor average heat flux and surface temperature change parameters leading to the average used for the calculation. Estimated λ is also presented. Similar to the first element is the λ-value used to obtain a steady state thermal transmittance value for the Splitkon element.

Table 24: Splitkon λ-value and corresponding U-value parameters

HF1	HF2	DT1	DT2	R_{Se}	R_{Si}	λ
28,1	24,1	25,6	26,4	0,04	0,13	0,10

$$\lambda = 0,10 \rightarrow U - value = 0,859$$

The table 24 show noticeable outdoor and indoor heat flux differences. The outside meter record larger flux than the inside. Figure 50 illustrate significant outbreaks in the beginning of the experiment. The first 5 hours the outside heat flux drastically dropped while the indoor increased. I took twelve hours to stabilize it at the average calculation value. These first hours are partly the reason why the outdoor flux was higher. When the element is subjected to surface changed conditions, the heat obtained is released. Initial low indoor heat flux indicated that only a small amount of heat migrate through the surface. Opposite, the outside meter recorded a much higher flux. Lower indoor than outdoor measured heat flux occurred due to the mentioned heat release. In addition, warmer inside caused the heat outwards. Gradually freeing of heat provide the element the ability to store new. Figure 51 show that through the experiment the surface temperature differences increased. With the initial heat release the element slowly regain new heat, increasing the surface temperature. Significant heat flux differences lead to a higher λ-value compared to Norsk Massivtre.

4.1.2.2 Dynamic U-value

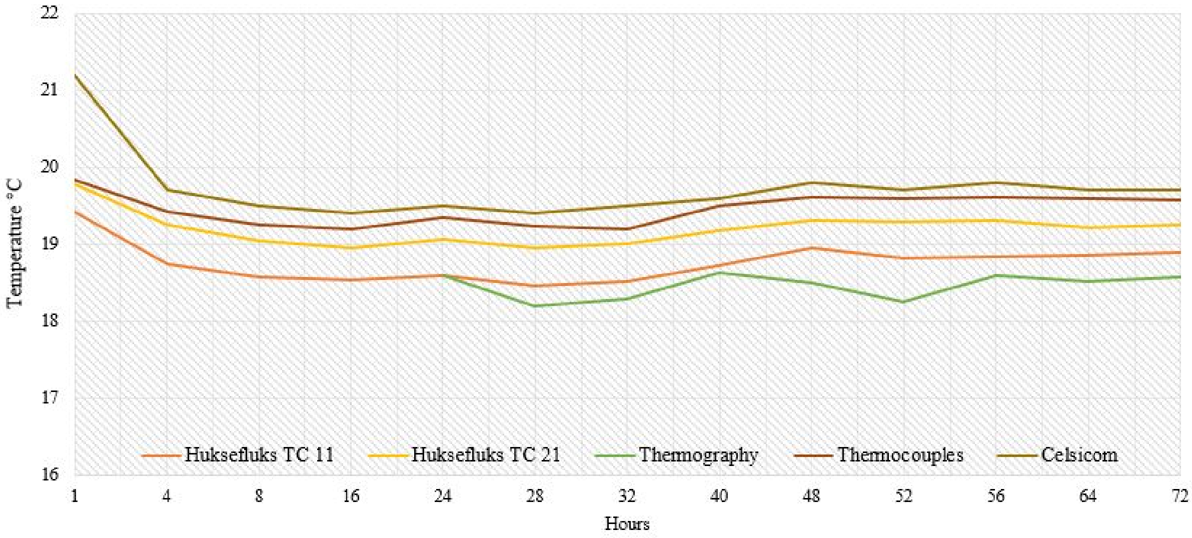


Figure 52: Indoor surface temperature comparison Splitkon

The obtained surface temperatures for the Splitkon element dynamic measurement are expressed in figure 52. Celsicom sensed the highest surface temperatures and the infrared camera the lowest. Notice that the thermography was unable to measure until the second day of the experiment. Technical issues caused the camera to turn off, not recording any temperatures the first 24 hours. The camera was turned back on during the refilling of the humidifier. It then recorded the last to days of the experiment. Note that the temperatures maintained stable throughout the entire experiment, despite a dip the first four hours. Initial escalation of relative humidity caused temperature to fall, Celsicom especially, affecting the surface temperature as shown in figure 53. The temperature descend continued until the first humidification cycle peaked, then stabilized at 19,6-19,7°C. Notice also that the same relative humidity and temperature comparison pattern reoccurs. Every humidification period the room temperature decreased, while recovering during the dehumidification period. The issues occurring for the previous experiment was clearly present for the Splitkon test.

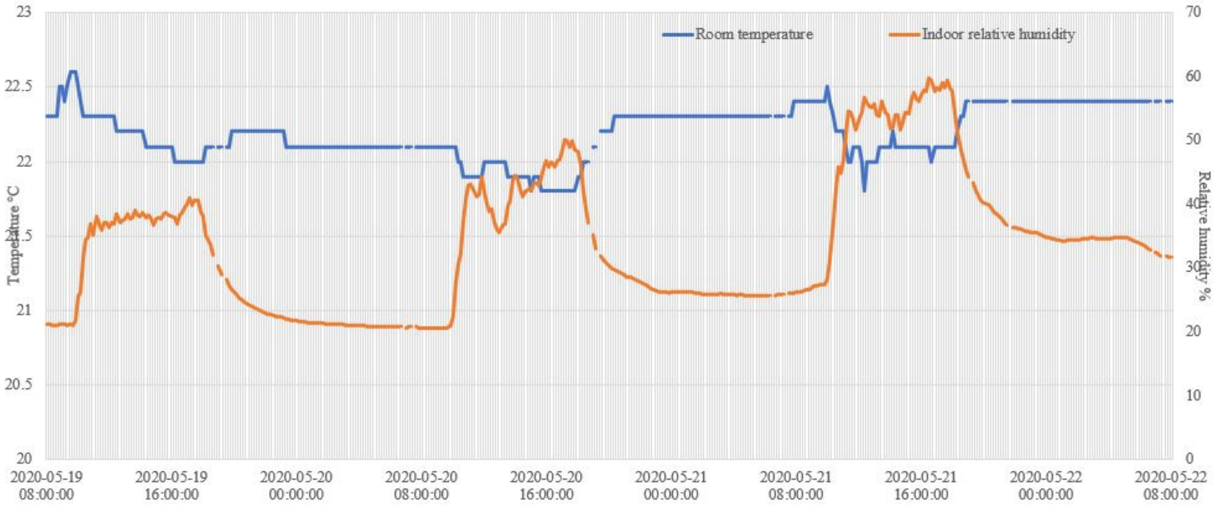


Figure 53: Room temperature and relative humidity relationship Splitkon (Celsicom)

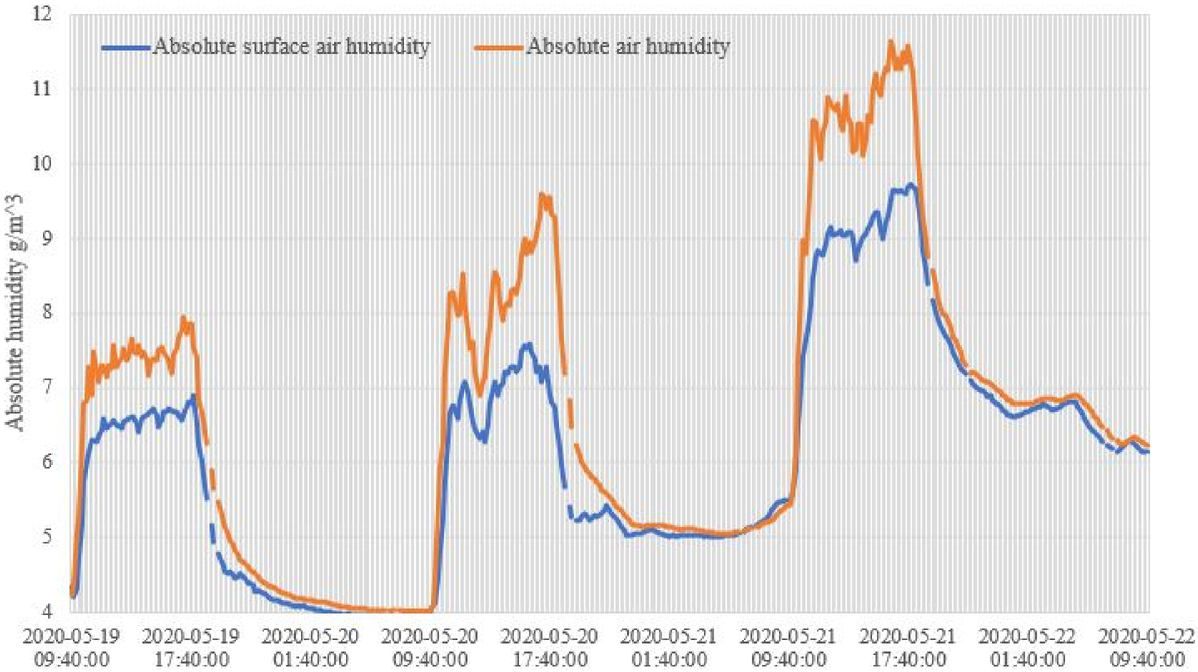


Figure 54: Surface and air absolute humidity comparison Splitkon

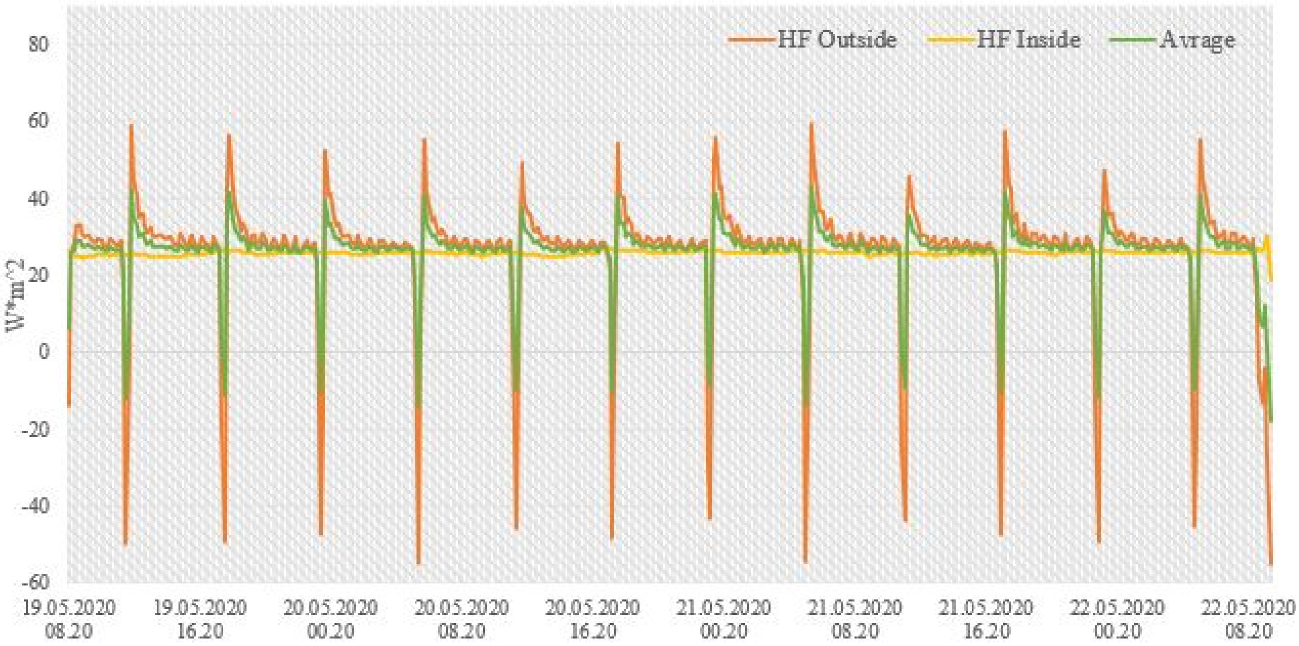


Figure 55: Measured average heat fluxes used for dynamic λ-measurements Splitkon

Figure 56: Average temperature differences for dynamic λ-measurements Splitkon

Table 25 present the heat flux values obtained through each humidification cycle with their respective temperature differences. Heat flux and temperature measurements produced new dynamic λ-values, one for each cycle. Note that the average out-facing flux measurement vary significantly more than the indoor one. This was caused by the continuously changing cold story temperature. Indoor temperature however remain stable. It is also noticed that larger heat flux indoor and outdoor variations provide a larger λ-value. New, dynamic -values induced three dynamic U-values.

Table 25: Dynamic U-value average calculation parameters Splitkon

Cycle	HF1	HF2	DT1	DT2	R_{se}	R_{si}	λ
I	26,9	25,6	26,1	27,1	0,04	0,13	0.099
II	27,3	25,9	26,2	27,2			0,100
III	25,12	25,8	26,1	27			0,096

Comparing the steady state outdoor heat flux measurements with the dynamic ones signify that the release ended during the first experiment. That being said, the three cycles still vary The earlier stated heat release continued in the dynamic part. Cycle one and two still displayed higher outdoor heat flux than indoors. However, the steady state measured alterations are reduced for each cycle. Figure 55 does not noticeably illustrate the gathering due to the considerably varying heat flux occurred. In the third cycle is the freeing sequence ended. This was the first time the solid timber element recorded higher indoor than outdoor flux. With the figure 56 showing no surface temperature change, the heat flux combined with the growing moisture content was the decisive factor for the significantly heat conductivity reduction in cycle three. Increased moisture content allow the element to absorb more moisture. Finally able to store moisture again, the element refills. More heat and moisture is absorbed, leading to the λ reduction. The new dynamic U-values obtained during the different cycles are presented in figure 57.

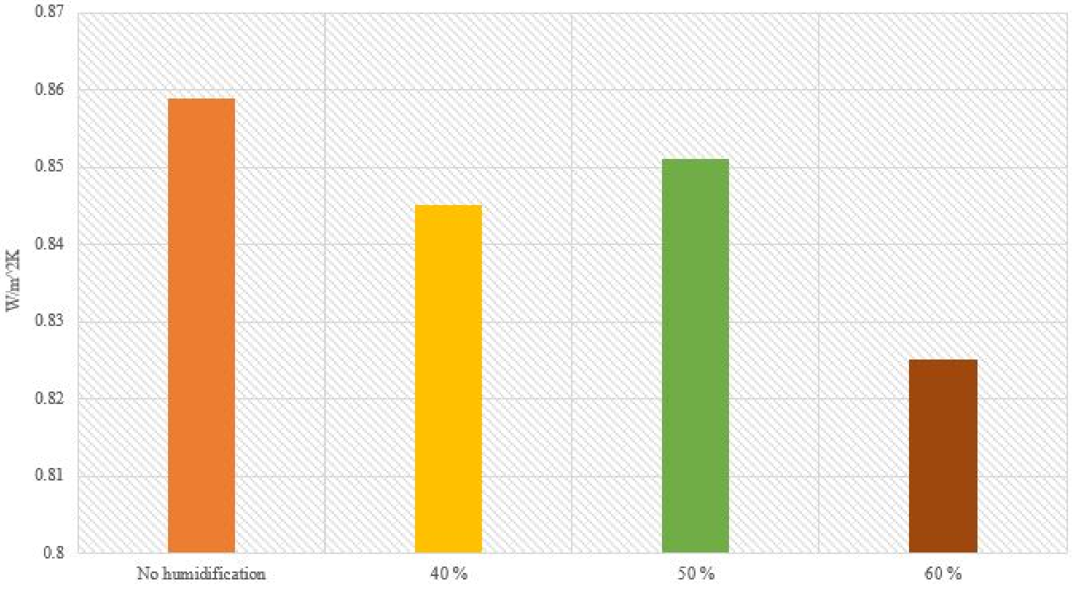


Figure 57: U-value comparison Splitkon

4.1.3 Element comparison

When performing laboratory experiment of different solid timber element is a comparison necessary. Being assembled and structured dissimilar make it interesting to match the two up against each other and evaluate the results. This section therefore consist of a steady state, dynamic and moisture buffering comparison of the two elements.

4.1.3.1 Steady state λ-value

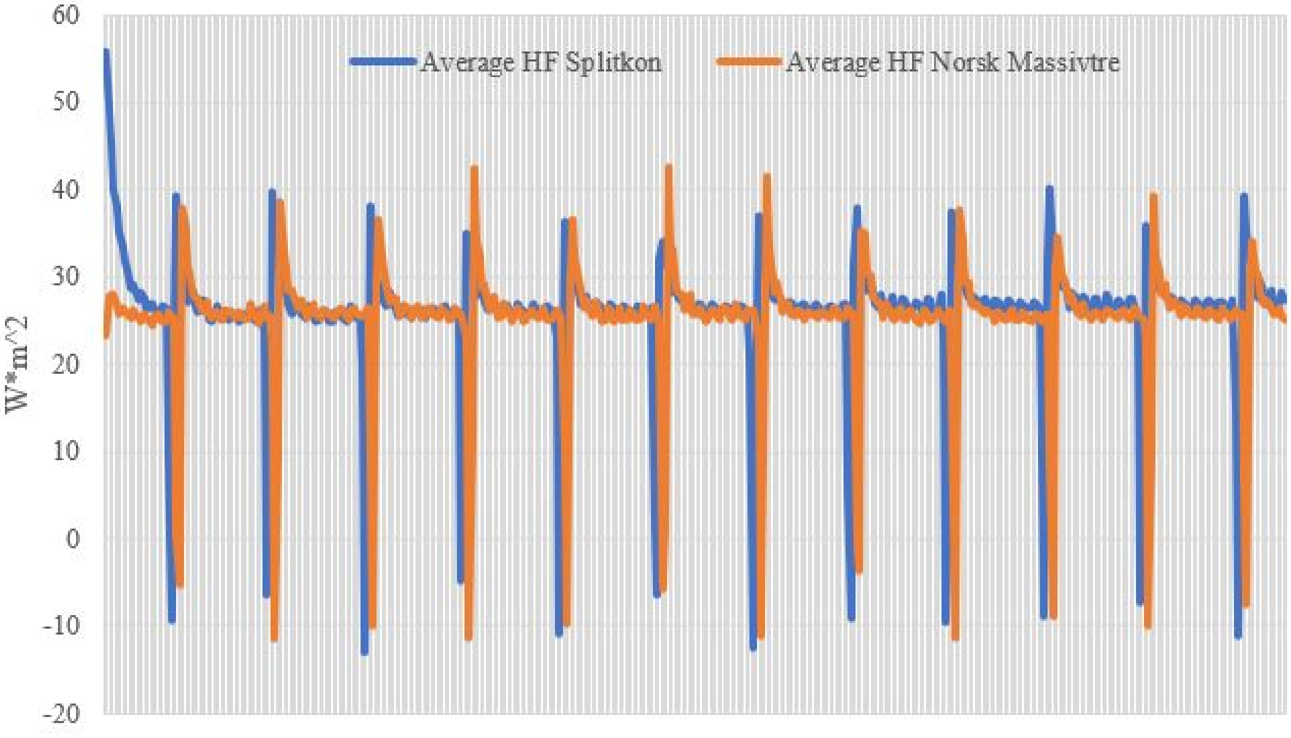


Figure 58: Measured average heat flux comparison

Figure 58 and figure 59 illustrates a comparison between the two elements steady state heat fluxes and surface temperature differences. Level experimental moisture conditions anly allow the thermal mass to initiate. The heat flux figure clearly show the difference of being exposed to the experimental conditions for a period before the test. Splitkon's heat release took place throughout the entire steady state experiment. This is also addressed in figure 59 showing initial temperature alterations. As mentioned earlier does the release affect the λ-value. That being said, structure might also influence the heat conductivity. Norsk Massivtre assembly their element with wooden screws. Splitkon however, use a special glue to attach their perpendicular layers. Connecting layers with screws allow air gaps between the layers. Glue however, fill these potential gaps. Air, having better insula-

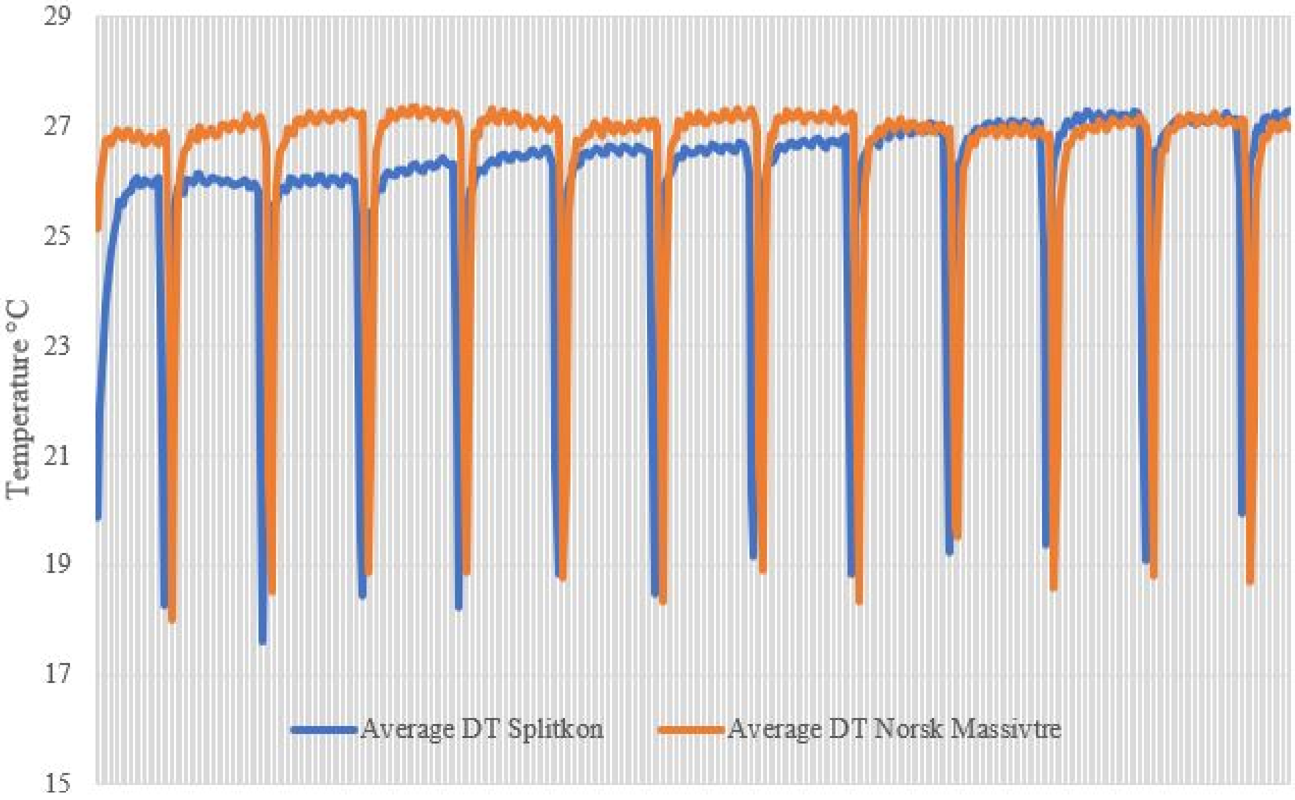


Figure 59: Average temperature differences comparison

tion abilities than glue, will therefore improve the heat conductivity of the element. Table 26 address the already mentioned heat fluxes, temperature changes and elements initial steady state λ-values. The comparison show a distinct steady state insulation advantage for the element from Norsk Massivtre.

Table 26: Steady state λ-value element comparison

Timber element	HF1	HF2	DT1	DT2	R_{Se}	R_{Si}	λ
Norsk Massivtre	24,4	26,7	26,8	26,9	0,04	0,13	0,095
Splitkon	28,1	24,1	25,6	26,4			0,10

4.1.3.2 Dynamic U-value

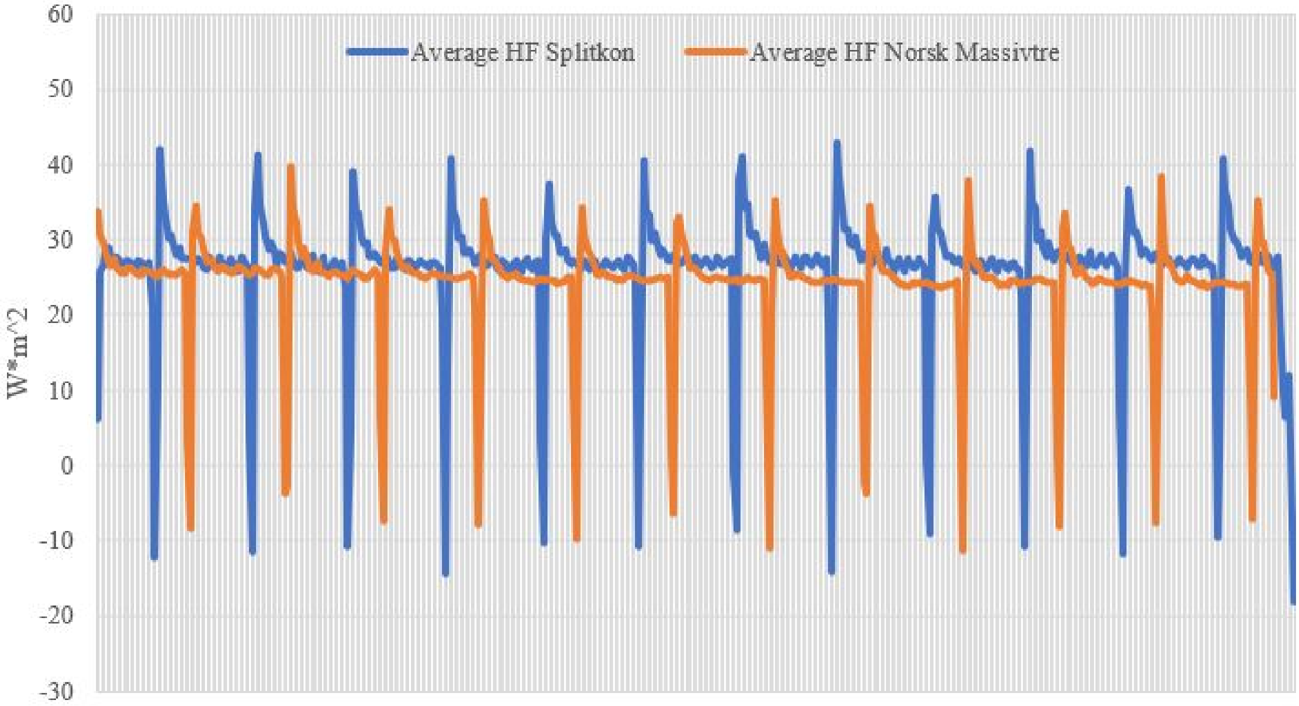


Figure 60: Measured average heat fluxe comparison

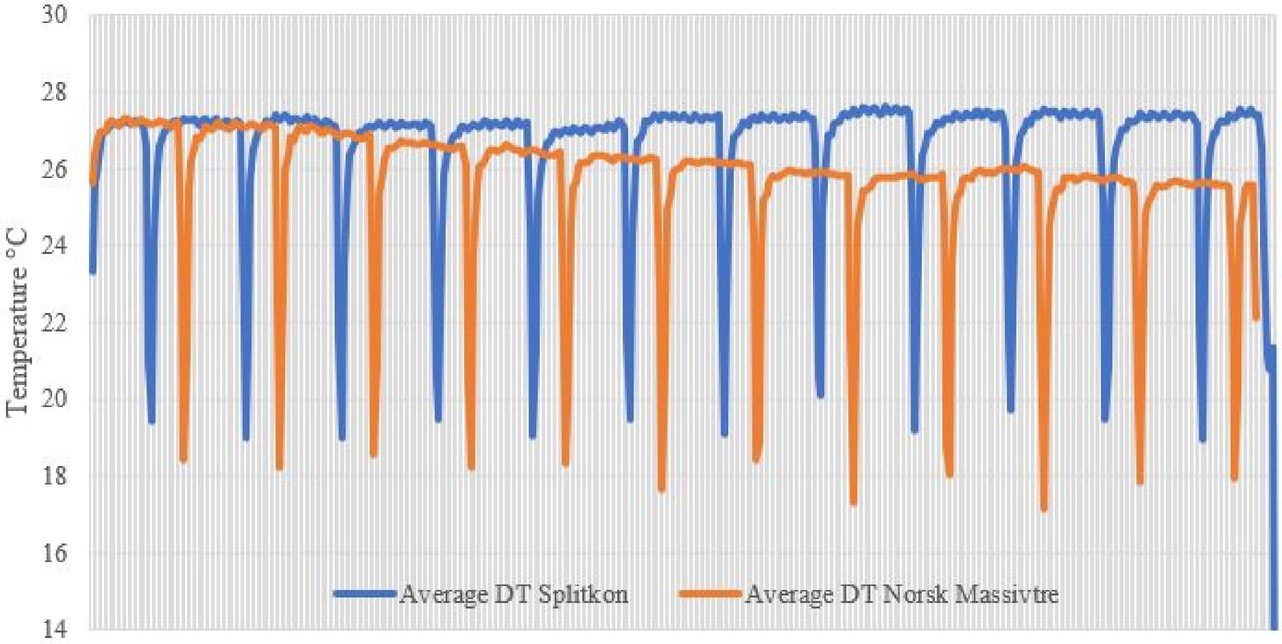


Figure 61: Average temperature differences comparison

The steady state measurements established a significant heat conductivity difference between the element. How growing moisture content affect this distinction is therefore interesting to evaluate. Supplying the room with additional moisture influence the element, initiating moisture buffering. With the increasing moisture, the heat fluxes decreases. Figure 60 expresses average heat flux values for both elements. Initially, the two elements maintains an identical heat flux. Also the surface temperatures, figure 61, are recorded to be even. The arise of the temperature problem force the elements part ways. Norsk Massivtre gradually decreased with the increased moisture content. Splikon's element however, finished the heat release before decreasing the allowed migrated heat, as table 27 state.

Table 27: Comparison of dynamic U-value calculation parameters

Timber element	Humidification	HF1	HF2	DT1	DT2	R_{Se}	R_{Si}	λ
Norsk Massivtre	I	24,2	26	26,4	26,3	0,04	0,13	0.095
	II	23,3	25,1	25,7	25,6			0,094
	III	21,9	23,8	24,3	24,3			0,093
Splitkon	I	26,9	25,6	26,1	27,1			0.099
	II	27,3	25,9	26,2	27,2			0,100
	III	25,12	25,8	26,1	27			0,096

Both elements recorded dynamic U-values that was improved with the growing moisture content in the room. The exception was the second cycle for the Splitkon element. Recording a higher outdoor flux, while still displaying equal temperature differences as the other cycles, λ increased. Improved U-value was obtained when the indoor heat flux was higher than the one outside, implying influence by moisture buffering. The temperature issues exposed the element from Norsk Massivtre with higher moisture content than intended. That being said, the U-value improvement occurring did not reflect that. Splitkon however, expressed a considerably improvement from the steady state U-value to the one obtained from the last humidification cycle. After releasing all the stored heat, the absorbed element quickly absorbed the indoor moisture, significantly reducing the U-value. In fact, the U-value difference from the steady state measurements was drastically reduced as figure 62 illustrate. Splitkon's last cycle was also the most omproved one. The element from Norsk Masivtre improved its dynamic U-value with 0,012 W/m^{2}K from steady state to 60% relative humidity. Splitkon however, saw a reduction of 0,022 W/m^{2}K.

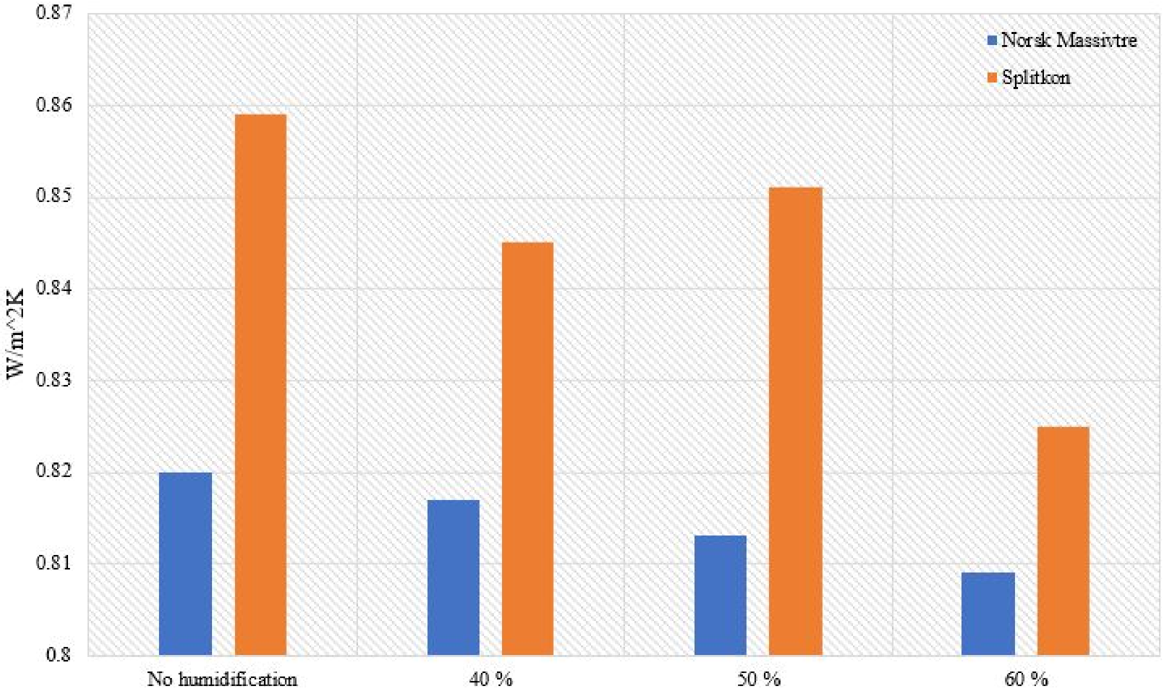


Figure 62: U-value comparison of steady state and dynamic measurements

4.2 Building Energy and Hygrothermal Simulation

Throughout the research 36 initial simulation have been performed. Three different surface examples exposed to distinctive ventilation rates, ventilation controls and humidification and dehumidification. Based on the initial results was six cases further simulated to try to optimized the buildings performance. The simulated results are presented and discussed in this section.

4.2.1 Initial simulation (36 simulations)

4.2.1.1 Overview

The simulations was divided into two main groups based on their ventilation rate. NS 3031 allows higher air flow than NS 3701, making it interesting to identify how it would influence the three exposed surfaces. Investigating the building's response to different air flow rates showed that the passive house simulations demanded an average of almost 5000 kWh less heating than the conventional building. This eventually make the passive house more energy efficient. Table 28 results addressed a significant difference between the three surface coatings. Concerning heating, the painted surface required less heating when exposed to NS 3031, for all three ventilation methods. Exposed wood was not far behind. The gypsum board however, required considerably more heat than the other two. Interestingly, changing to NS 3701 ventilation rate, the exposed wooden surface overtook the painted simulations, perform the best of the three. A reasonable explanation is that NS 3031 ventilation rate require more rapid change of air than NS 3701. Higher change rate prevent the exposed surface hygroscopic characteristics to initiate because the air is withdrawn before the wood is able to buffer moisture. It is however noticed that even with rapid air changes exposed wood performed better than the gypsum board. Gypsum board also absorb moisture, but less compared to wood. The results illustrate that a material with greater hygroscopic characteristics absorb moisture even in unfavourable conditions.

Table 28: Total heating and humidifaction/dehumidification demand for the 36 initial simulations

Standard	Ventilation control	Surface coating	Heating demand	Humidification (dehumidification)
NS 3701	CO_2 control	Exposed wood	35213,4	7468,7 (26,6)
		Gypsum board	37453,3	7390,3 (34,4)
		Paint	35248,6	7640 (62,9)
		Exposed wood	35337,6	-
		Gypsum board	37584,6	
		Paint	35349,8	
	RH control	Exposed wood	31727,2	2520,9 (0)
		Gypsum board	33946,8	2523 (0)
		Paint	31791	2673,8 (0)
		Exposed wood	31832,8	-
		Gypsum board	34029,3	
		Paint	31837,3	
	Temperature control	Exposed wood	31588,4	7037,5 (299,8)
		Gypsum board	33810,1	6661,1 (314,2)
		Paint	31669,3	7501,9 (368,5)
		Exposed wood	31583,3	-
		Gypsum board	33808,6	
		Paint	31659,5	
NS 3031	CO_2 control	Exposed wood	39706,4	10195,9 (19,9)
		Gypsum board	41949,3	10021,3 (27,1)
		Paint	39406	8993,1 (54,4)
		Exposed wood	39874,9	-
		Gypsum board	42153,7	
		Paint	39522,3	
	RH control	Exposed wood	36865,6	6151,6 (0)
		Gypsum board	39098,4	6036,4 (0,2)
		Paint	36583,2	4900,5 (0)
		Exposed wood	37193,8	-
		Gypsum board	39407,4	
		Paint	36697,5	
	Temperature control	Exposed wood	36770,8	10181,5 (193,2)
		Gypsum board	39007,6	9584,5 (207,9)
		Paint	36505,7	8935,4 (264,2)
		Exposed wood	36857,7	-
		Gypsum board	39137,3	
		Paint	36552,7	

With NS 3031 minimal ventilation requirement could influencing the hygroscopic characteristics. Also, the simulated building is constructed as a passive house. The initial results also expressing that heating demand was considerably higher for the conventional building. NS 3701 simulations was therefore further investigated. The intention was to closer evaluate the ventilation methods and affect of implementing humidification and dehumidification. Notice that these are the average values concerning the whole building when zone six, the unheated zone, is left out.

Table 29: Indoor relative humidity and humidification/dehumidification demand for the NS 3701 simulations

Ventilation control	Surface coating	Relative humidity			Humidification (dehumidification)
		Min	Max	Mean	
CO_2 control	Exposed wood	26,5	55,5	36,9	7468,7 (26,6)
	Gypsum board	26,4	55,3	37	7390,3 (34,4)
	Paint	25,7	56,1	37	7640 (62,9)
	Exposed wood	20,9	56,1	35,9	-
	Gypsum board	20,5	56,4	36	
	Paint	19	58,2	36,1	
RH control	Exposed wood	27,7	55,7	38,2	2520,9 (0)
	Gypsum board	27,5	55,5	38,3	2523 (0)
	Paint	27,1	57,9	38,2	2673,8 (0)
	Exposed wood	24	56,9	39,3	-
	Gypsum board	23,8	57	39,4	
	Paint	22,1	56,5	37,5	
Temperature control	Exposed wood	16	55,6	36,2	7037,5 (299,8)
	Gypsum board	15,7	55,5	36,4	6661,1 (314,2)
	Paint	15	57,6	36,5	7501,9 (368,5)
	Exposed wood	13,7	58,8	37	-
	Gypsum board	13,9	58,8	37,5	
	Paint	12,9	60,9	38	

The table clearly shows that the indoor relative humidity fluctuated frequently for all three ventilation methods. Temperature control provided the biggest fluctuation, while RH control the lowest. RH controlled ventilation also allow hygroscopic material to influence the indoor humidity. Smallest relative humidity variations generally occurred for less moisture resistant surface coatings expressed just that. Comparing exposed wood with gypsum board indicated that the exposed wooden surface performed better for almost all simulations. The painted surface recorded the biggest relative humidity variations. It is also the material with the highest Sd-value.

Maintaining low relative humidity variations is desirable to improve the indoor environment. Humidification and dehumidification implementation was therefore performed to keep the indoor relative humidity more stable and avoid dry indoor environment. Even with the implementation was temperature control far from maintaining fluctuations within prEN 15251:2006 design values. A building demand humid when the relative humidity drops below an assigned level. If it rises too high, dehumidification dries the building. Significant humidification and dehumidification demand therefore imply difficulty stabilizing relative humidity variations. Relatively large humidification demand provided only a small improvement for the temperature controlled ventilation. Highest humidification demand was required by the CO_2 controlled ventilation system. Unlike the temperature control, CO_2 controlled ventilation improved the relative humidity alterations the most. Despite reporting the largest humidification demand was dehumidification demand significantly lower than for temperature control. It is reasonable to believe that the CO_2 concentration reached ventilation initiation level before the relative humidity attained dehumidification level. Also notice that exposed wood demanded less drying assistance both for CO_2 and temperature controlled simulations. Smaller dehumidification demand imply less relative humidity levels above prEN 15251:2006 upper design value.

Relative humidity controlled ventilation maintained less relative humidity variation. Compared to the other controlling systems was the humidification demand considerably reduced. In addition, dehumidification demand was non existent. With drying starting at 60% and humidification at 25%, the ventilation system makes sure the relative humidity stays between these values. The table indicates that exceeding the upper level was avoided. Humidification demand however, show that the building occasionally became to dry, intruded humidification. For temperature and CO_2 control required the gypsum board less humidification. RH control however, implied smaller humidification demand for the exposed wooden surface. As earlier mentioned, wood's buffering abilities are greater than gypsum. Smaller humidification requirement thereby imply contribution of hygroscopic characteristics prevented relative humidity fluctuations.

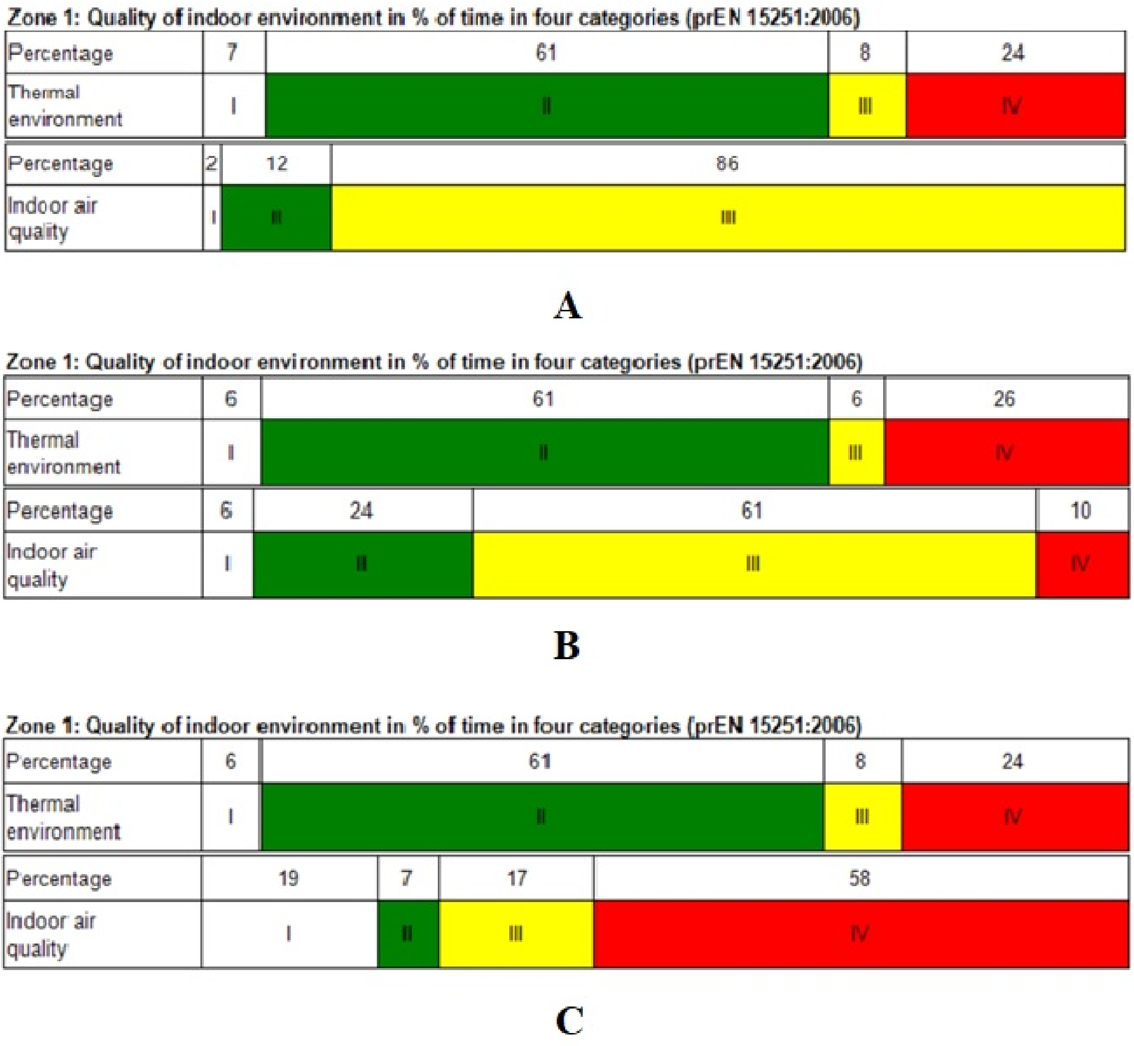
4.2.2 Interaction between exposed wood and humidification

The two tables 28 and 29 only provides a total overview of the entire building based on heating and humidification/dehumidification demand. To better understand the ventilation controlling systems' impact on the indoor environment, is it necessary to further appraise each simulation. Findings above expressed that exposed wood has the ability to perform as good as, and sometimes even better, than other surface coatings. It is therefore decided to further investigate exposed wood simulations with humidification. The tree most commonly occupied zones in the building, zone 1, 2 and 5. Results from each zone will be presented, then summarized and entirety discussed.

Before presenting the results is it necessary to readdress the four prEN 15251:2006 categories mentioned in section 3.3.7. These categories are crucial to determine the indoor environment status, and to amend it. Category IV does not satisfy the claims of securing an healthy indoor environment. The third category could at some occasions be approved, but only in small percentage. Category I and II are expressed as mandatory to secure a indoor environment that does not harm the buildings occupants.

Zone 1

First is zone 1 presented. Containing mostly offices is the indoor environment important to the schools staff. Inspecting how ventilation control impact the indoor environment shows alterations between the three. Quality of indoor environment for the first zone is presented in figure 63.



Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	61	8	24
Thermal environment	I	II	III	IV

Percentage	2	12	86
Indoor air quality	I	II	III

A

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	6	61	6	26
Thermal environment	I	II	III	IV
Percentage	6	24	61	10
Indoor air quality	I	II	III	IV

B

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	6	61	8	24
Thermal environment	I	II	III	IV
Percentage	19	7	17	58
Indoor air quality	I	II	III	IV

C

Figure 63: Indoor environment quality for zone one, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 30: Zone 1 indoor environment values

Ventilation control	Temperature		Relative humidity		Heating demand	Humidification (dehumidification)
	Min	Max	Min	Max		
CO_2	19	29,1	45,7	61,6	2558,5	0 (26,6)
RH	19	28,5	51,3	62,5	2524,4	0 (0)
Temperature	19	29,1	13,9	62,5	2469,9	29 (299,8)

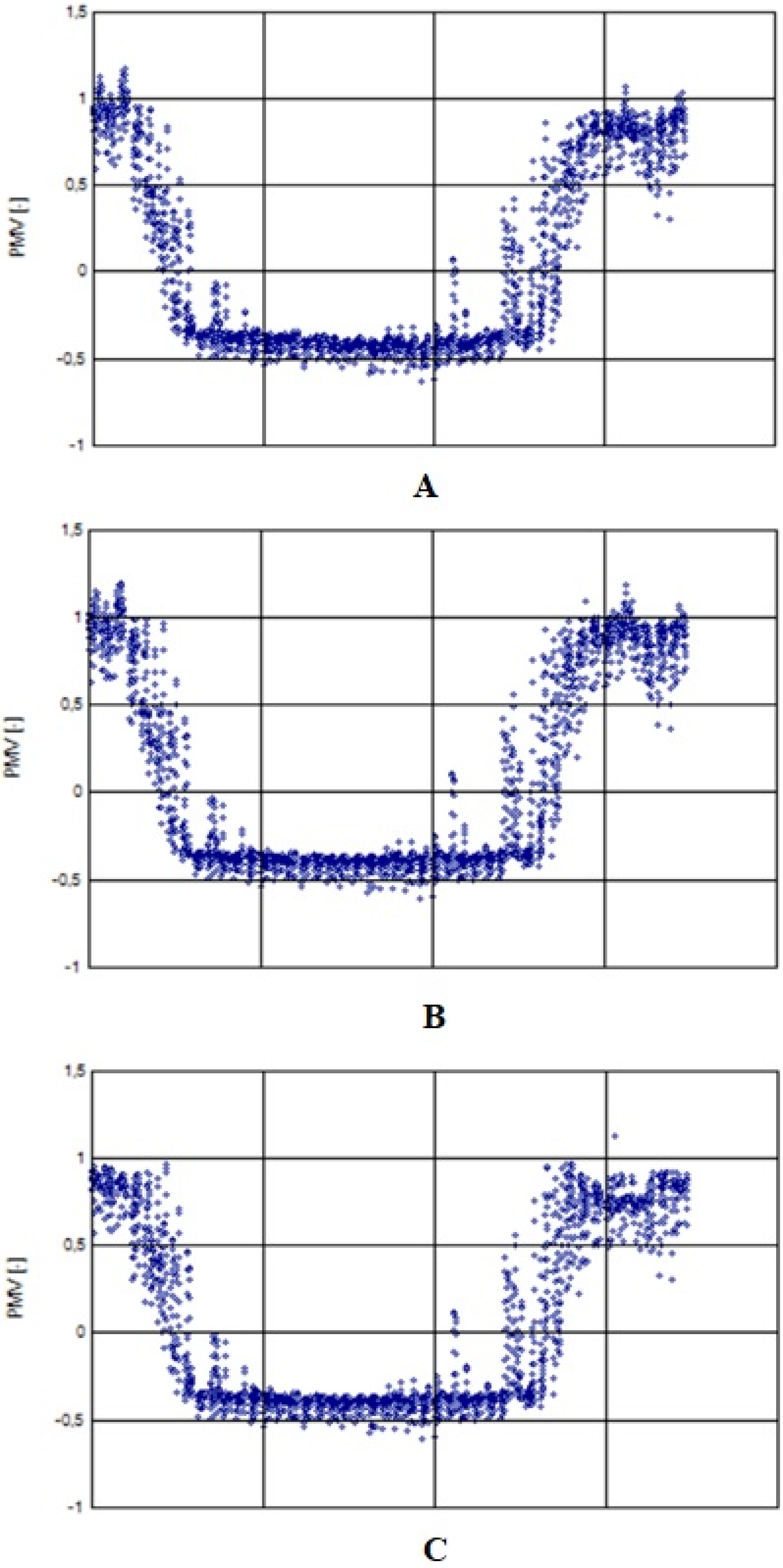


Figure 64: Zone 1 PMV:
A) CO_2 control, B) RH control, C) Temperature control

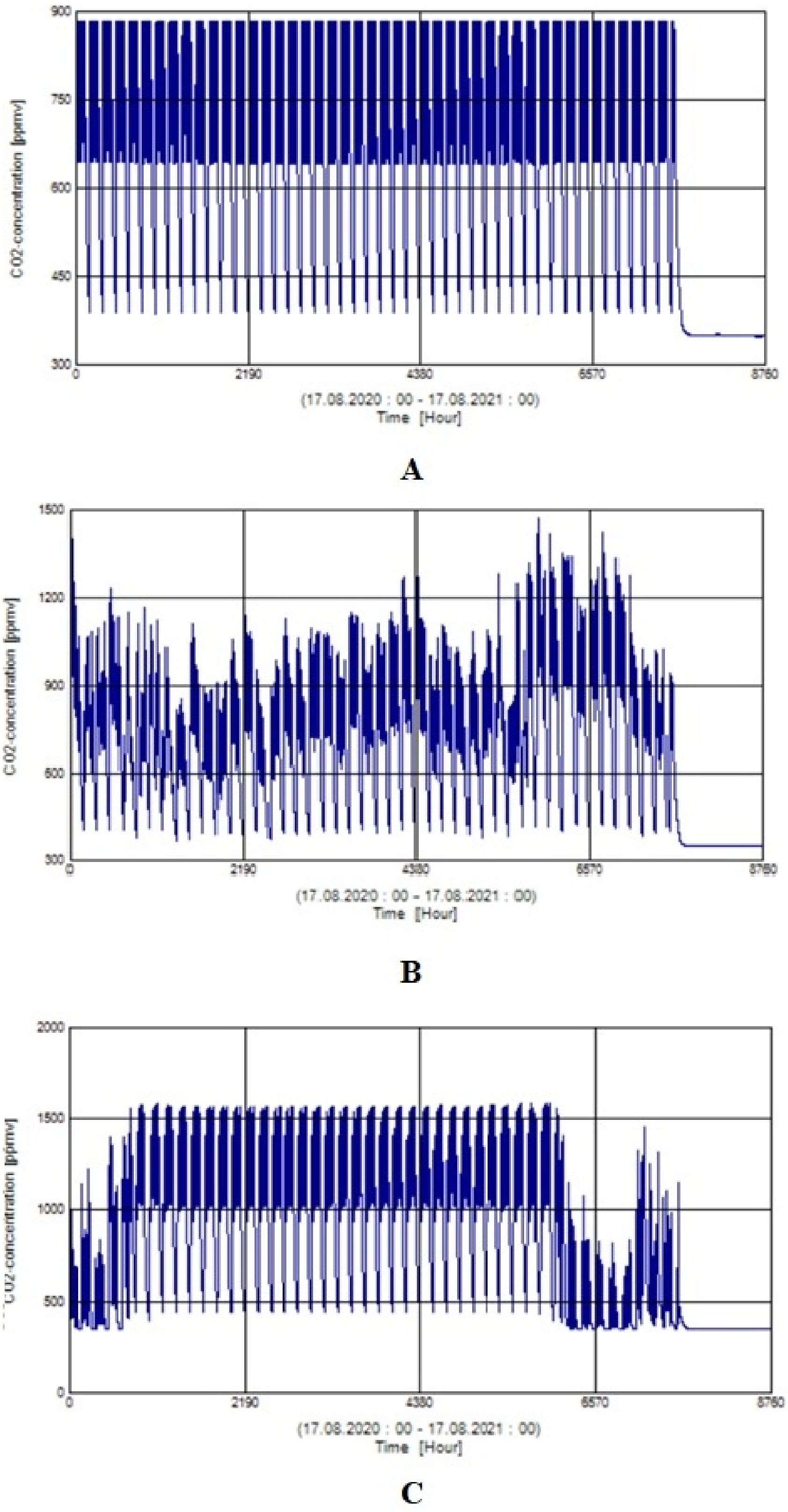
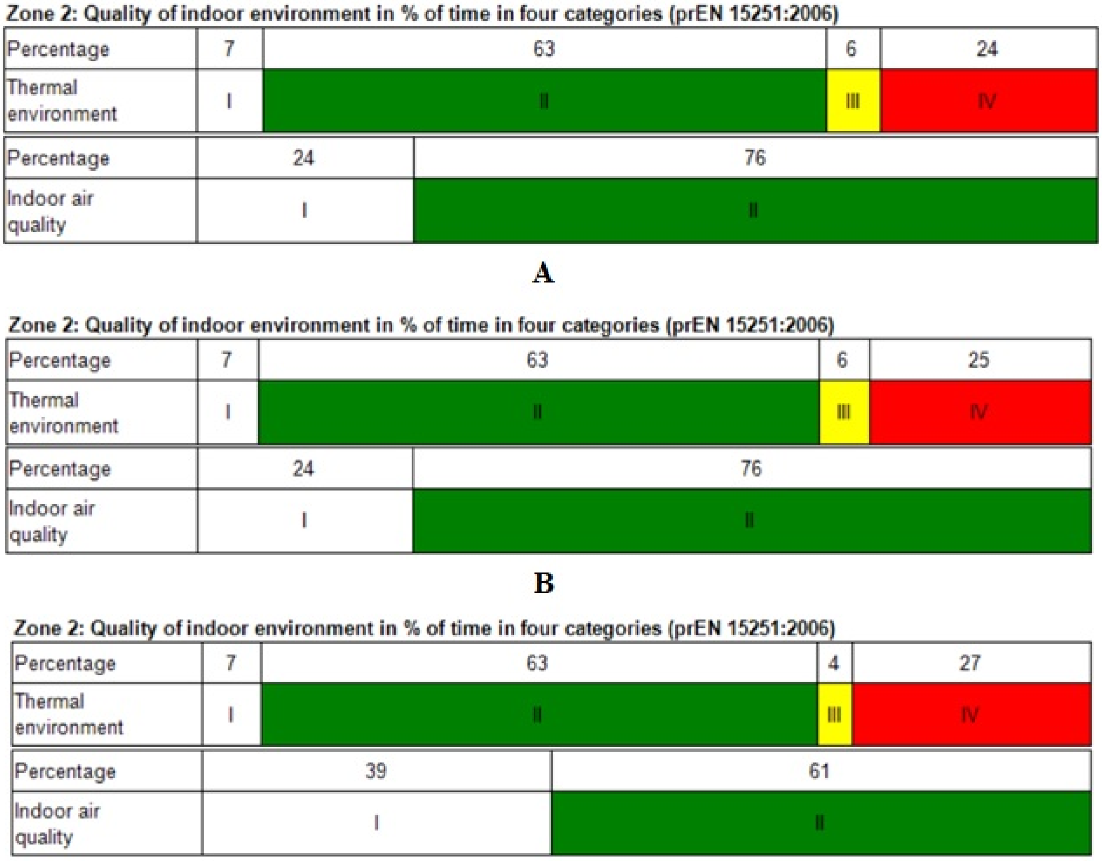


Figure 65: CO2 concentration for zone 1:
A) CO_2 control, B) RH control, C) Temperature control

Zone 2

The second zone is also the one with the smallest occupation load. It includes meeting rooms, groups rooms, hence rooms that are used infrequently. The zone is also the one with the smallest assigned activity level because of its rarely use. Nevertheless, the indoor environment and air quality is equally important as zone one. Figure 66 addresses the indoor environment quality for zone two. Comparing it to the previous zone immediately expresses alterations, most concerning the indoor air quality.



Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	63	6	24
Thermal environment	I	II	III	IV

Percentage	24	76
Indoor air quality	I	II

A

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	63	6	25
Thermal environment	I	II	III	IV

Percentage	24	76
Indoor air quality	I	II

B

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	63	4	27
Thermal environment	I	II	III	IV

Percentage	39	61
Indoor air quality	I	II

C

Figure 66: Indoor environment quality for zone two, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 31: Zone 2 indoor environment values

Ventilation control	Temperature		Relative humidity		Heating demand	Humidification (dehumidification)
	Min	Max	Min	Max		
CO_2	19	27,9	24	54,5	4947,8	504,2 (0)
RH	19	27,9	24	55	4879,2	484,7 (0)
Temperature	19	28	15,9	54,6	4863,4	1320,1 (0)

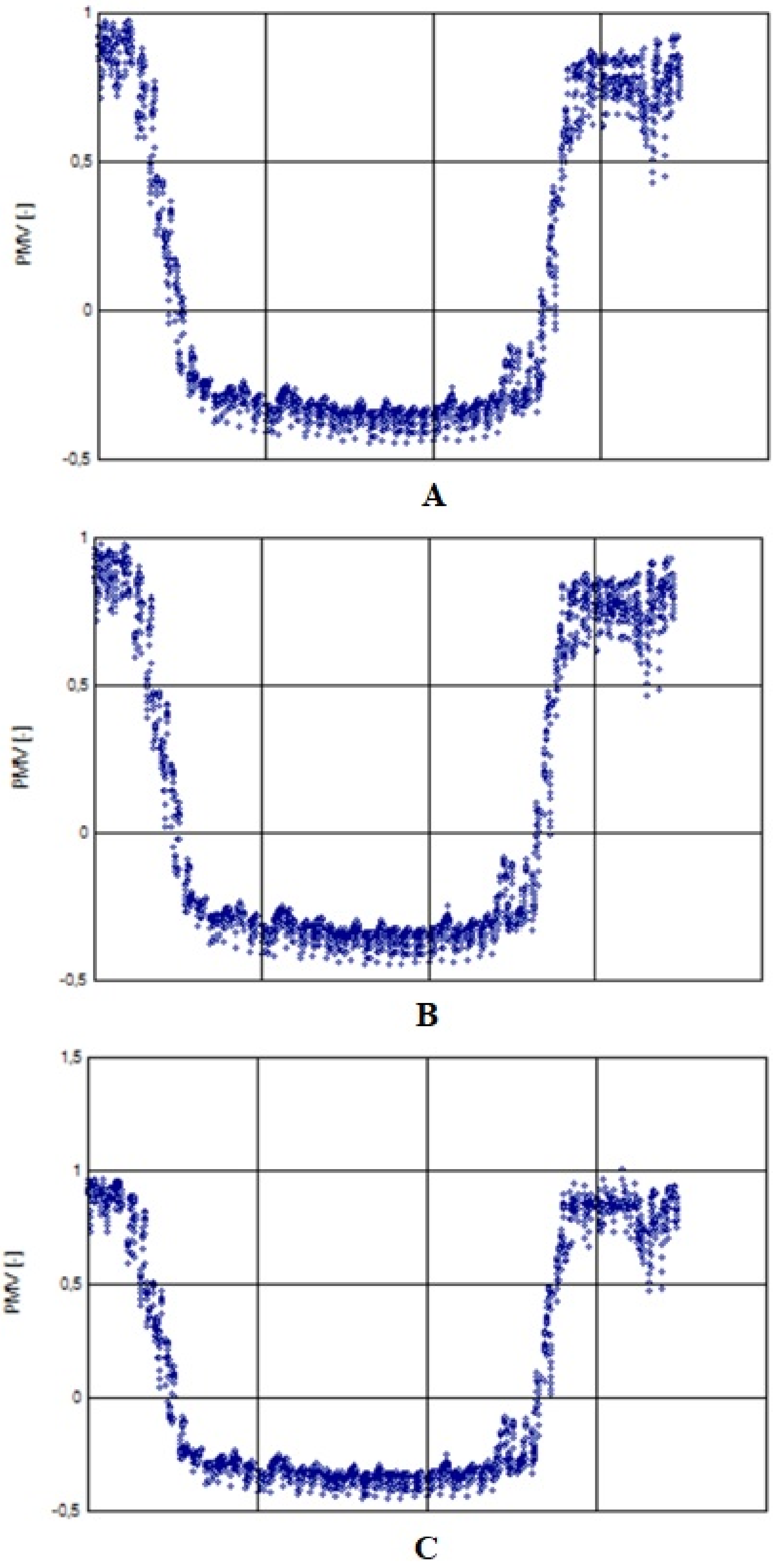


Figure 67: Zone 2 PMV:
A) CO_2 control, B) RH control, C) Temperature control

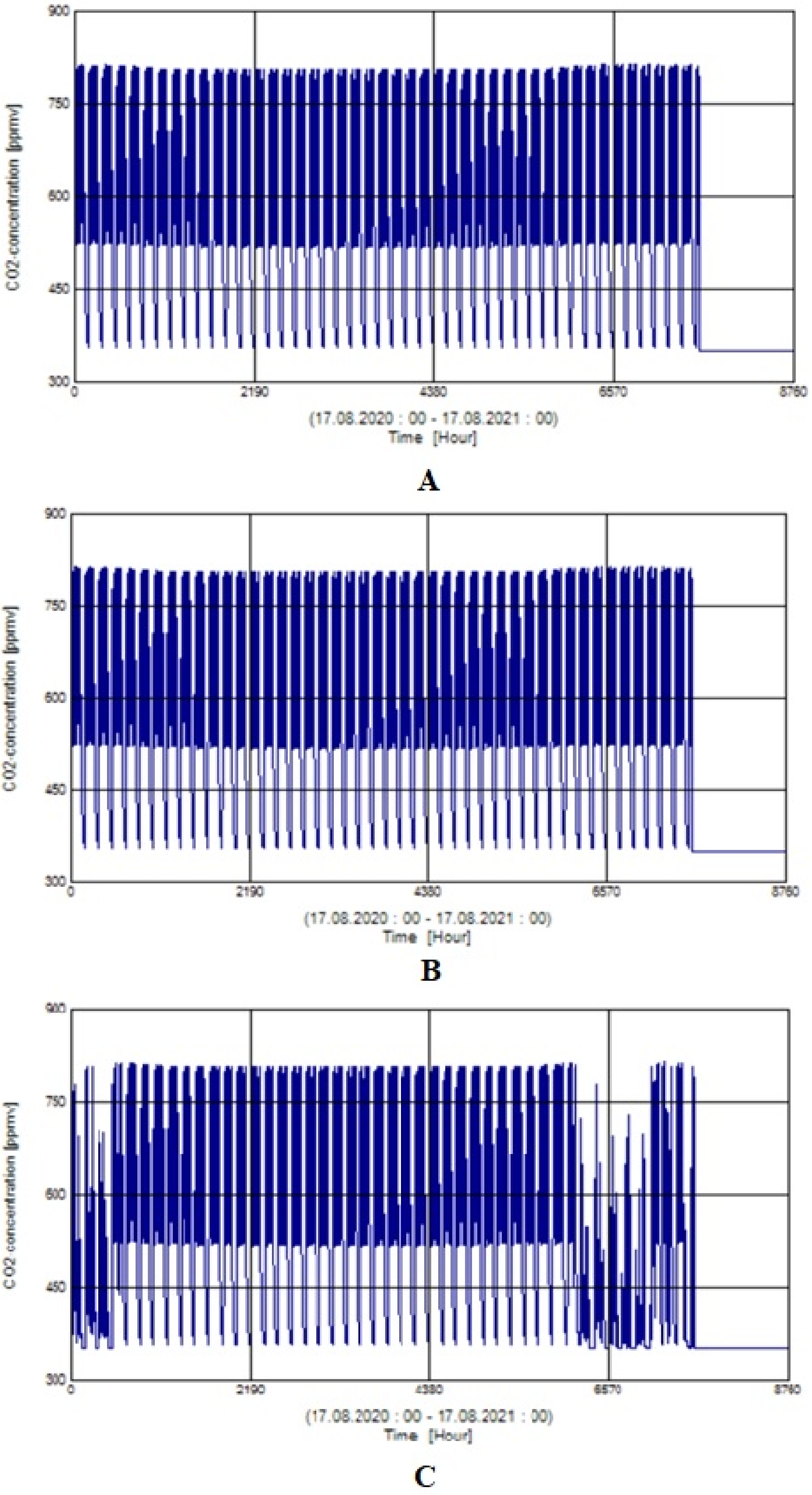
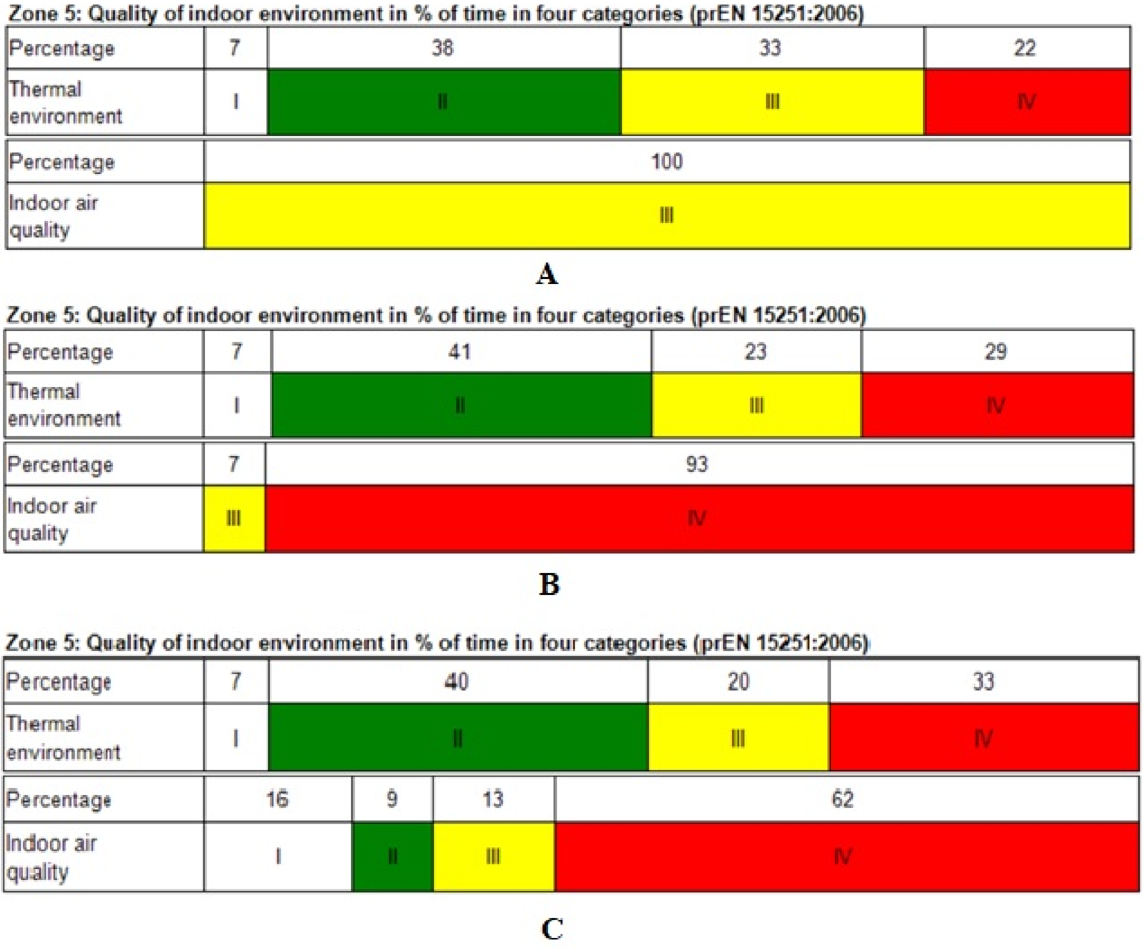


Figure 68: CO2 concentration for zone 2:
A) CO_2 control, B) RH control, C) Temperature control

Zone 5

The fifth zone is one of the most important zones. It includes all classrooms where the pupils spend most of their time during schools operational hours. High activity does affect the indoor temperature. More occupants also increases CO_2 concentration, requiring correct ventilation rate necessary. Figure 69 shows the zone distribution for the three ventilation situations.



Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	38	33	22
Thermal environment	I	II	III	IV

Percentage	100
Indoor air quality	III

A

Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	41	23	29
Thermal environment	I	II	III	IV

Percentage	7	93
Indoor air quality	III	IV

B

Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	7	40	20	33
Thermal environment	I	II	III	IV

Percentage	16	9	13	62
Indoor air quality	I	II	III	IV

C

Figure 69: Indoor environment quality for zone three, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 32: Zone 5 indoor environment values

Ventilation control	Temperature		Relative humidity		Heating demand	Humidification (dehumidification)
	Min	Max	Min	Max		
CO_2	19	28,6	20	50,2	7729,6	5286,6 (0)
RH	19	29,2	20	50,2	5077,5	786,1 (0)
Temperature	19	28,8	14,4	50,2	5068,5	3282 (0)

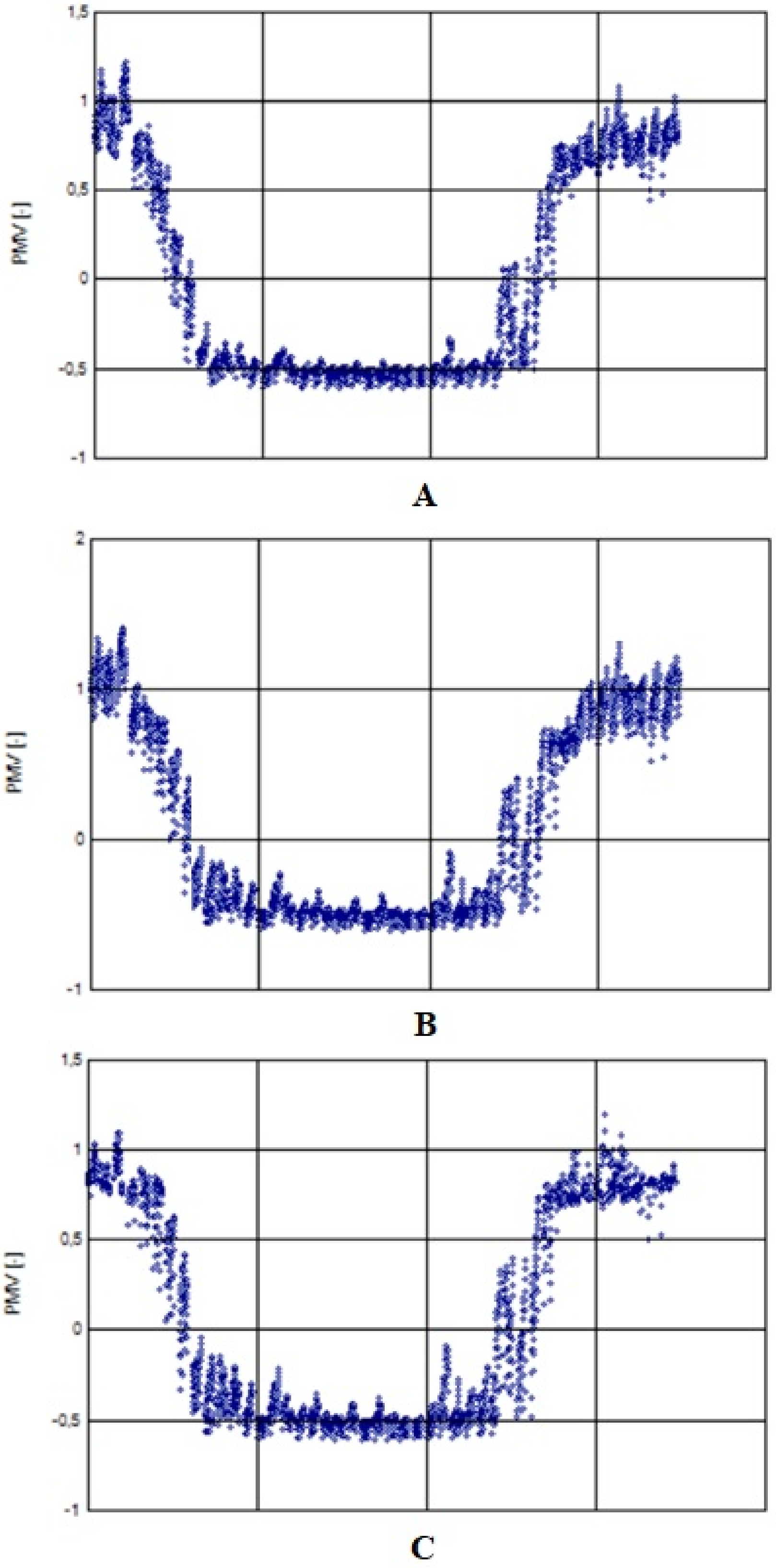


Figure 70: Zone 5 PMV:
A) CO_2 control, B) RH control, C) Temperature control

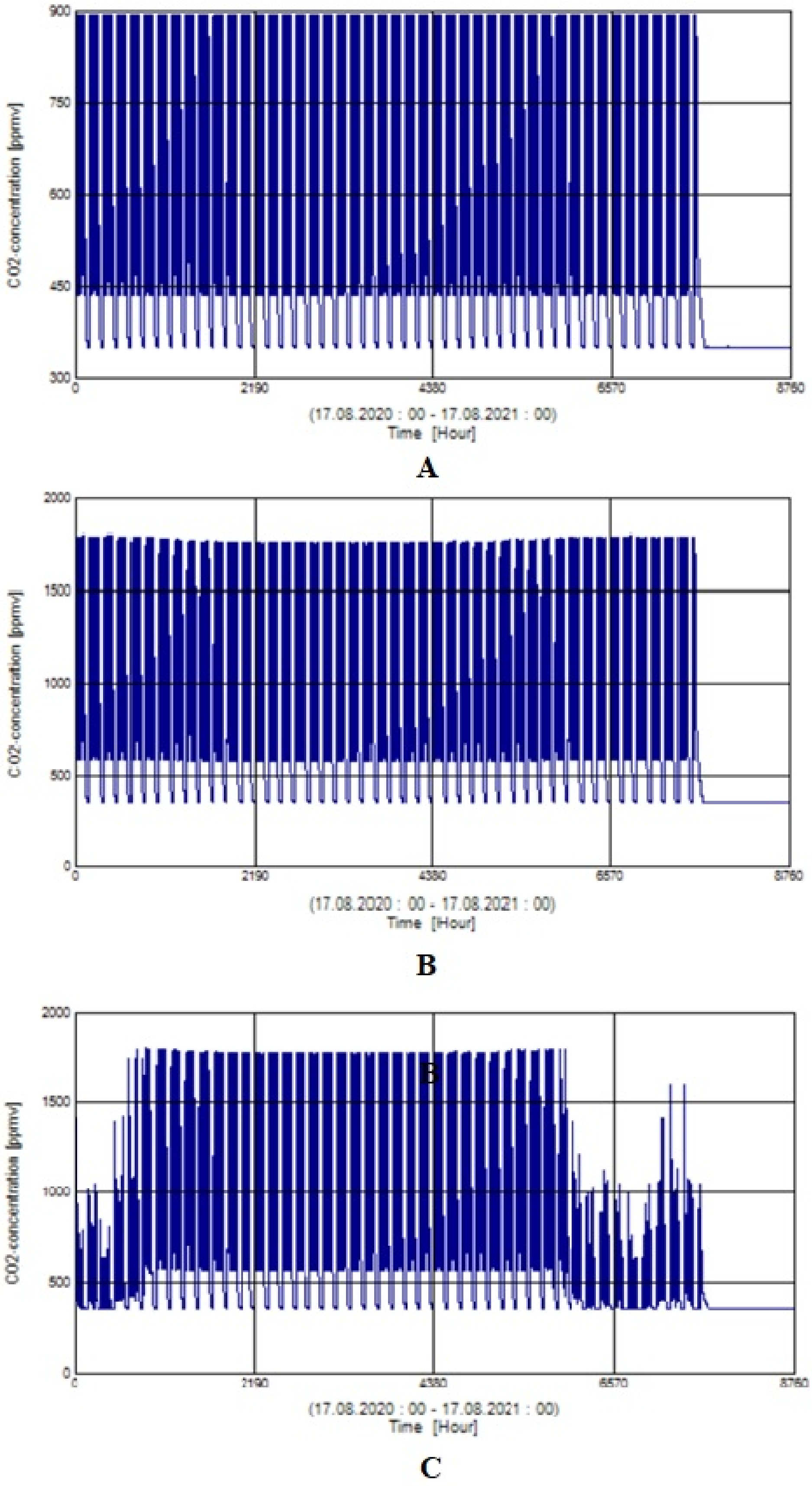


Figure 71: CO2 concentration for zone 5:
A) CO_2 control, B) RH control, C) Temperature control

Discussion

Thermal environment is decided by a number of different parameters. Air temperature, surface temperature, relative humidity, activity and clothing all impact the thermal environment. Relative humidity, activity and clothing are converted into corresponding temperatures based on prEN 15251:2006. Zone one simulated almost identical thermal environment for all controlling methods due to similar PMV, shown in Figure 64. PMV is decided by how occupants categorize the environment. Results showed that above 15% of the building's occupants felt too hot during the summer. Temperature distribution is shown in table 30. The maximum temperature exceed recommended standard value, hence noticeable category IV percentage. In addition, 10% of the occupants felt cold. Minimal temperature of 19°C is acceptable to maintain a PMV of -0,5, satisfying category II. Relative humidity also impact the thermal environment. RH controlled ventilation displayed smaller PMV fluctuations than the others. No surprise with the system being controlled to suit relative humidity design levels.

Thermal environment results from zone two implied almost identical percentages, just like zone one. Figure 67 expresses PMV within acceptable values. The small distinction separating the three controlling systems was caused by PMV scale differences. Both CO_2 and RH control maintained values under 1 PMV, while temperature control displayed values above. The distinction is caused by relative humidity alterations. CO_2 controlled ventilation provided less variations, only beating RH control by a small margin. Temperature control however, displays a solid alteration that results in increased category four. In addition, temperature control demanded significantly higher humidification.

Results concerning zone five showed the first significant thermal environment differences. Figure 69 illustrate that CO_2 controlled ventilation provided the smallest category four contribution. The largest share of category four was accounted for by the temperature control. RH control came out in the middle of the two. The indoor environmental values in table 32 expresses why. Similar to previous zones does maximum temperature exceed cooling requirements, leading to unwanted categories. Figure 70 address that RH control grew significantly above 1 PMV. Nevertheless, it displayed the low relative humidity alterations. Allowing higher minimum relative humidity increases category one and two percentages. Temperature control required less heating, but significantly more humidification than RH control. Considerably humidification demand was found both for CO_2 and temperature control. However, even with humidification assistance results came out poorly.

Evaluating the indoor air quality however, shows a distinct change for each ventilation situations for all zones. Indoor air quality is dependent air CO_2 concentration, thereby also relying on ventilation. CO_2 concentration for zone one is presented in figure 65. CO_2 control displayed the best results. With the majority of the concentration gathered around 900 ppmv is category III obtained. It is also noted that 14% of the concentration are lower than 850. 850 is the upper design level for category II.

Relative humidity control occasionally reported lower CO_2 concentration than CO_2 control. Concentration below 850 ppmv increases the environmental performance. However, RH control also exhibit the fourth unwanted category. It occurs because the concentration raised well above 1000 and peaked at 1200 ppmv. Note that the CO_2 concentration varies during the year. Less concentration occurs during the winter than warmer periods. Colder winter periods initiate the ventilation system. Increased ventilation air change withdraw substantially more CO_2 than lower air change. Temperature controlled ventilation provided the same ventilation effect, but for opposite seasons. It displayed highest concentration during the winter and less during summer periods. Therefore, temperature control displayed the highest category I percentage. However, it also recorded the highest concentration of all ventilation methods.

Zone two displayed noticeably low concentration. CO_2 controlled ventilation did not record any concentration above category three. The same occurred for the relative humidity controlled simulation. Figure 68 indicate concentration levels below 800 ppmv through the whole year for all simulations. In fact, temperature control allowed higher category one percentage due to increased ventilation air changes. Interestingly, zone two was assigned the same maximum CO_2 concentration design values as zone one. No category three and four indicate sensible ventilation rate concerning the zone's size.

One of the schools largest zones also lead to the biggest indoor air quality differences. Classrooms require good indoor air quality. Results from the simulations showed far from acceptable concentration levels. Even CO_2 controlled ventilation reached the design limit value. RH control recorded concentration levels up to 1700 ppmv. So did the temperature control. Similar to the other simulations was temperature control's CO_2 concentration reduced during the summer. Reduction resulted in 25% of the concentration within category one and two levels, best of the three.

4.2.3 Optimized simulation (6 simulations)

4.2.3.1 Overview

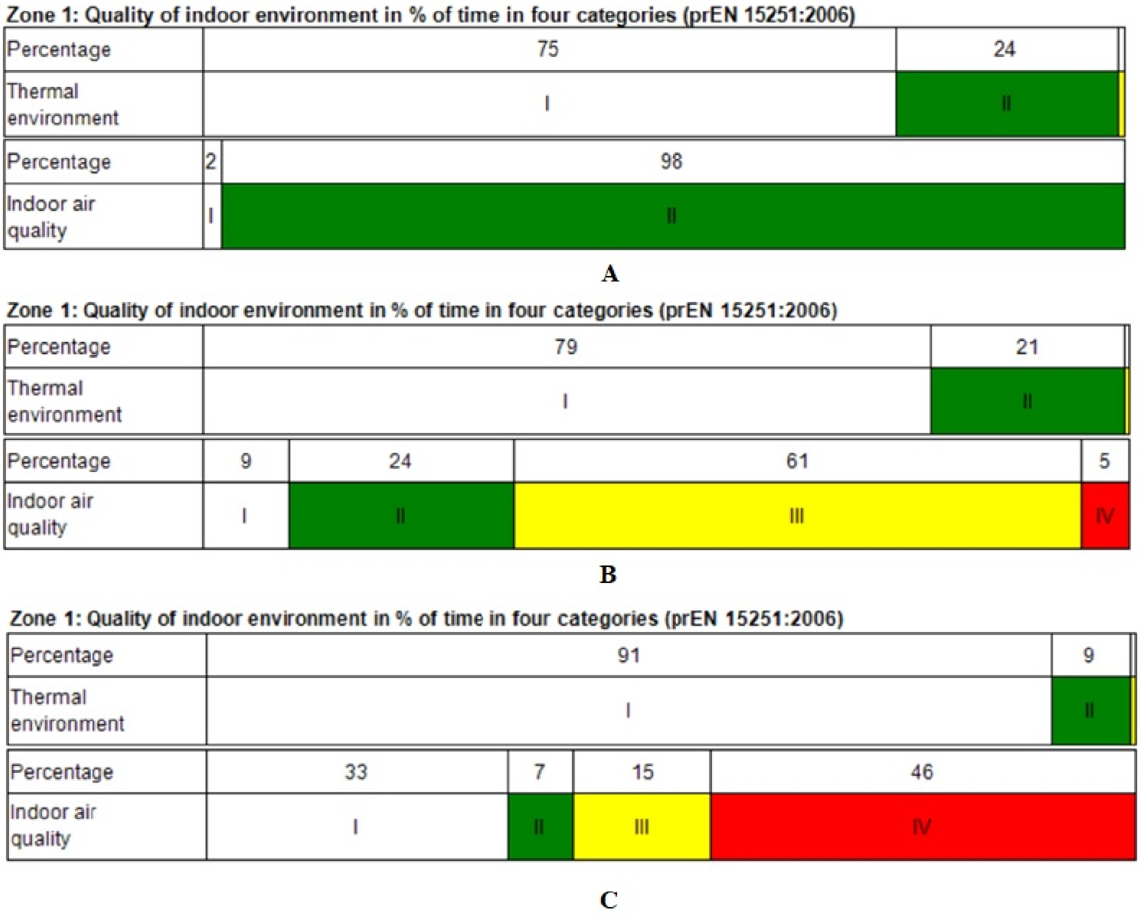
The initial simulations all had decisive issues. High temperatures and significant relative humidity fluctuations affected the thermal environment. Indoor temperatures exceeded cooling requirements without adding cooling. Low minimal and high maximum relative humidity caused the zones to be too dry and too humid. In addition, considerably CO_2 concentration levels provided the initial simulations with poorly indoor air quality. The simulations was therefore provided different optimization steps. Each step was implemented individually to investigate their impact. The first optimization step consisted of supplying cooling to the simulations. Second step assigned the ventilation system with moisture recovery. In addition, the optimization also included a CO_2 concentration reduction from 900 ppmv to 850 ppmv. It was done prior to both steps. Table 33 introduce the affects of the different optimization steps. Similar to the initial exposed wood simulation, are also the optimizations steps further investigated. The significance of each optimization step are therefore carefully evaluated in this section to spot the pros and cons of the step.

Table 33: Exposed wood optimization steps compared to initial simulation for the three zones

Ventilation control	Zone	Optimization	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
			Min	Max	Min	Max			
CO_2 control	1	Initial	19	29,1	45,7	61,6	2558,5	0	0 (26,6)
		Cooling	19	30	44,1	61,4	2759	242,8	0 (33,5)
		Moisture recovery	19	30	52,1	63,4	2728,5	247	0 (760,8)
	2	Initial	19	27,9	24	54,5	4947,8	0	504,2 (0)
		Cooling	19	29,8	24,1	56,3	5449,6	276,5	252,8 (0)
		Moisture recovery	19	30	33,5	51,5	5369,9	287,9	12,5 (0)
	5	Initial	19	28,6	20	50,2	7729,6	0	5286,6 (0)
		Cooling	19	30	20	56,3	9144,5	2389	5904,8 (0)
		Moisture recovery	19	30	28	60	9071,4	2580,2	0 (0,4)
RH control	1	Initial	19	28,5	51,3	62,5	2524,4	0	0 (0)
		Cooling	19	30	50,9	62,8	2703,4	243,4	0 (0,1)
		Moisture recovery	19	30	52	63,4	3074	202,7	0 (57,6)
	2	Initial	19	27,9	24	55	4879,2	0	484,7 (0)
		Cooling	19	29,8	24,1	56,3	5425,7	275,2	252,1 (0)
		Moisture recovery	19	29,9	33,8	51,5	5327,9	284,4	11,8 (0)
	5	Initial	19	29,2	20	50,2	5077,5	0	786,1 (0)
		Cooling	19	30	20	56,4	5760,8	3506,1	616,6 (0)
		Moisture recovery	19	30	41,6	60,6	5605,7	3705,4	0 (84,2)
Temperature control	1	Initial	19	29,1	13,9	62,5	2469,9	0	29 (299,8)
		Cooling	19	30	20,7	62,8	2608,8	119	0,8 (197,6)
		Moisture recovery	19	30	40	66,4	2630,1	135,7	0 (582,1)
	2	Initial	19	28	15,9	54,6	4863,4	0	1320,1 (0)
		Cooling	19	30	17,4	51,9	5386,1	147,9	672,6 (0)
		Moisture recovery	19	30	25,6	50,9	5287,1	138,2	12,2 (0)
	5	Initial	19	28,8	14,4	50,2	5068,5	0	3282 (0)
		Cooling	19	30	13,5	53,6	5680,5	2893,6	1984,3 (0)
		Moisture recovery	19	30	27,7	60,5	5469,3	2947,6	0 (3,2)

4.2.3.2 Cooling optimization without moisture recovery

Zone 1



Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	75	24
Thermal environment	I	II

Percentage	2	98
Indoor air quality	I	II

A

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	79	21
Thermal environment	I	II

Percentage	9	24	61	5
Indoor air quality	I	II	III	IV

B

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	91	9
Thermal environment	I	II

Percentage	33	7	15	46
Indoor air quality	I	II	III	IV

C

Figure 72: Indoor environment quality for zone 1 with cooling, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 34: Zone 1 indoor environment values with cooling

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	30	44,1	61,4	2759	242,8	0 (33,5)
RH	19	30	50,9	62,8	2703,4	243,4	0 (0,1)
Temperature	19	30	20,7	62,8	2608,8	119	0,8 (197,6)

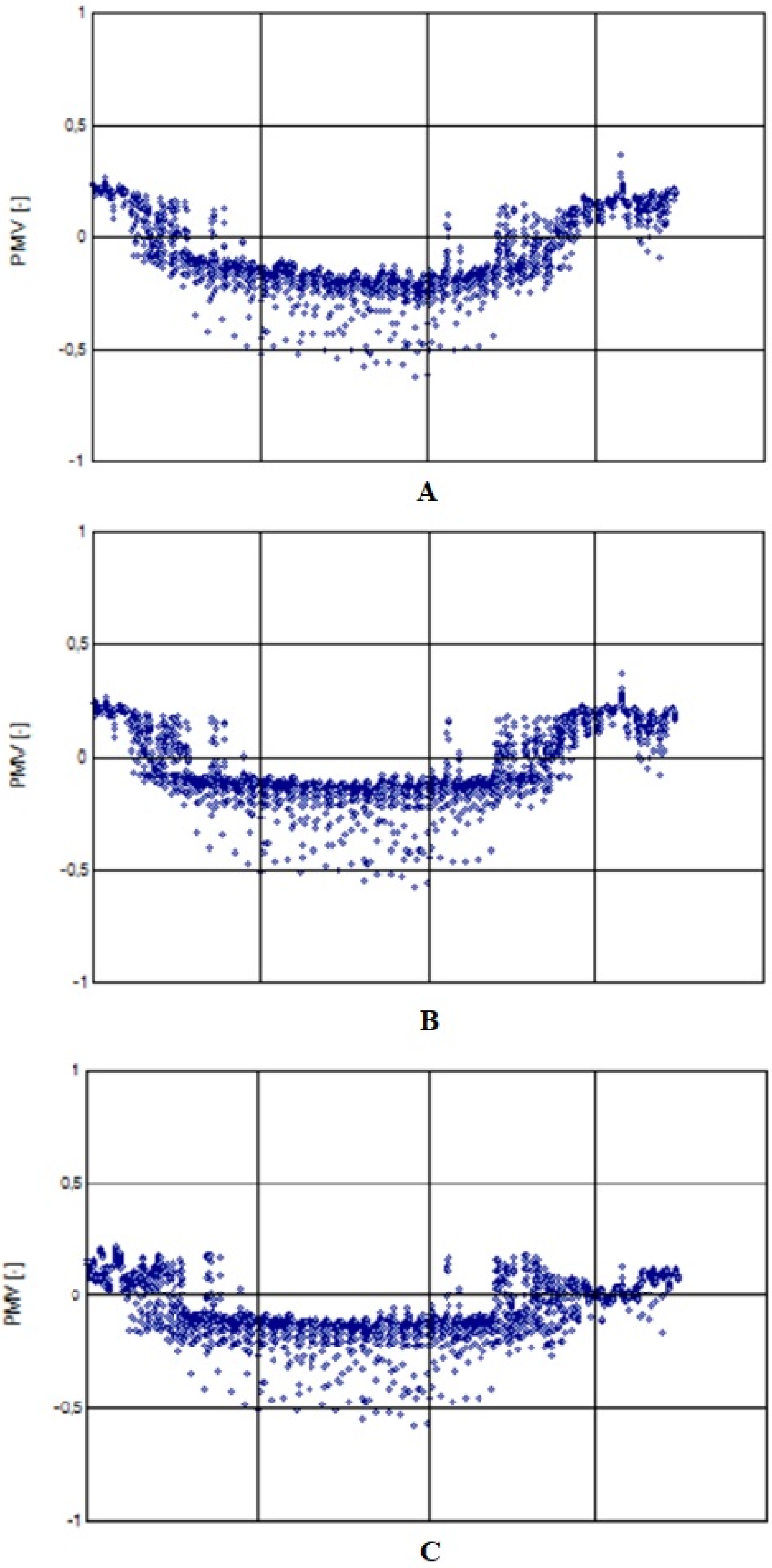


Figure 73: Zone 1 PMV with cooling:
A) CO_2 control, B) RH control, C) Temperature control

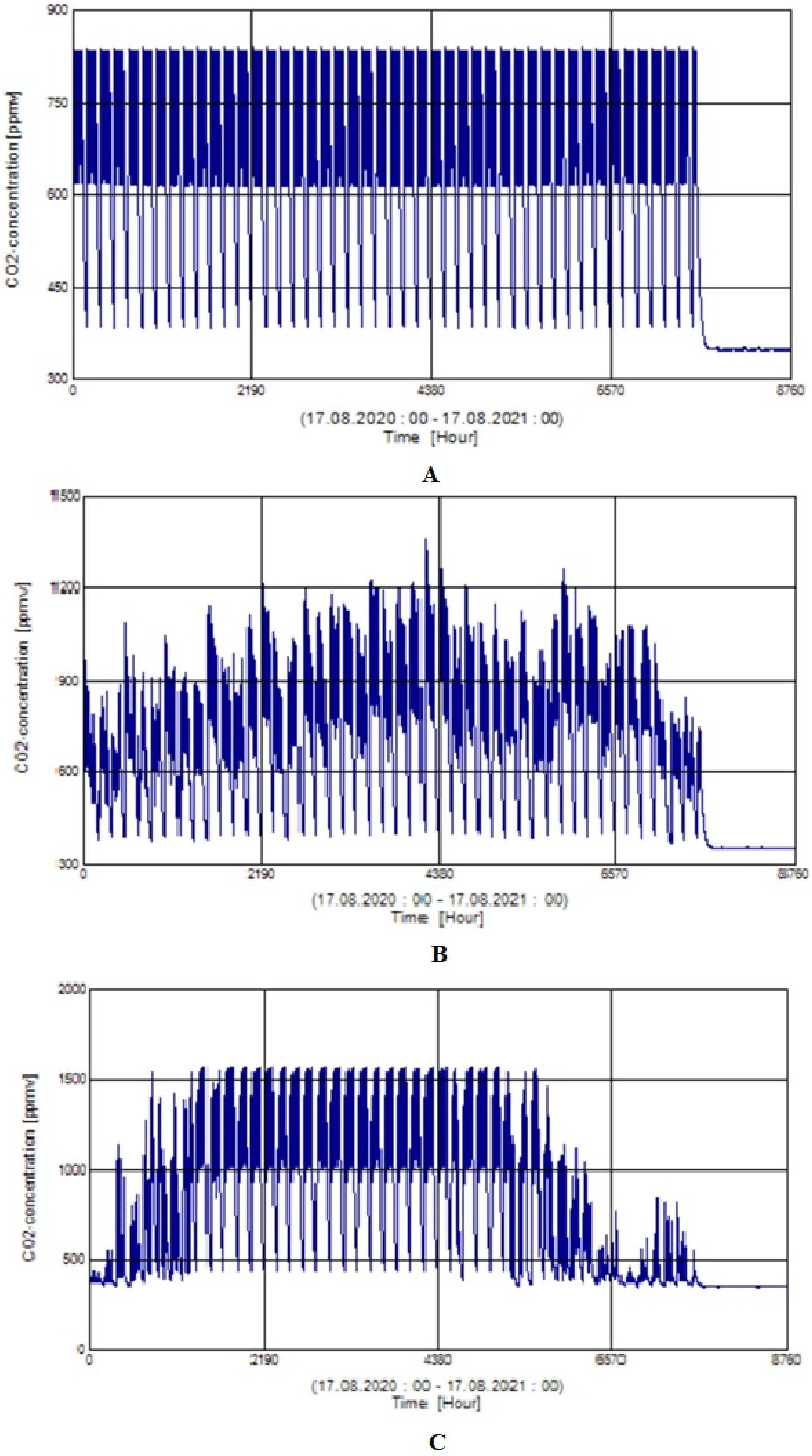
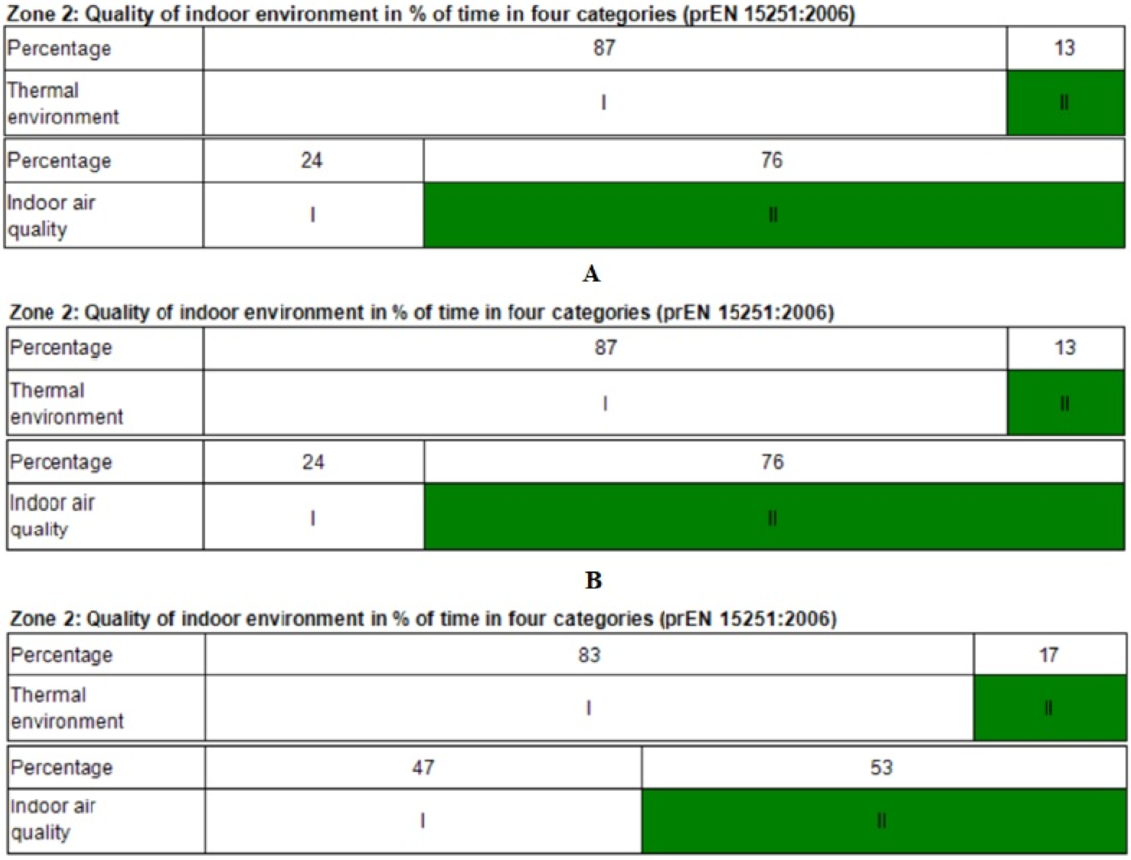


Figure 74: CO2 concentration for zone 1 with cooling:
A) CO_2 control, B) RH control, C) Temperature control

Zone 2



Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	87	13
Thermal environment	I	II

Percentage	24	76
Indoor air quality	I	II

A

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	87	13
Thermal environment	I	II

Percentage	24	76
Indoor air quality	I	II

B

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	83	17
Thermal environment	I	II

Percentage	47	53
Indoor air quality	I	II

C

Figure 75: Indoor environment quality for zone 2 with cooling, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 35: Zone 2 indoor environment values with cooling

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	29,8	24,1	56,3	5449,6	276,5	252,8 (0)
RH	19	29,8	24,1	56,3	5425,7	275,2	252,1 (0)
Temperature	19	30	17,4	51,9	5386,1	147,9	672,6 (0)

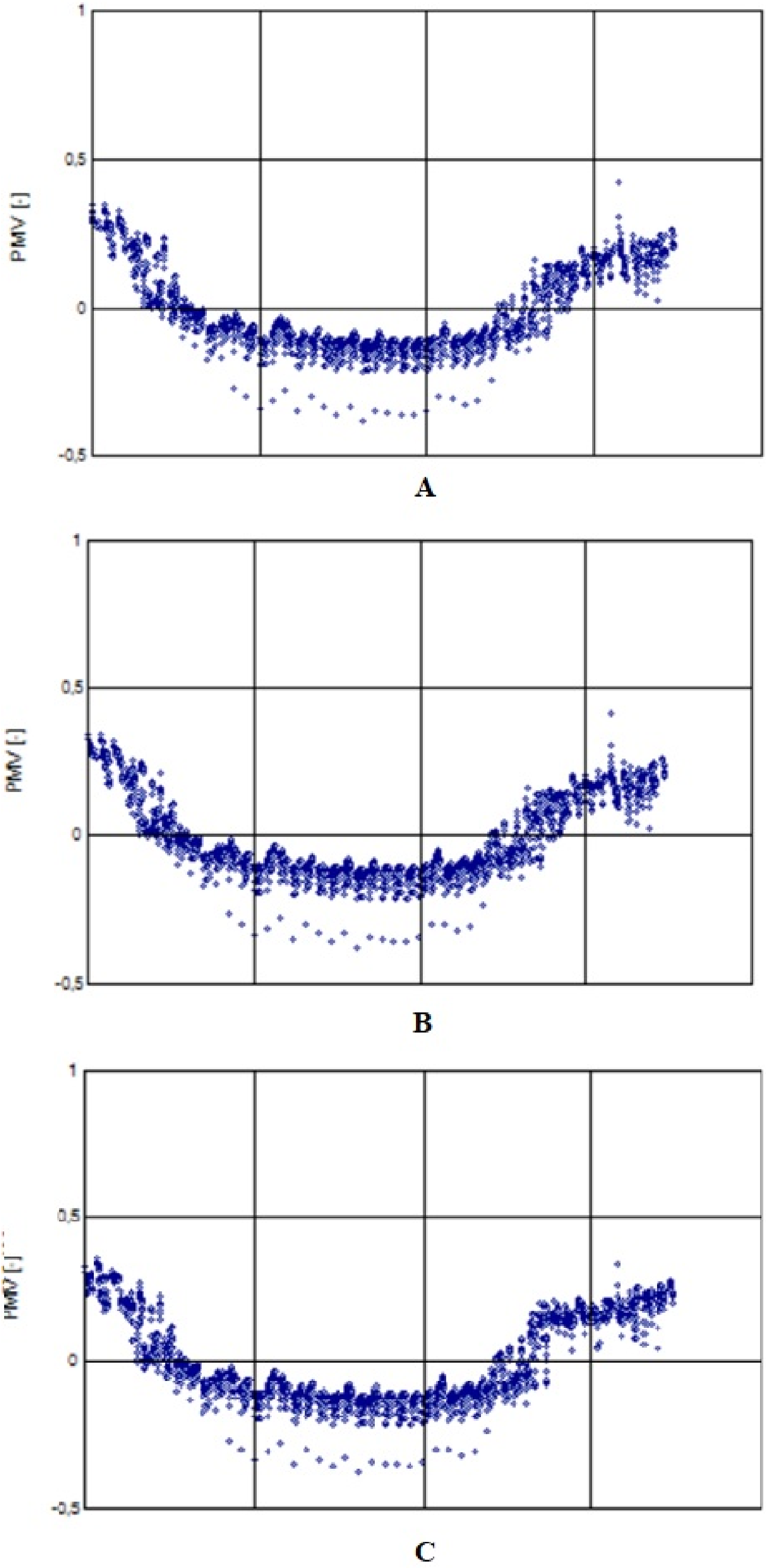


Figure 76: Zone 2 PMV with cooling:
A) CO_2 control, B) RH control, C) Temperature control

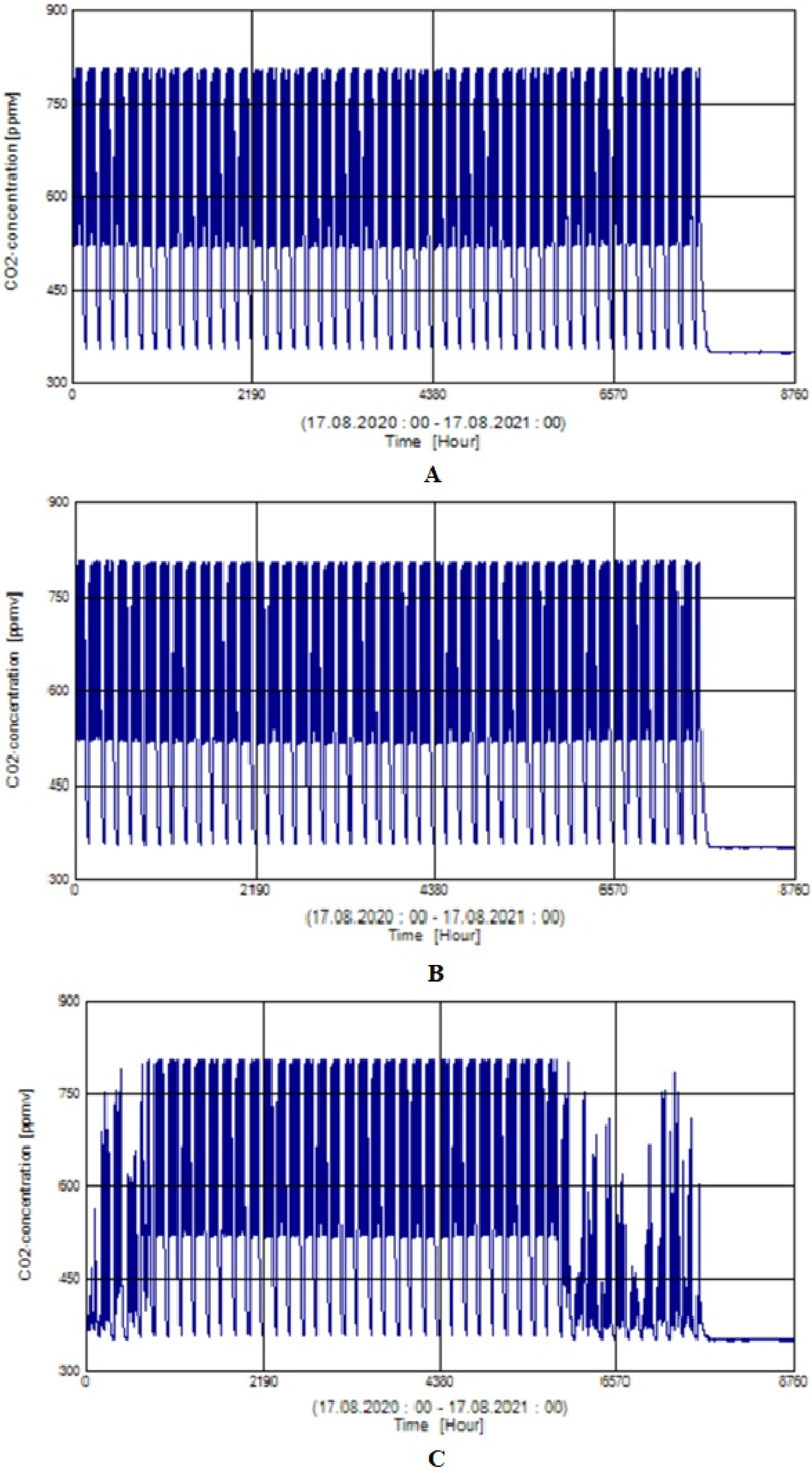
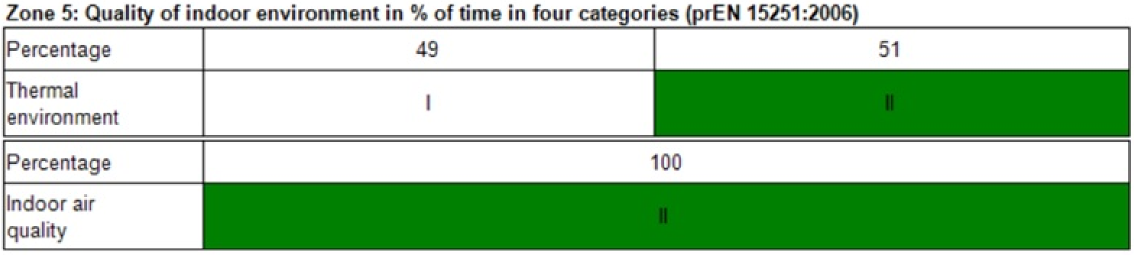


Figure 77: CO2 concentration for zone 2 with cooling:
A) CO_2 control, B) RH control, C) Temperature control

Zone 5

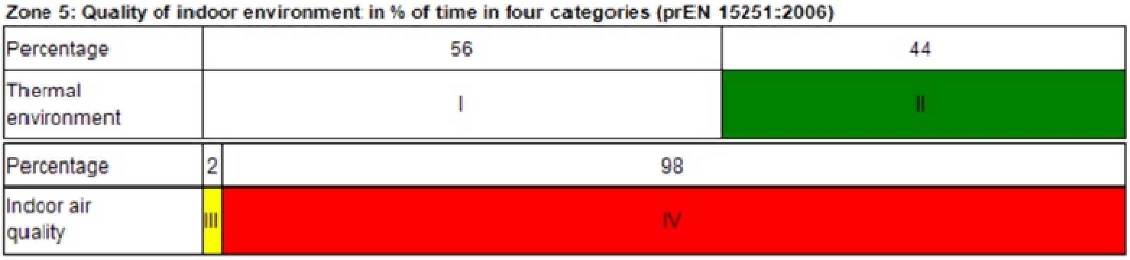


Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	49	51
Thermal environment	I	II

Percentage	100
Indoor air quality	II

A

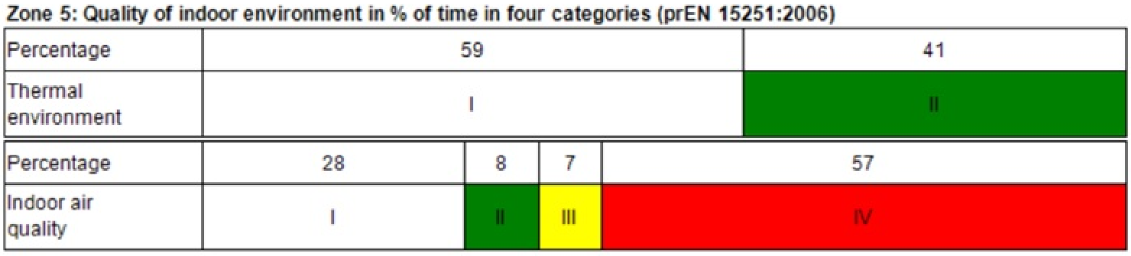


Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	56	44
Thermal environment	I	II

Percentage	2	98
Indoor air quality	III	IV

B



Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	59	41
Thermal environment	I	II

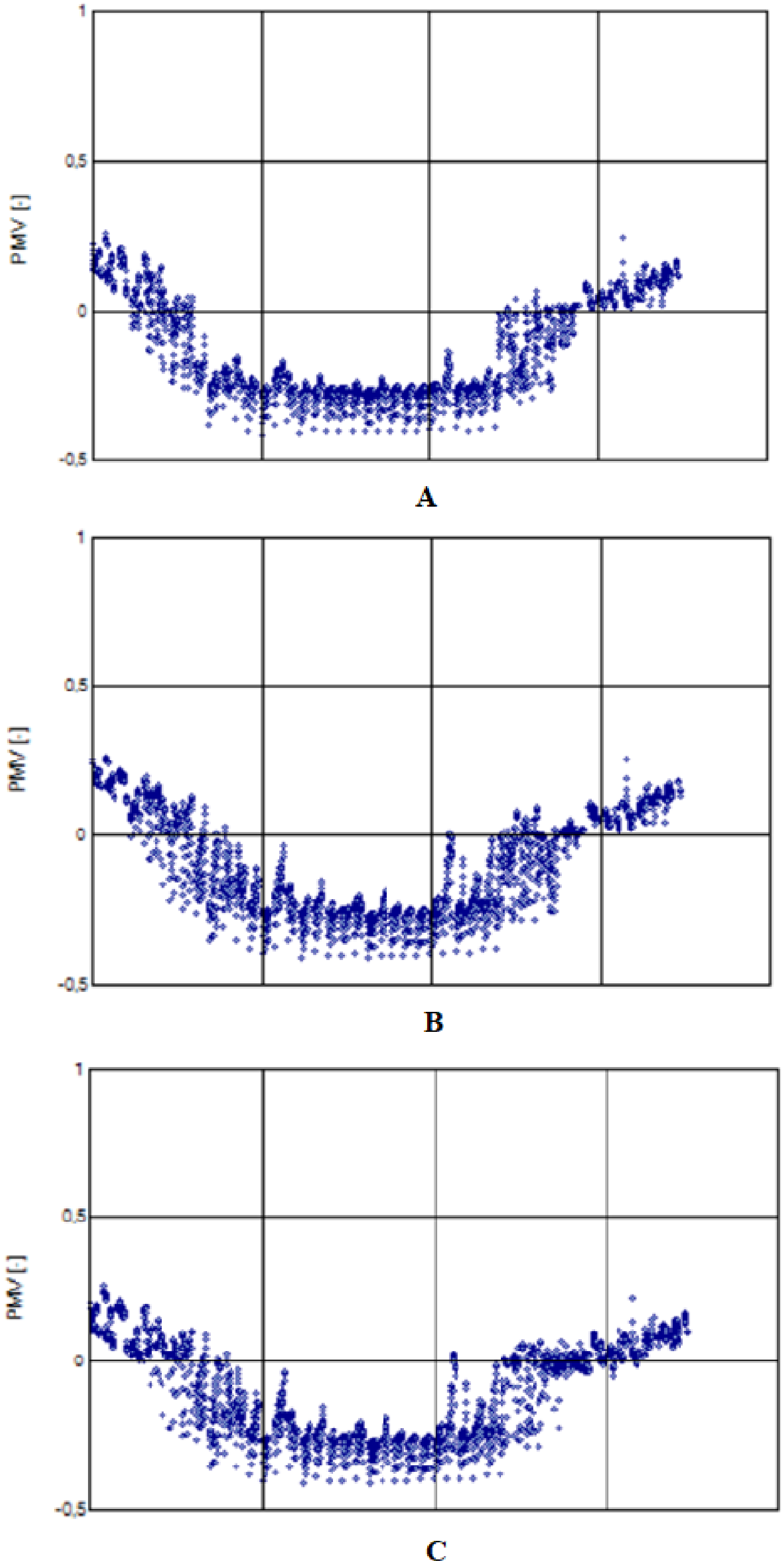
Percentage	28	8	7	57
Indoor air quality	I	II	III	IV

C

Figure 78: Indoor environment quality for zone 5 with cooling, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 36: Zone 5 indoor environment values with cooling

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	30	20	56,3	9144,5	2389	5904,8 (0)
RH	19	30	20	56,4	5760,8	3506,1	616,6 (0)
Temperature	19	30	13,5	53,6	5680,5	2893,6	1984,3 (0)

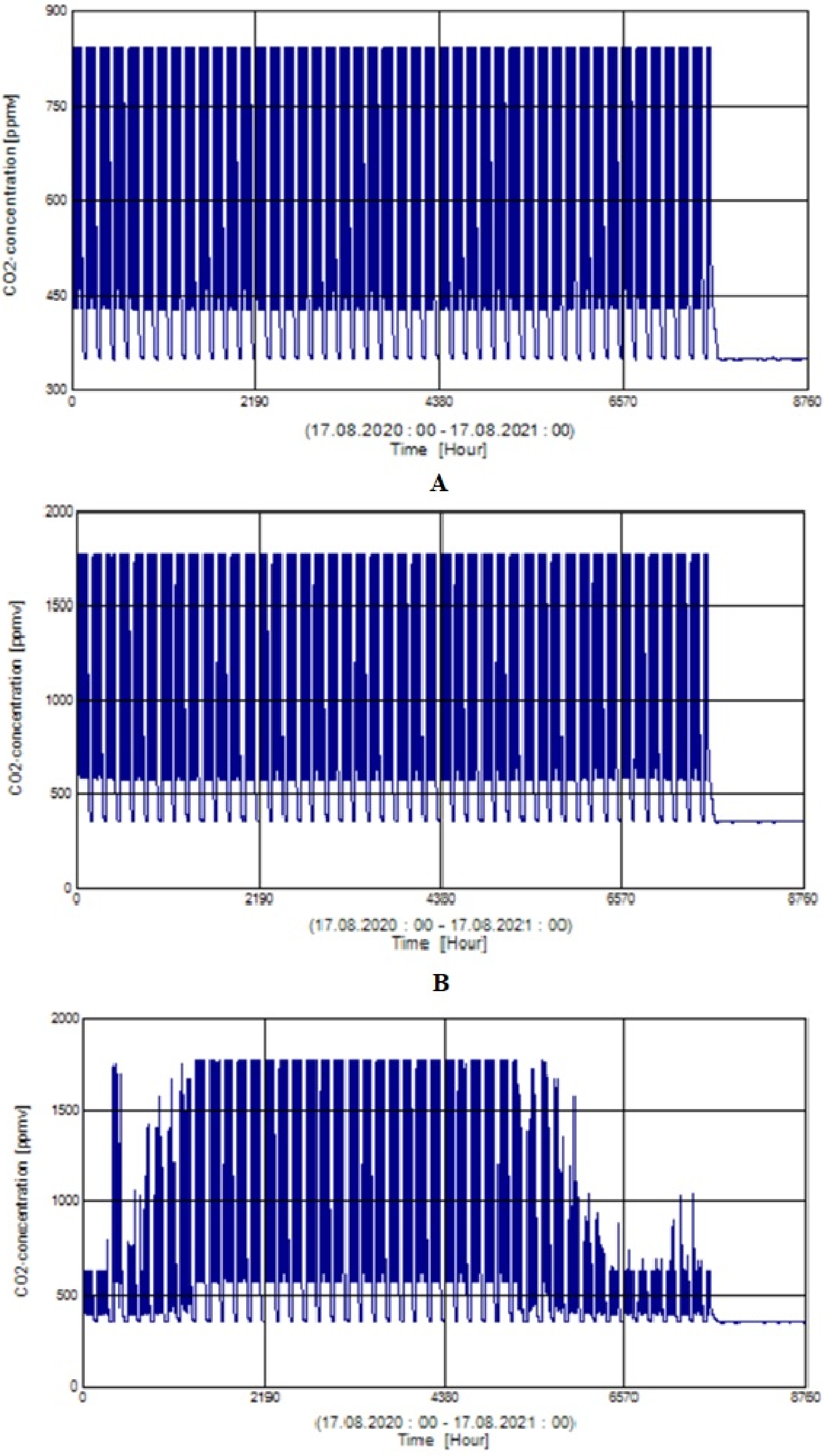


A

B

C

Figure 79: Zone 5 PMV with cooling::
A) CO_2 control, B) RH control, C) Temperature control



A

B

C

Figure 80: CO2 concentration for zone 5 with cooling:
A) CO_2 control, B) RH control, C) Temperature control

Discussion

Implementing cooling showed to be crucial. Compared to the initial simulations every thermal environment, for all controlling systems, improved. All zones experienced reduction eliminating the initial simulations third and fourth categories.

Zone one significantly improved its thermal environment as 72 show. Interestingly, initial simulations expressed lower maximum temperature compared to the ones found in 34. Cooling design levels allow temperatures to reach the outside operation design temperature 30°C, hence higher temperature. Even with increased max temperature figure 73 indicate that former temperature issue was reduced noticeably. All controlling systems maintained category two obtained by PMV values between -0,5 and 0,5. The figure also explains the reason CO_2 controlled ventilation provided the lowest category one percentage, while temperature control the highest. Controlling with temperature, not surprisingly, resulted both in lower heat and cooling demand. Temperature control also improved its relative humidity alterations, though still demanding significant humidification. Cooling aggravated the other two systems relative humidity differences. However, they still fluctuate significantly less than temperature controlled. Note that cooling also increased heating demand to maintain stable temperature.

Growing heating requirement was also found for zone two. The already comfortable initial thermal environment was improved to near excellent as illustrated in 77. Notice that where temperature control displayed the greatest thermal environment in zone one, it record the lowest category one percentage in zone two. With almost identical temperatures, low relative humidity, table 35, became the decisive factor. Drier environment is one of temperature controlled ventilation's greatest challenges in combination with exposed wood.

Zone five did not separate from the two other zones. All ventilation controls improved, and the pattern from zone one repeated it self for zone five. Temperature expressed the greatest thermal environment, respectively followed by RH control and CO_2 control. controlling depending on CO_2 did however part from the other two. The heating required to maintain an acceptable indoor environment, fond in table 36, was substantially compared to the other two. Significantly higher humidification demand also expressed issues preventing alterations. Both these demands was decisive keeping within acceptable PMV values showed in figure 79.

Reduction of allowed CO_2 concentration improved the indoor air quality perceptibly. It was most noticeably for CO_2 control recording the lowest concentration levels. Initial simulations exhibited opposite concentration levels for temperature control and RH control ventilation based on the season. After changing design value both recorded highest concentration during the winter, shown in figure 74. Notice that RH control permitted less CO_2 concentration than temperature control, fluctuating between 500-1200 ppmv. Temperature control continued its pattern displaying 1000-1500 ppmv in the winter, while significantly lower during the summer. Periodically low concentrations provided the simulation with the leading category one. Winter highs, on the other hand, assigned the simulation considerably increased category four.

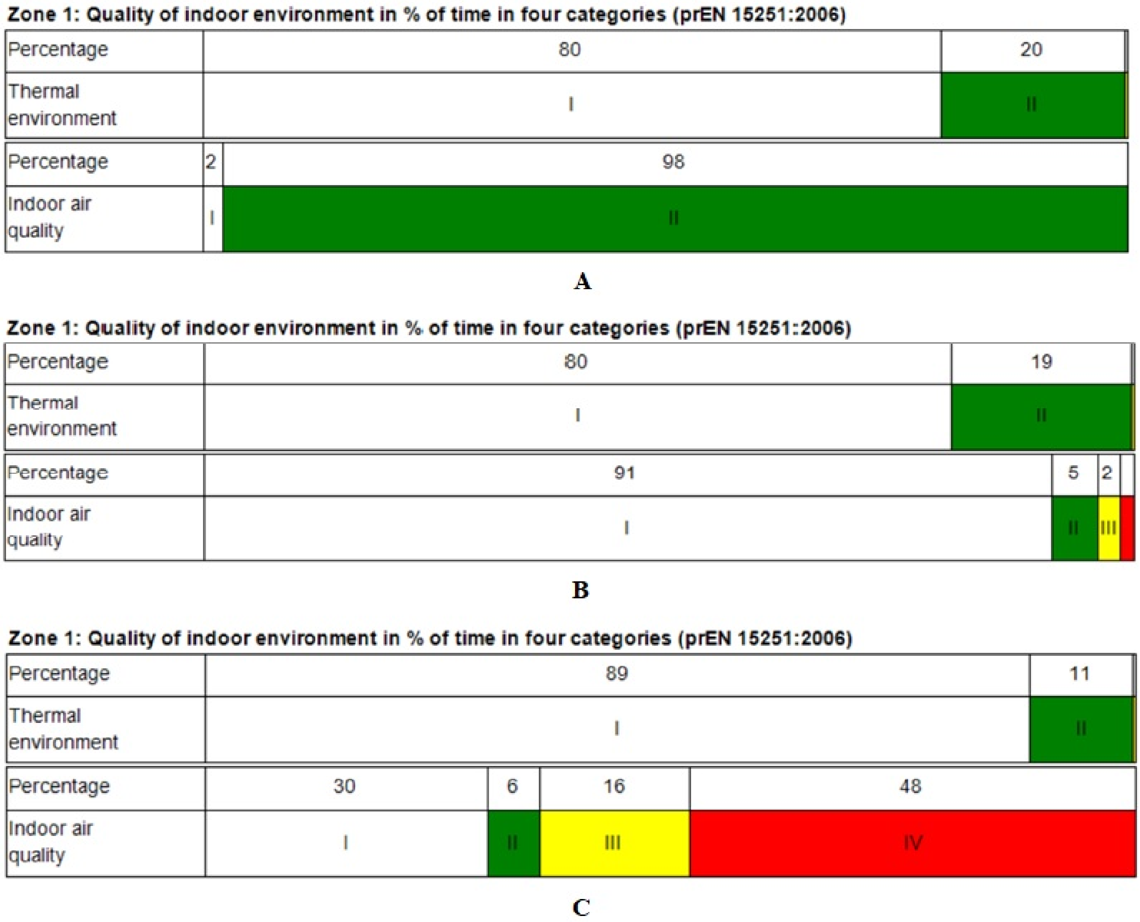
Temperature control's CO_2 concentration trend reoccurred in zone two, resulting in the highest category one percentage. With no controlling methods producing unwanted categories, temperature control performed the best indoor air quality. Compared to zone one RH control's fluctuating CO_2 concentration stayed more even. It followed the same shape as CO_2 control showed in figure 77. Same concentration levels resulted in identical air quality.

Transition from 900 ppmv to 850 ppmv turned out to be the decisive factor for zone five. CO_2 control achieved approved indoor air quality. Temperature controlled ventilation also experienced improvement. Figure 80 displayed a longer ending period at low concentration levels. Spending more time at these levels increased the category one percentage. Interestingly, reducing CO_2 concentration design level aggravated the indoor air quality for RH controlled ventilation. Lowering the allowed level increased the concentration above, providing less concentration below desired levels.

4.2.3.3 Cooling optimization with moisture recovery

With knowledge about wood's hygroscopic characteristics, the last optimization step introduced ventilation moisture recovery. Recover and reuse the moisture withdrawn from the building increases the building's energy efficiency taking advantage of already produced moisture.

Zone 1



Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	80	20
Thermal environment	I	II

Percentage	2	98
Indoor air quality	I	II

A

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	80	19
Thermal environment	I	II

Percentage	91	5	2	
Indoor air quality	I	II	III	

B

Zone 1: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	89	11
Thermal environment	I	II

Percentage	30	6	16	48
Indoor air quality	I	II	III	IV

C

Figure 81: Indoor environment quality for zone 1 with moisture recovery, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 37: Zone 1 indoor environment values with moisture recovery

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	30	52,1	63,4	2728,5	247	0 (760,8)
RH	19	30	52	63,4	3074	202,7	0 (57,6)
Temperature	19	30	40	66,4	2630,1	135,7	0 (582,1)

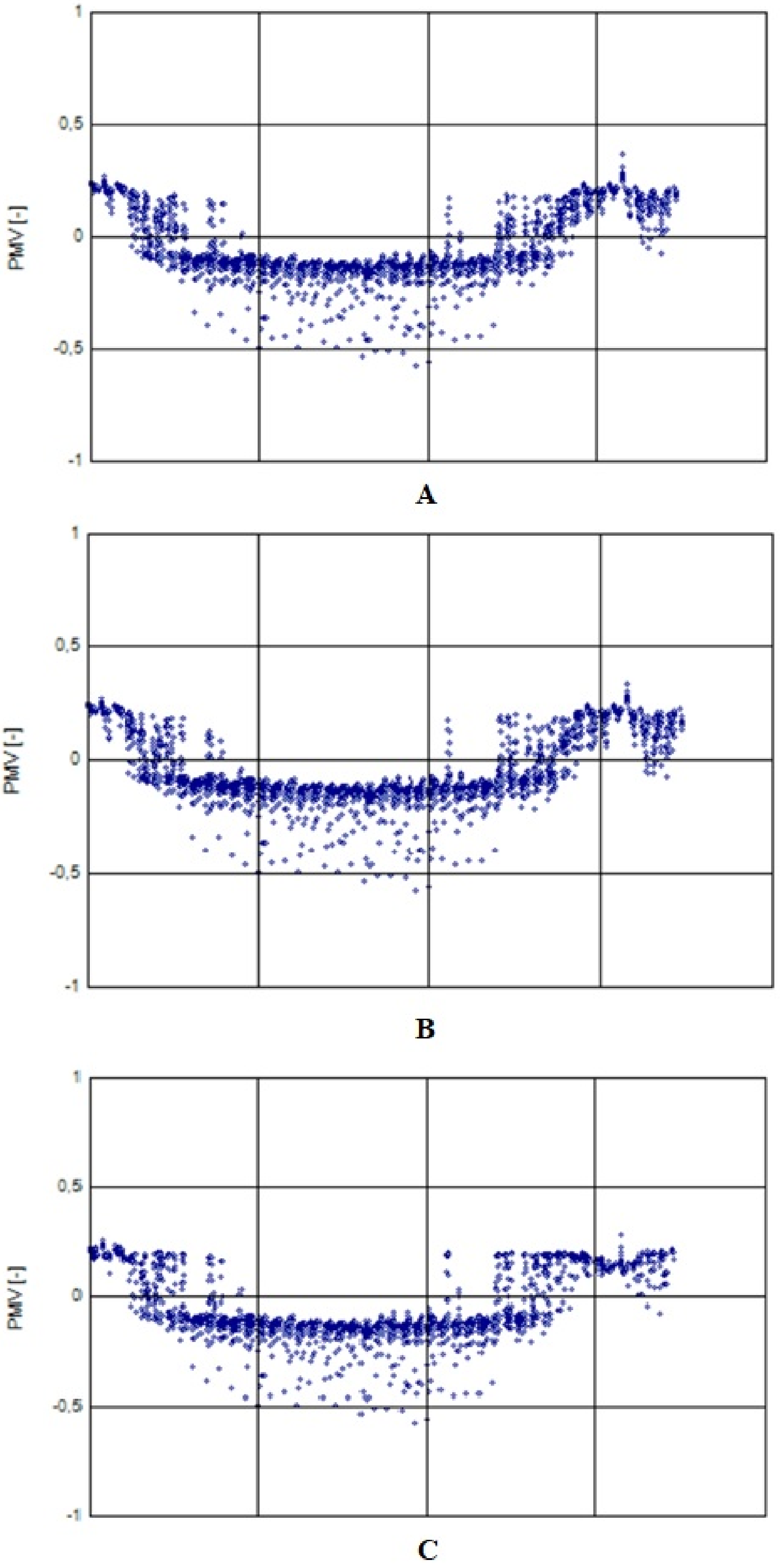


Figure 82: Zone 1 PMV with moisture recovery:
A) CO_2 control, B) RH control, C) Temperature control

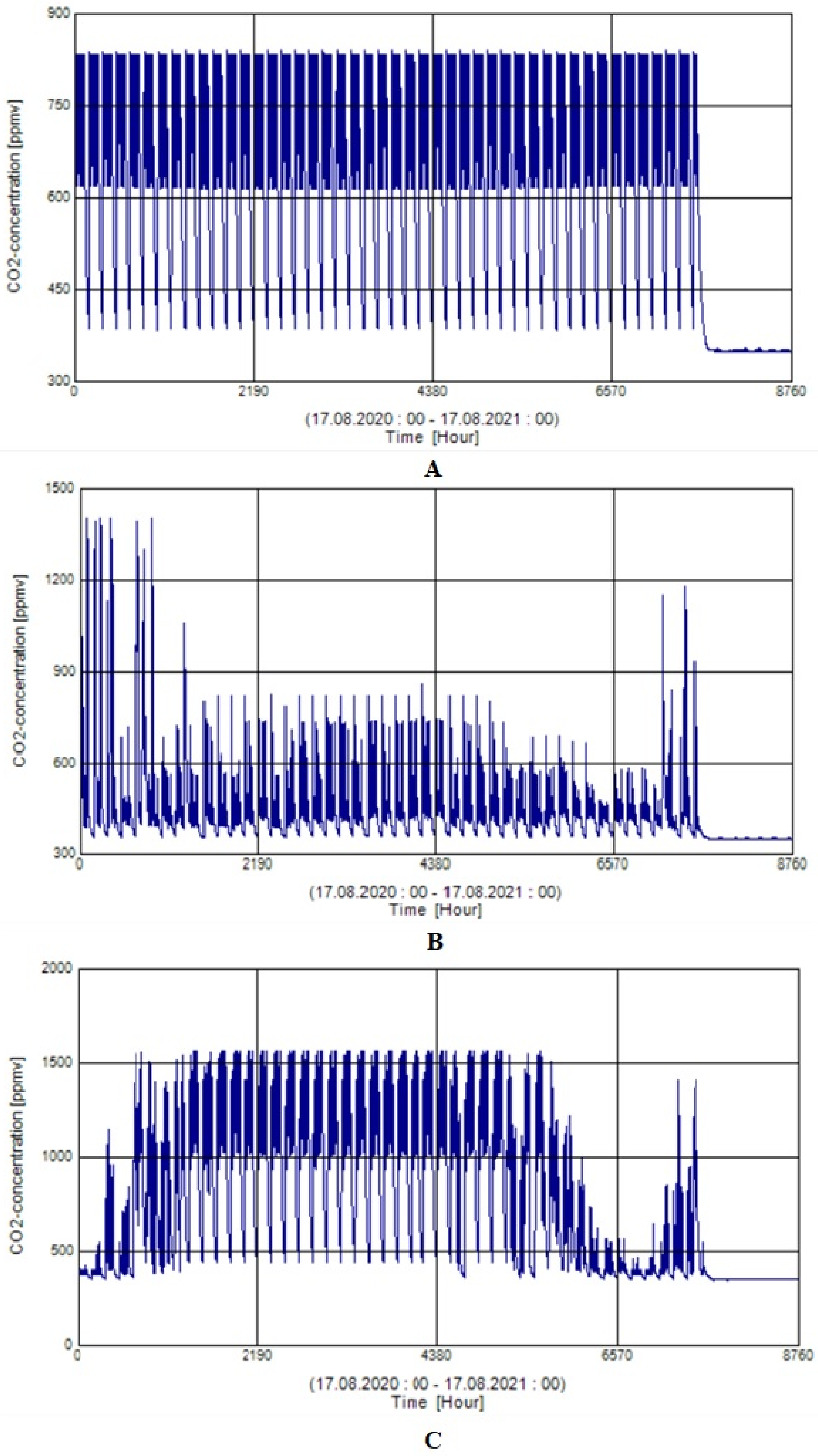
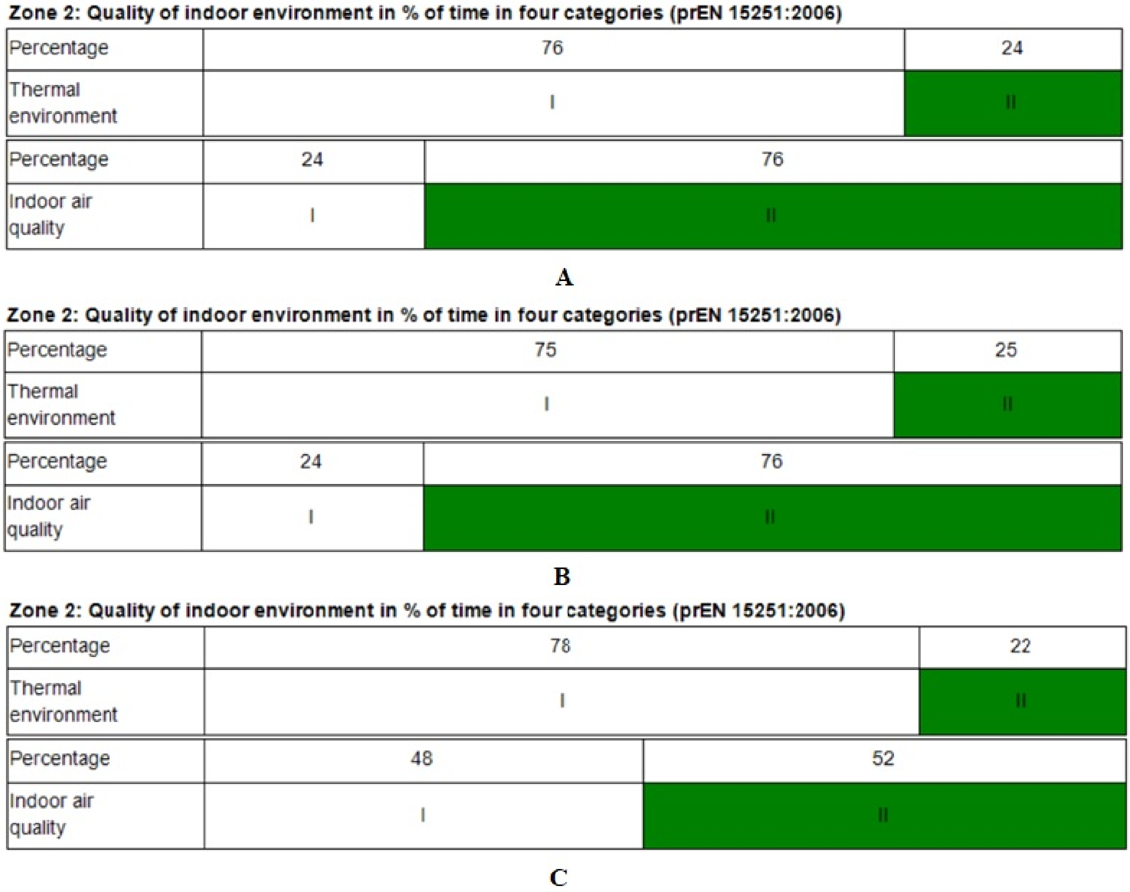


Figure 83: CO2 concentration for zone 1 with moisture recovery:
A) CO_2 control, B) RH control, C) Temperature control

Zone 2



Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	76	24
Thermal environment	I	II

Percentage	24	76
Indoor air quality	I	II

A

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	75	25
Thermal environment	I	II

Percentage	24	76
Indoor air quality	I	II

B

Zone 2: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	78	22
Thermal environment	I	II

Percentage	48	52
Indoor air quality	I	II

C

Figure 84: Indoor environment quality for zone 2 with moisture recovery, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 38: Zone 2 indoor environment values with moisture recovery

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	30	33,5	51,5	5369,9	287,9	12,5 (0)
RH	19	29,9	33,8	51,5	5327,9	284,4	11,8 (0)
Temperature	19	30	25,6	50,9	5287,1	138,2	12,2 (0)

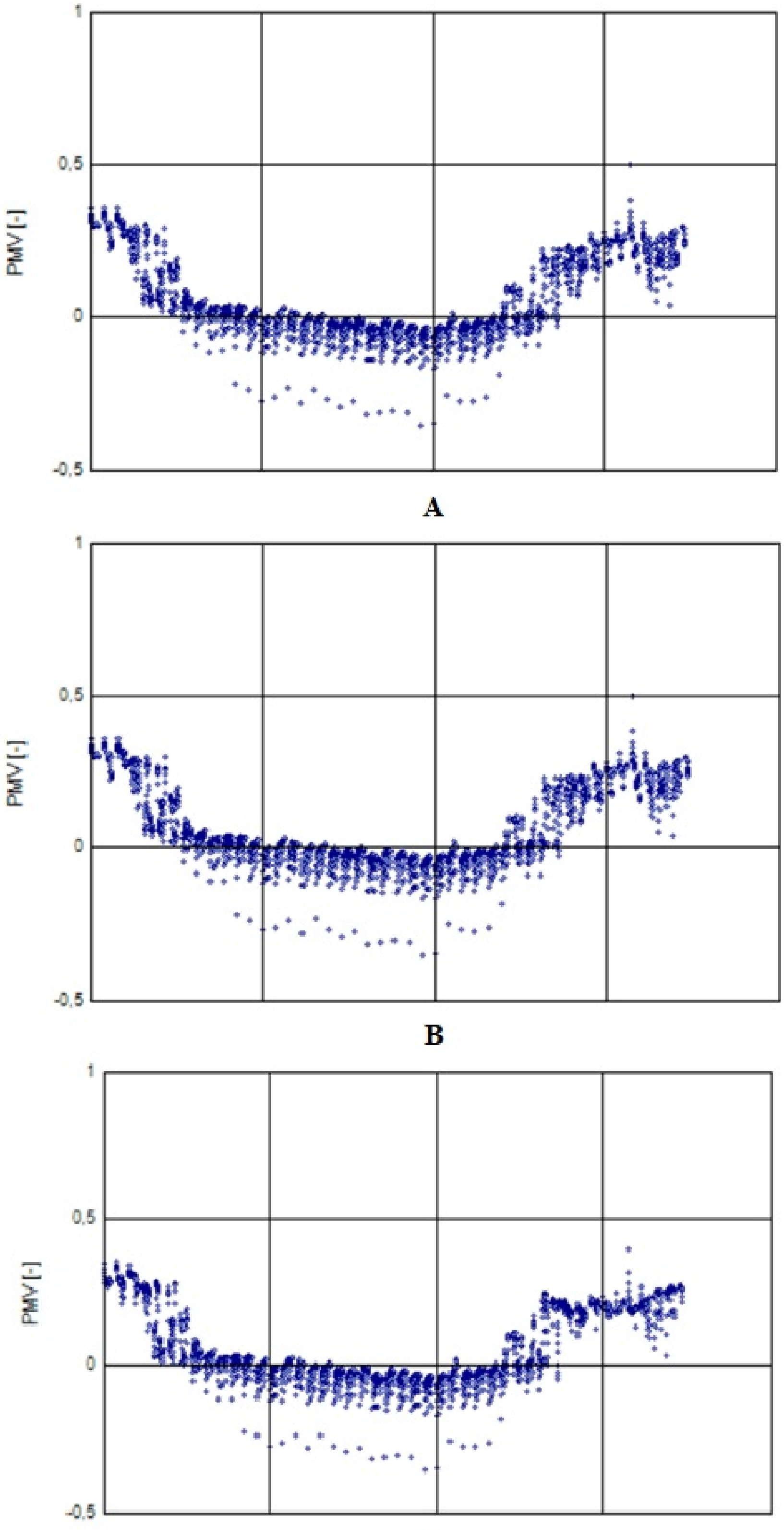


Figure 85: Zone 2 PMV with moisture recovery:
A) CO_2 control, B) RH control, C) Temperature control

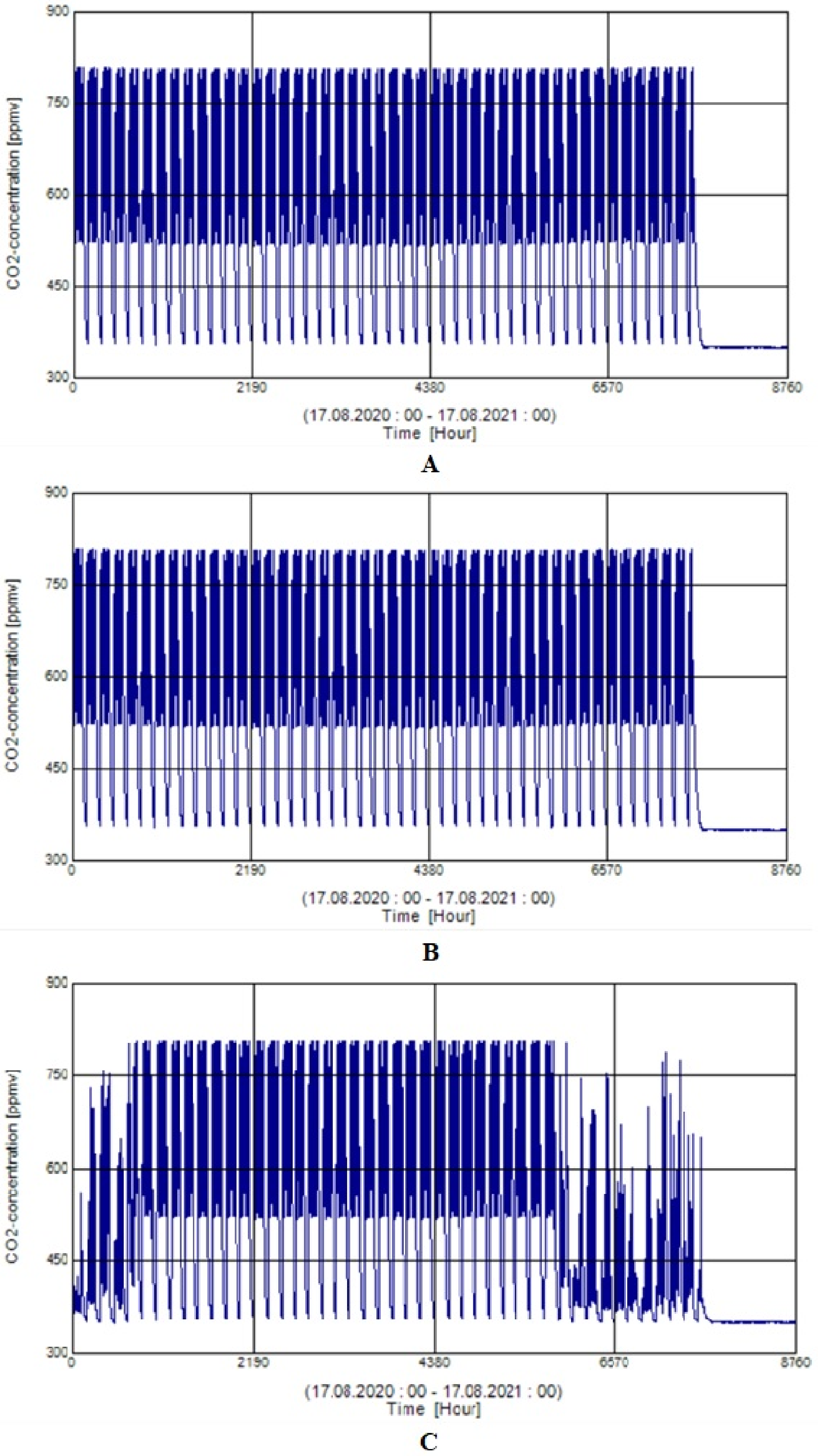


Figure 86: CO2 concentration for zone 2 with moisture recovery: A) CO_2 control, B) RH control, C) Temperature control

Zone 5

Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	72	28
Thermal environment	I	II

Percentage	100
Indoor air quality	II

A

Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	65	35
Thermal environment	I	II

Percentage	9	91
Indoor air quality	III	IV

B

Zone 5: Quality of indoor environment in % of time in four categories (prEN 15251:2006)

Percentage	92	8
Thermal environment	I	II

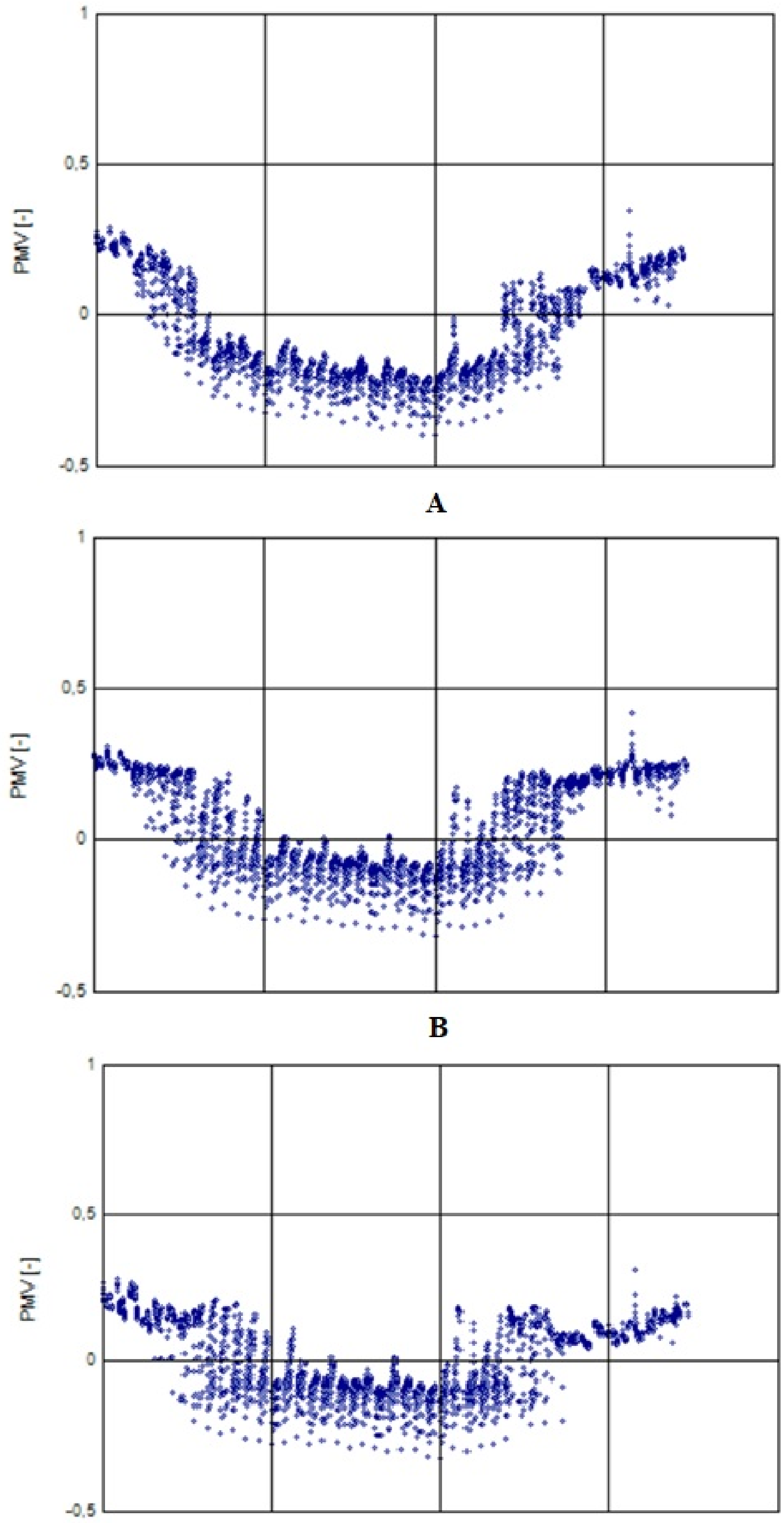
Percentage	29	8	9	55
Indoor air quality	I	II	III	IV

C

Figure 87: Indoor environment quality for zone 5 with moisture recovery, exposed to the three ventilation systems: A) CO_2 control, B) RH control, C) Temperature control

Table 39: Zone 5 indoor environment values with moisture recovery

Ventilation control	Temperature		Relative humidity		Heating demand	Cooling demand	Humidification (dehumidification)
	Min	Max	Min	Max			
CO_2	19	30	28	60	9071,4	2580,2	0 (0,4)
RH	19	30	41,6	60,6	5605,7	3705,4	0 (84,2)
Temperature	19	30	27,7	60,5	5469,3	2947,6	0 (3,2)



A

B

C

Figure 88: Zone 5 PMV with moisture recovery:
A) CO_2 control, B) RH control, C) Temperature control

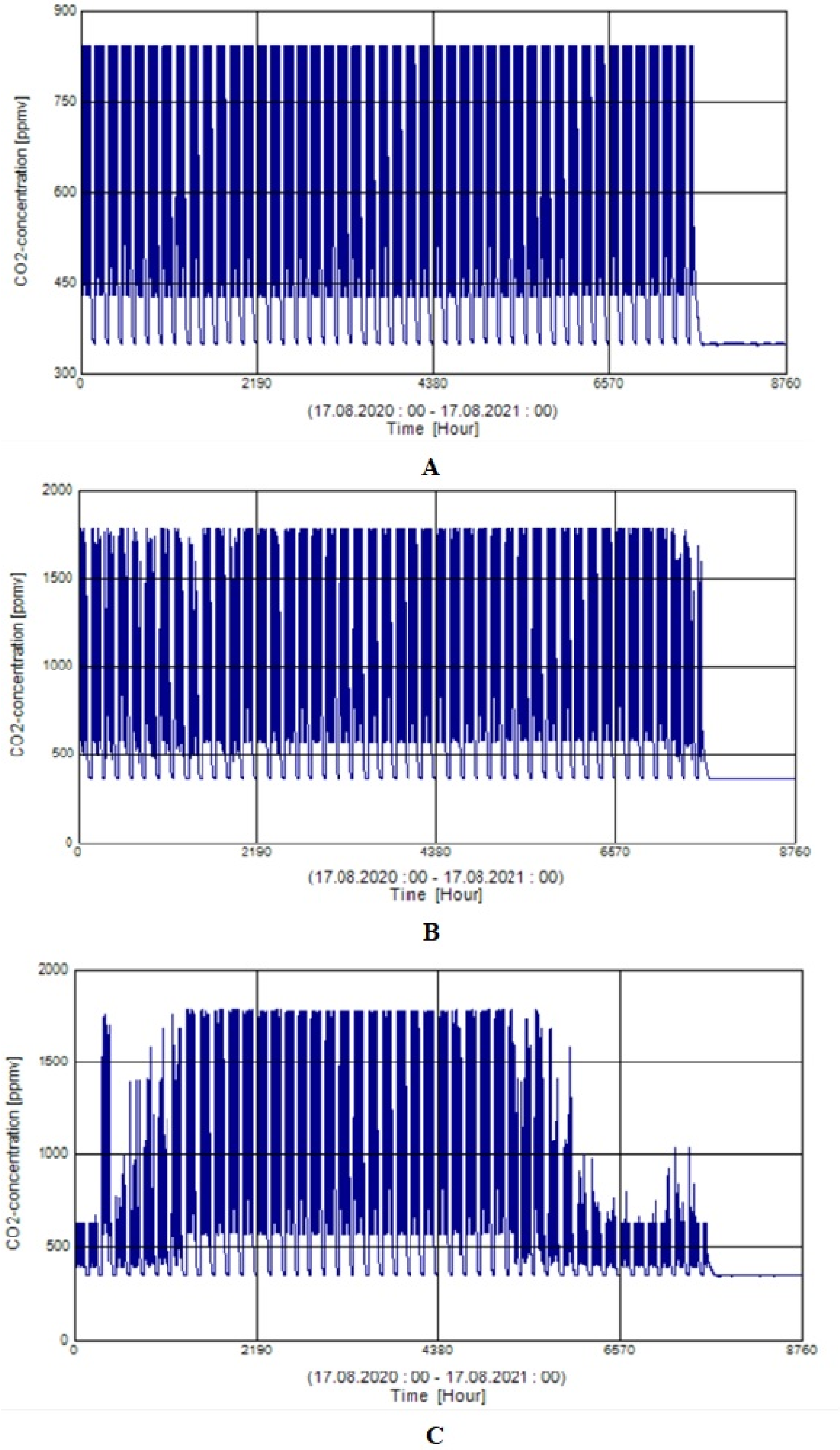


Figure 89: CO2 concentration for zone 5 with moisture recovery:
A) CO_2 control, B) RH control, C) Temperature control

Discussion

A ventilation system that recovers moisture from the withdrawn air. The restored moisture is transferred to the supplied air, and reused. Moisture dependent optimizations is more likely to influence a ventilation system that allow considerably more moisture than others.

Since the moisture recovery was assigned the ventilation system, thermal environment was not considerably improved. However, an advantage of restoring and reusing moisture is its contribution to stabilize the relative humidity in the building. The substantial increase of minimal relative humidity level for temperature controlled ventilation, shown in table 37, was a result of that. Compared to the previous optimization step, minimal allowed relative humidity level for zone one nearly doubled. Both CO_2 control and RH control also increased, but not as significant. Note that a minimum indoor relative humidity of 40% indicate humid environment. Adding moisture to the supply air also raised maximum humidity in the building, hence increased dehumidification demand. It is also noticed, from figure 81, that temperature and CO_2 control thermal environment slightly improved. However, temperature control experienced growth in category two, worse than earlier. Nevertheless, indoor thermal environment for zone one was found to be well within acceptable levels.

Zone two displayed an excellent thermal environment already before introducing moisture recovery. Instead, moisture recovery decreased category one for all three control systems seen in figure 84. Figure 85 does however express that the cold feeling occupant percentage was notably improved. All three ventilation controls had lower concentration around 0 PMV. With no major differences occurring, zone two possibly had reached its optimization potential.

The most significant changes occurred for zone five. Table 39 show that minimum indoor relative humidity considerably increased, but with no humidification assistance. Instead, improvement was caused by moisture recycling. Not surprisingly, RH control significantly improved, while the other two gained less. Nevertheless, all increased their minimum relative humidity as shown in figure 87. Note that moisture recovery lead to less heating demand, but required more cooling. Figure 88 expresses the same pattern as the first zone. Fewer felt cold during the winter, while hotter in the summer. Thereby explaining lower heating and more cooling demand.

Introducing moisture recovery displayed an interesting indoor air quality improvement. RH control benefited the most of this implementation. No surprise, being controlled depending on moisture levels. Especially zone one air quality was massively improved. Table 37 addressed RH control's strict alterations. Allowing sever humidity fluctuations demand increased ventilation impact to stabilize it. Figure 89 show ventilation supply maintaining

CO_2 concentration well withing category one. RH control performed significantly greater indoor air quality than CO_2 control. Note that the other two controlling methods not improved with moisture recovery. This proved its significance to RH controlled ventilation.

Mentioned above, implementation of moisture recovery lead to no thermal environment improvement for zone two. The same occurred for indoor air quality. CO_2 concentration stayed identical to the previous optimization step. Moisture recovery therefore had no decisive impact. Zone five however experienced improvement, again for RH control. The other two remained the same. RH control slightly improved its third category due to a period with increased ventilation impact, shown in figure 89. The improvement was not impressive, but increased the category by 7%. All improvements are important for a indoor air quality mostly recording unwanted values. The importance of moisture recovery was therefore found to be significant with a ventilation system controlled based on relative humidity levels.

4.2.4 Comparison of initial and optimized exposed wood simulations

Further investigation each zones ventilation control influence, indicated room for improvement. During the summer was the building generally, for all controlling methods, experienced too warm. A smaller percentage also expressed that they felt cold during the winter. Relative humidity results addressed that the building occasionally was to dry. A dry indoor thermal environment is one of the challenges with exposing solid timber. The combination of these provided the building with a unacceptable thermal environment. In addition, high CO_2 concentration in the air lead to poor indoor air quality. Nevertheless, each ventilation control had its pros and cons. One displayed better indoor air quality than the other two. Another slightly greater thermal environment. The potential for improvement was noticeable and needed.

It was no surprise that the implementation of cooling resulted in temperature controlled ventilation displaying the best thermal environment. Neither that the CO_2 concentration reduction turned out to be crucial for CO_2 control. It was also expected that moisture recovery would distinctively improve relative humidity controlled ventilation's performance. Instead, the impact of the less favourable optimization steps is compared to evaluate which ventilation method allowed exposed wood to perform as intended.

Implementation of cooling turned out to one of the most crucial optimizations. All ventilation methods experienced high indoor temperature. PMV expressed a growing percentage felt warm during the summer. Allowing high temperature without cooling impacted the thermal environment. After supplying cooling, the thermal environment came out significantly better. Both temperature control and CO_2 control massively improved, eliminating unacceptable categories. Almost identical performances was separated by CO_2 demanding more heat to maintain acceptable levels.

The indoor air quality is dependent of CO_2 concentration in the air. Initially, which controlling method performed the best was dependent on the evaluated zone. RH control presented better indoor air quality for the smallest zone, but worst for the biggest. Temperature control displayed more even for all zones. In addition, it was always the controlling method that simulated the highest category one percentage. The established trend, RH control performing better for one zone than the other and temperature control more evenly, continued with CO_2 concentration reduction optimization. RH control improved in zone two, and was aggravated in zone five. Temperature control slightly improved in both zones, increasing its best category. High category one was caused by increased ventilation during the summer periods. Frequent air changes reduced the concentration of CO_2 in the air and improved the quality. ventilation rate facilitated zone one was more suited for its size. Zone five however, was not supplied with enough air changes. Ventilation distribution was found to be a key to ensure approved indoor air quality. Zone two, for example, had concentration within acceptable levels even before design value reduction.

Last optimization step implemented moisture recovery to the ventilation system. As earlier mentioned, moisture recycling provided a more stable indoor relative humidity. The implementation neither improved the thermal environment nor the indoor air quality of temperature or CO_2 controlled ventilation. However, their relative humidity fluctuations significantly changed. Earlier expressed dry environment with temperature control considerably improved with moisture recovery. CO_2 control also experienced an improvement. Reducing relative humidity alterations required additional heat, corresponding to the increased heating demand found in table 33.

The numerical simulations showed that choosing the most suitable ventilation method with exposed wood is not easy. CO_2 control provided the best air quality, but demanded significantly more energy than the other two. Temperature control performed extremely well, presenting both great thermal environment and considerably improved air quality. However, low relative humidity values indicate a dry environment when exposing solid wood. Lastly, RH control presented neither the best thermal environment nor air quality levels. But improved markedly with the optimized steps. All performed great results, and was considerably optimized with the implementations.

5 Conclusion

The last couples of decades, more interest regarding solid timber's hygroscopic properties have been researched. The hygroscopic properties provide wood the potential to absorb and release moisture. Different researchers have expressed that HVAC systems that allow moisture buffering, would influence the indoor environment. Improved indoor environment would demand less energy, making the building more efficient. The effect of exposing solid timber to an indoor environment lead to establishment of two research questions. The first evaluated the variation of solid timber's thermal transmittance when exposed to different indoor environments. The second, hygroscopic properties of solid timber's influence on the HVAC system, and how the latter is optimized. The investigation was utilized by two laboratory experiments and a numerical simulation, both exposing solid timber.

The laboratory experiment implied significant element differences. The elements structure and assembly was discovered to be crucial. Screwed assembly allow air gaps to occur between the layers. Attaching layers with glue fills the same air gaps. With insulation properties being greater for air than glue it affected the heat conductivity. In addition, being exposed to the experimental conditions prior to the test affected the measurement. Initial steady state heat coefficient was therefore found to be better for Norsk Massivtre. It was measured to be 0,095 W/mK, while Splitkon expressed a λ-value 0,1 W/mK.

Implementation of moisture variations initiated the elements hygrothermal mass. Allowing the elements to buffer moisture affected their dynamic U-value. Increased moisture supply provided both elements with improved U-values. Norsk Massivtre experienced a continuous reduction for all supply cycles. Steady state U-value compared to the last cycle showed an improvement of 0,012 W/m^{2}K. Splitkon however, improved significantly more. The affect of moisture buffering allowed the U-value to improve form a steady state 0,858 W/m^{2}K to 0,824 W/m^{2}K. Exposing solid timber elements to humid fluctuations thereby improve the elements thermal transmittance, due to wood's hygroscopic properties.

The numerical simulation expressed that exposed solid timber was equally as energy efficient as other material surfaces. In fact, performing considerably better than the gypsum board. From an energy reduction perspective both temperature and RH control was found to be more favourable than CO_2 control. Through all simulations it required a higher energy demand. Utilizing the hygroscopic characteristics however, favours RH control. Temperature control withdraw moisture at a rate that prevent initiating of buffering. With moisture recovery activated, relative humidity significantly increased. Improving the relative humidity decreased the dry environment issue. Improvements caused by the optimizations proved to be significant. Compared to initial simulations, all controlling methods considerably performed both thermal environment and indoor air quality improvements.

Laboratory experiments expressed the significance of increasing moisture load to improve the solid timber elements properties. To fully exploit these is it necessary to combine solid timber with a HVAC system that allow high moisture content for a longer period of time. Not only did it improve the thermal transmittance, it also contributed to reduce humidity fluctuations. The lower fluctuations increases the buildings energy efficiency.

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