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Investigation of stabilizing the indoor environment using building technologies

A case study: Viking Age museum in Norway

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Abstract:
The objective of this thesis has been to investigate concepts for how temperature and relative humidity fluctuations can be dampened, by passive measures. The case study for the thesis is the new Viking Age museum that will be finished in 2022/2023, in Norway.

One concept for temperature stabilization (PCM) and one for stabilization of relative humidity (Moisture buffering) was investigated. A dynamic whole-building simulation program was used for the study, based on drawings received from the consultancy company Hjellnes Consult.

The study proves that PCM can reduce the indoor temperature fluctuations for buildings fulfilling the TEK-requirements and the Passive house standard. The stabilizing effect is dependent on the surface area of the incorporated PCM. In general, the temperature stabilization is greater for a passive house than a building in fulfilling TEK-requirements. The temperature fluctuation can be reduced by up to 1.1°C for the Passive house, and 0.9°C for the TEK-house, when reasonable amounts of PCM is incorporated in the building.

Simulations for relative humidity stabilization was conducted with cellular concrete, lime plaster gypsum board and spruce wood panels. Lime plaster and gypsum showed less than 1% decrease of the RHS-index for the TEK-house and the Passive house. Exchanging concrete with cellular concrete had no effect on RHS-index for the TEK-house, while a reduction of up to 3.3% for the Passive house. Spruce wood panels gave the best reduction of the RHS-index, with a decrease of up to 2.3% for the TEK-house, and up to 5% of the Passive house

Keywords:

1. Stabilization of indoor environment
2. Building Performance Simulation
3. IDA ICE
4.

Rebecca C. Lundqvist

Preface

This thesis concludes 5 years of study at Norwegian University of Science and Technology, and was written the fall semester of 2017. The work has been like a rollercoaster with countless of ups and downs, and surprises around every turn. The topic has been challenging, but also very interesting. It has taught me a lot about problem solving for engineers, museums, Viking ships and building performance simulation.

Thank you to my supervisor, Mohamed Hamdy. Your encouragement, comments and discussions have been of high importance for me this semester, as well as preparing me for my professional life. Also, Cristina Cornaro and Gaurav Chaudhary deserve thanks for helping me out with understanding PCM and how to simulate it in IDA ICE.

Thank you to Tekna, NITO, Gullsmed Dahlsveen and everyone else that constantly reminded me of my upcoming deadline through SMSs, emails and social media.

Last, but not least I would like to thank my friends and family. Thank you, Dad, for supporting and motivating me through the toughest times of thesis. A special thanks to the friends that have shared this past years of study with me.

Rebecca C. Lundqvist

Rebecca Celine Lundqvist

Oslo, January 2018

In loving memory of my mum

Nomenclature and definitions

Some terms that will be used later in the thesis are presented her, in case they are unfamiliar to the reader.

MET – Metabolic Equivalent of Task. 1 MET is set to the metabolic rate of an average person that is seated at ret physiological measure of activities, which states how much energy people spend on activities.

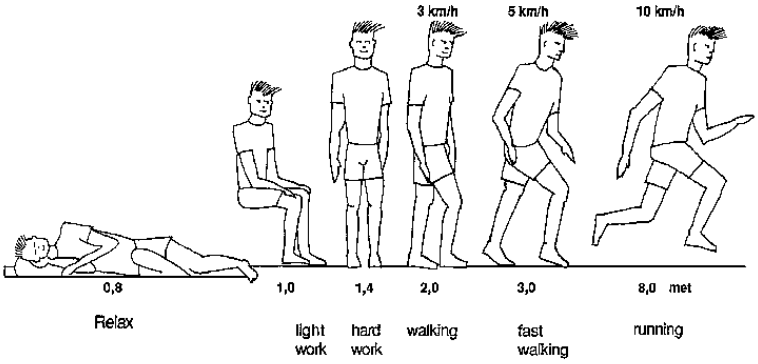

Figure 1: How peoples metabolism depends on activity level [20]

CLO – insulation level of peoples' clothes, defined as the thermal resistance between the surface of the skin and the outer surface of the clothing. Per definition 1 clo = 0.155m^{2}K/W [1].

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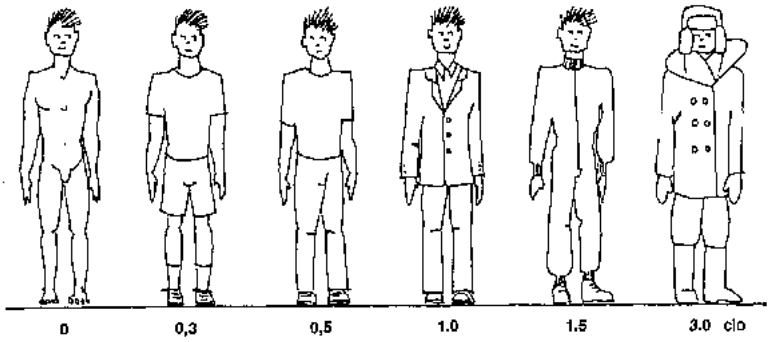

Figure 2: Insulation of different clothes [20]

IFC – Industry Foundation Classes.
Made by buildingSMART to enhance the interoperability between digital tool for the building industry. In the IFC-file construction components has to be categorized as windows, walls or other components) which contains information about building components. For interoperability between programmes

BIM – Building Information Model. An information system that makes it possible to share up-to-date information digitally with all stakeholders of a construction project. Digital representation of the building.

TEK - The minimum requirements that are used for this thesis is the same for TEK10 and TEK 17, and term TEK and TEK-house will be used to refer to requirements from these standards.

Summary

The objective of this thesis was to investigate techniques for temperature and relative humidity stabilization for the new Viking Age museum in Oslo. The thesis is based on a project conducted at Hjellnes Consult at the same time as this is written.

Research questions that was investigated

1. What kind of building technologies can be used to stabilize the indoor environment in northern countries?
2. By how much can the temperature and relative humidity be dampened, and is there a difference in possible effects for a TEK building and a Passive house building?

One concept for temperature stabilization and one for stabilization of relative humidity was investigated. For temperature stabilization the building technology based on Phase Change Materials (PCM) was looked at, while moisture buffering in wall enclosures by different materials were looked at for relative humidity stabilization. For this work a model was made in the dynamic whole-building simulation program IDA ICE, based on a BIM-model of the museum. A model of the whole building was made, while only results of temperature and relative humidity for the exhibition zones that will host the Viking Skips were analysed.

Simulations proved that PCM can reduce the indoor air temperature fluctuations for the Passive house by maximum 1.6℃, and by 1.1℃ for the TEK-house. This occurs when the amount of PCM is equal to the area of internal walls and floor in the zone. It is more realistic to incorporate PCM in the only internal floors, which gave reduction of temperature of 1.1℃ and 0.9℃ for the Passive house, and TEK-house respectively. The temperature is dampened more in a passive house, than in a TEK-house when the same amount of PCM is incorporated.

Materials that have proved to have good moisture buffering capacity were chosen for simulations. The tested materials were cellular concrete, lime plaster, gypsum board and spruce wood board. A relative humidity stabilization (RHS) parameter was defined to quantify the stabilization effect on the fluctuation. Lime plaster and gypsum board reduced the relative RHS with less than 1% for the TEK-house, and the Passive house. Cellular concrete had no impact for the TEK-house, while it reduced the RHS with up to 3.3% for the passive house. Spruce wood panels had the best stabilizing effect reducing the RHS with up to 2.3% and 5.5% for the TEK-house and passive house respectively. In general, the simulations could not prove that the moisture buffering materials has a good dampening effect on the relative humidity. The dampening effect that was estimated, was higher for the passive house than for the TEK-house.

It was concluded that more experiments on large-scale buildings needs are needed. Studies on how PCM incorporated in buildings works with occupants, internal gains, and HVAC-systems must be done to be able to say more about the possible effect on temperature stabilization. Quantification of the moisture buffering effect of materials for buildings with strict relative humidity requirements should also be looked at.

Sammendrag

Formålet med denne oppgaven har vært å se på hvordan ulike bygningsteknologier og strategier kan dempe svingninger i luftfuktighet og temperatur. Oppgaven er basert på et prosjekt som blir gjennomført hos Hjellnes Consult på dette tidspunktet, nemlig nytt Vikingtidsmuseum i Oslo.

Følgende forskningsspørsmål som skal bli besvart

1. Hvilke strategier/bygningsteknologier kan bli bruk for å stabilisere inneklimaet i nordlige land?
2. Hvor mye kan temperatur og/eller luftfuktighet bli dempet, og er det en forskjell på effekten for bygg bygget etter TEK og etter passivhusstandarden?

Et konsept for stabilisering av temperatur, og et for stabilisering av luftfuktighet ble sett på. For stabilisering av temperatur ble en bygningsteknologi basert på faseendrende materialer undersøkt. Fuktbuffring i vegger ved hjelp av ulike materialer ble sett på for passiv demping av relativ luftfuktighet. Til arbeidet ble det laget en modell i det dynamiske bygningssimuleringsprogrammet IDA ICE laget, basert på en BIM-modell av museet. En modell av hele det nye museumsbygget ble laget, mens analyser kun ble gjort av resultatene for temperatur og luftfuktighet for utstillingssonene.

Simuleringene viste at PCM kan dempe svingninger i temperaturen for passivhuset med opp til 1.6℃, og med 1.1℃ for TEK-huset. Dette gjelder dersom arealet av PCM tilsvarer arealet for alle innvendige vegger, samt gulv i sonene. Det er mer realistisk å anta at PCM er kun i gulv, noe som ga reduksjon i temperatursvingninger på 1.1℃ for passivhuset og 0.9℃ for TEK-huset. Effekten av PCM på temperatursvingningene viste seg å være større om museet er bygget etter passivhusstandarden enn om det innfrir minimumskravene i TEK, dersom samme mengde PCM er i sonen.

Materialer som har blitt vist at har god kapasitet for fuktbuffring ble valgt for simuleringer. De testede materialene var porebetong, kalkgips, vanlig gipsplater og grantreplater. En parameter kalt relativ fuktighets stabilisator (RFS) ble definert for å kvantifisere stabiliseringseffekten de ulike materialene har på luftfuktigheten. Både kalkgips og vanlige gipsplater viste seg å redusere RFS med mindre enn 1% for både TEK-huset og passivhuset. Porebetong hadde ingen innvirkning for TEK-huset, mens den minket RFS med 3.3% for passivhuset. Grantreplater hadde den beste stabiliseringseffekten, og reduserte RFS med 2.3% for TEK-huset, og 5.5% for passivhuset.

Det ble konkludert med at forskning på større bygninger bør bli gjennomført, for å se hvordan PCM direkte innlemmet i bygninger samspiller med personer, internlaster og HVAC-systemer. Dette for å kunne si noe mer om effekten PCM han ha på stabilisering av temperatur i ordentlige bygninger. Det bør også bli sett på hvordan fuktbuffring av materialer kan fungere for bygninger med strenge krav til relativ fuktighet.

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1. Introduction

1.1. Background

The focus on and knowledge of climate change is well known today, and the release of greenhouse gases by humans must be reduced to limit severe consequences for the earth. Buildings in Norway accounts for close to 40% of the total energy use in Norway [2]. Both IPCC and IEA have stated the most efficient and cheapest measure to reduce greenhouse gases is energy efficiency of buildings [3]. Strict requirements to minimize energy demand and heat loss in buildings require more use of passive measures to stabilize the indoor environment.

Some buildings have special social responsibilities in the society. One of these is the Viking Ship Museum in Norway. The first wing of the building was raised in 1926, and the last part of the museums was finished in 1957 [4]. The museum hosts the world's best preserved Viking ships, in addition to other objects from the Viking age. The Viking ships are made of wood, which is a hygroscopic material that adsorb and release moisture depending on the humidity of the ambient air. This makes the wood expand and shrink and leads to degradation. Fluctuations in relative humidity and temperature will make the ships degrade faster than under stable conditions. Therefore, it is necessary to stabilize the indoor environment. The current museum "Viking ship museum" is too small to host the Viking ships and other objects, as well as it doesn't provide stable conditions for preservation. It is therefore decided from the Norwegian government that a new Viking Age museum will be built. The museum is expected to provide better conditions for the visitors, maintain the Viking ships better, and to become a corner stone for telling the history of the Viking age. Statsbygg is a governmental agency, that maintains the buildings stock and real estate policy for the Norwegian government.

Hjellnes Consult is a Norwegian consultancy company chosen by Statbygg to design the new Viking Age Museum in Norway. The goal of the project is to build an energy efficient museum, and at the same time ensure a stable indoor environment for the museum objects. The brown cross section on Figure 3 is the part of the museum that is currently in use, named the "Viking Ship Museum". The new part that is in the design phase is the grey rounded section, also visible on Figure 3 below. Together, these two building will host the Viking Age Museum from 2022/2023.

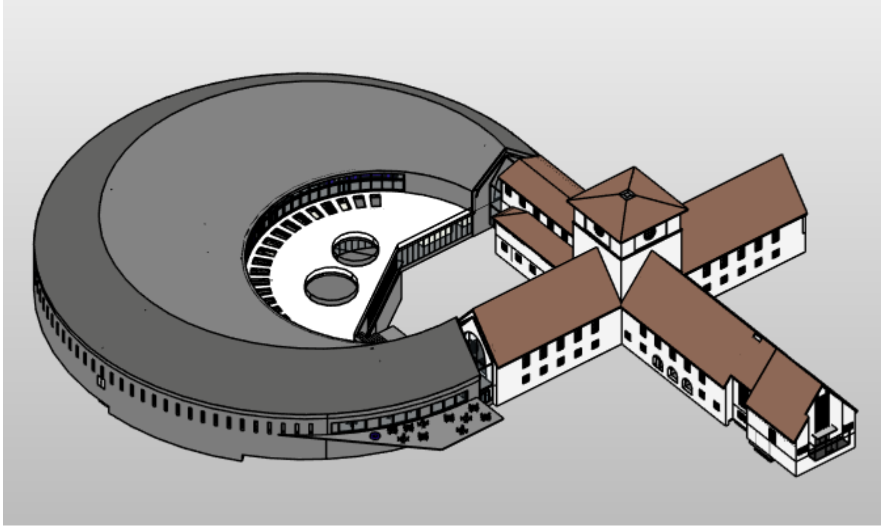


Figure 3: Architectural model of the Viking age museum. Brown cross section is the current museum building. The grey rounded part is the new building. Screenshot from Revit.

The museum will be energy efficient and fulfil the Norwegian passive house requirements for the building parts. Due to limited ground area, the space for technical equipment is limited. The cultural heritage from the Viking age is important to take care of, as it can’t be reproduced.

1.2. Purpose

The purpose of this master thesis is to investigate how the temperature and relative humidity can be stabilized to ensure a good indoor environment in the museum. The focus will be on one concept for that can stabilize the temperature, and one concept that can stabilize relative humidity. An energy model in the whole-building simulation program IDA ICE will be made for this research.

1.3. Scope and limitations

During the work with the thesis, the objective was changed. In the beginning a range of concepts and technologies for enhancing building thermal mass was supposed to be simulated, and compared. Due to the complexity of the model and ad-ins in IDA ICE which are under development, technical issues came up, and the thesis was limited to look at one measure for dampening relative humidity and one for temperature stability.

On limitations, is has been decided that the museum will fulfil the passive house standard for heat loss of building parts, but not for energy use/demand. Possibilities of limiting energy use will therefore be outside the scope of this thesis. Materials and solutions that will be modelled in this thesis, might not be economically beneficial, but this is also outside the scope of this study as it is decided that protection of the Viking ships is of higher importance than the economy.

Acoustic comfort must be ensured in all building projects, and especially in museum buildings made of big concrete halls this could be an issue. Through the design it would be important to carefully choose amounts of concrete, PCM wallboards or PCM enhanced concrete balanced by acoustic dampeners (e.g. vertical blinds or others). It is not discussed further in this thesis, but it is understood that it is an issue, and careful design will be needed.

1.4. Structure of the report

In Chapter 2 relevant information and theory of the concepts that were simulated will be presented. In addition, the minimum requirements in the Norwegian building regulations and the Norwegian Passive house requirements will be presented.

Chapter 3 is an introduction to building performance simulation, the simulation program used for this thesis, IDA ICE. Issues with making energy models based on BIM-models will be presented, as it had influence on the model made for this thesis.

Chapter 4 gives a presentation of how the energy model was made in IDA ICE. The building is quite complex, so a detailed explanation will be done here.

In Chapter 5 the set up for simulation will be explained. The two reference cases will be presented, the implementation of the chosen techniques for temperature or RH stabilizing in IDA ICE as well as the simulation scenarios.

Chapter 6 consists of a presentation of the results from the simulation scenarios.

Chapter 7 contains a discussion of the energy model that was made, discussion of the results presented in Chapter 6, and the possible impacts of the simulation results. The results are compared to other studies on related topics.

Based on the discussion in Chapter 7, a conclusion of the most interesting findings will be presented in chapter 8.

At last, in Chapter 9 some suggestions for further work associated with the of the thesis will be given.

2. Theory

Previous researchers have investigated how different techniques can dampen fluctuations in temperature and relative humidity in buildings. One measure that has been used by humans for a long time is exposed thermal mass. Other technologies that will be investigated for stabilizing either humidity or temperature are:

- Phase change materials (PCM)
- Moisture buffering in materials

These concepts will be introduced in this chapter. In addition, the current building regulations in Norway and passive house standard will be presented, as they form the reference cases for the simulations.

2.1. Temperature stabilization

In this chapter some properties that are necessary for temperature stabilization will explained. For building purposes temperature stabilization must either be done mechanically by ensuring supply temperature at a constant temperature with a small dead band, by heating and cooling equipment with high capacity or by passive or active measures of heat storage in building materials.

2.1.1. Thermal mass

Passive means of temperature stabilization has been known to human beings for a long time. During the times of cave men, they realized that the temperature was more stable a couple of meters into the cave, than on the outside [5]. Today, use of heavy building materials, such as concrete and bricks, are still used in a large part of the world to passively dampen the outdoor temperature fluctuations. Solar gains, and heat emitted from internal gains heats up buildings. To be able to stabilize the indoor temperature, the construction materials have to adsorb this excess heat to reduce peak temperatures. Sensible heat is the process when the storing process leads to a temperature change of the material. In buildings this absorption or release of sensible heat will happen when there is a temperature difference between the room air and the material. The amount of sensible heat, Q [J], that can be absorbed by a material depends on some properties, given in the equation:

$$Q = mc\Delta T \;=\; \rho c V \Delta T$$

Where
$\rho = density\ [kg/m^3]$
$c = heat\ capacity\ [J/\ kg * K]$
$V = volume\ [m^3]$
$\Delta T = temperature\ change$

These properties are important as they define the amount of heat that can be stored. Another important property is the thermal conductivity, $\lambda\ [W/mK]$, as it determines the rate of the heat exchange between the material and the ambient. A high thermal conductivity will make the heat go through the material quickly, and be "lost" to the environment on the other side. A low thermal conductivity, will slow down the storage process and no heat will be stored. The definition of thermal mass for building purposes is by SINTEF defined as the part of the building mass that can be used to absorb, store and release thermal energy [6]. During the day when the room air is warm, the heat is absorbed by the thermal mass. When the night comes, and the room temperature gets cooler, the thermal mass release the absorbed heat and heats up the room temperature. Figure 4 illustrates this concept.

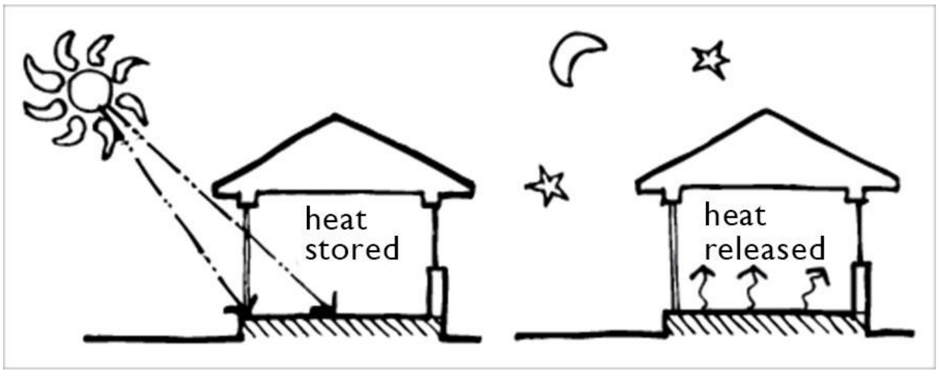


Figure 4: Illustration of thermal mass [7]

Some materials that works well as thermal mass in buildings, are heavy weight materials as concrete, bricks and stones [8]. Increased focus on energy efficiency and climate change has reintroduced thermal mass as a measure to reduce energy demand, cooling and heating needs and for load shifting. Several modern studies have investigated the impact of thermal mass on temperature fluctuation [9, 10]. Main findings from these studies are that the surface of the material must be in direct contact with the indoor air for the best dampening effect, and on the interior side of the insulation layer. Carpets, linoleum and other floor coverings limits the efficiency of the thermal mass, as the room air and thermal mass material are not in directly contact. In [10] Hyde et. al investigated if there was any limit of how much thermal mass one can insert in a building, where it won't have a stabilizing effect on the indoor temperature anymore. They concluded that an exponential relationship can be found between the quantity of thermal mass and diurnal temperature range, but could not conclude with an ideal amount of thermal mass. Even though this claims that the more thermal mass the better, it is not possible to fully stabilize the indoor temperature by passive measures alone. Other issues as bad acoustic environment might be an effect of large amounts of thermal mass [11].

2.1.2. Phase Change Material - PCM

While the passive use of thermal mass for sensible heat storage has been exploited by humans for a long time, the benefits of phase change materials has gotten increased focus the last years. The interest gained speed during the energy crisis in 1973 – 1974, and recent years the focus on climate change, and reduction of CO_2-emissions have speeded up the development and application of PCM again [12]. This increasing interest is supported by a study that counted the numbers of papers published related to PCM from year 2000 – 2014 [13]. A graphical representation can be found seen in Figure 5.

Figure 5: Number of PCM related papers published in 2000 – 2014 [13]

The high latent heat storage capacity of PCM materials is the reason for this increased interest. PCM can with the same volume as regular construction materials, like concrete and bricks, store 5 – 14 times as much thermal energy [14].

The heat storage capacity, Q, can for PCMs be defined as:

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT$$

Where,
$m = mass\ of\ material\ [kg]$
$C_p = specific\ heat\ capacity\ [kJ/kgK\ ]$
$T = temperature\ [K]$
$a_m = melted\ fraction\ of\ material$
$\Delta h_m = enthalpy\ of\ fusion\ (latent)[kJ/kg]$

The first differential is the solid fraction of the material for sensible heat, the second term is the latent heat of the phase change, and the last differential is the same as the first one, but for the liquid phase [15].

How PCM works

Phase change materials store and release heat when the material is changing its state (e.g. from solid to liquid). This happens at an almost constant temperature, and is called latent heat storage. The heat storage capacity during this transition has proven to be much higher than for sensible heat storage materials. In Figure 6 the heat capacity of some common construction materials is compared with the possible heat capacity of a regular phase change material.

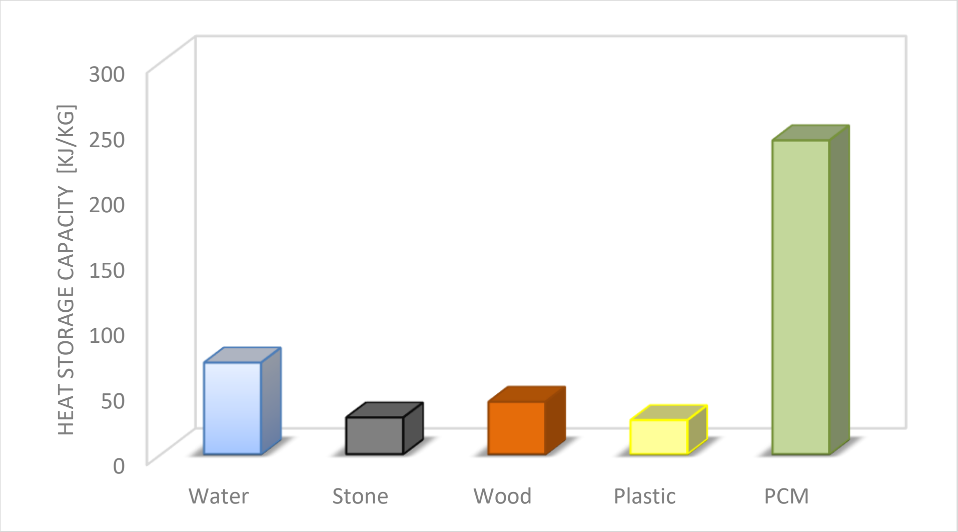


Figure 6: Heat storage capacity of some materials. Based on [13].

Figure 7 shows how PCM works, and the enthalpy-temperature diagram. Enthalpy is the heat absorbed or released from the material at each temperature step. PCMs have one peak melting/solidifying temperature, where a larger amount of heat is released or stored. This can be described as an enthalpy "jump", as on Figure 7. In theory, all of the material change state at this melting point, T_m, while in reality there's a temperature range where the phase change happens, where some of the material is liquid and some is solid.

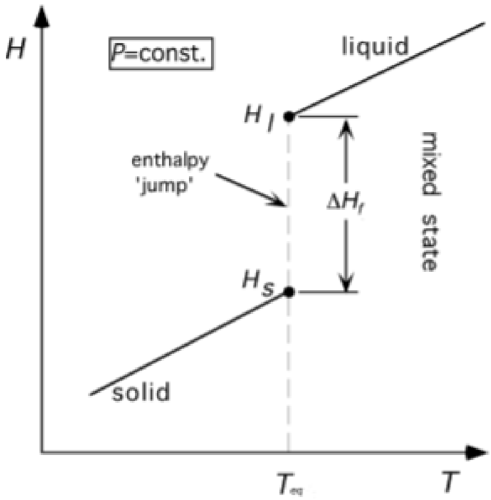


Figure 7: Example of temperature-enthalpy curve for phase change materials [16]

Classification of PCMs

Several natural or artificial materials are phase change materials. In Figure 8, an overview of classification of PCMs can be seen.

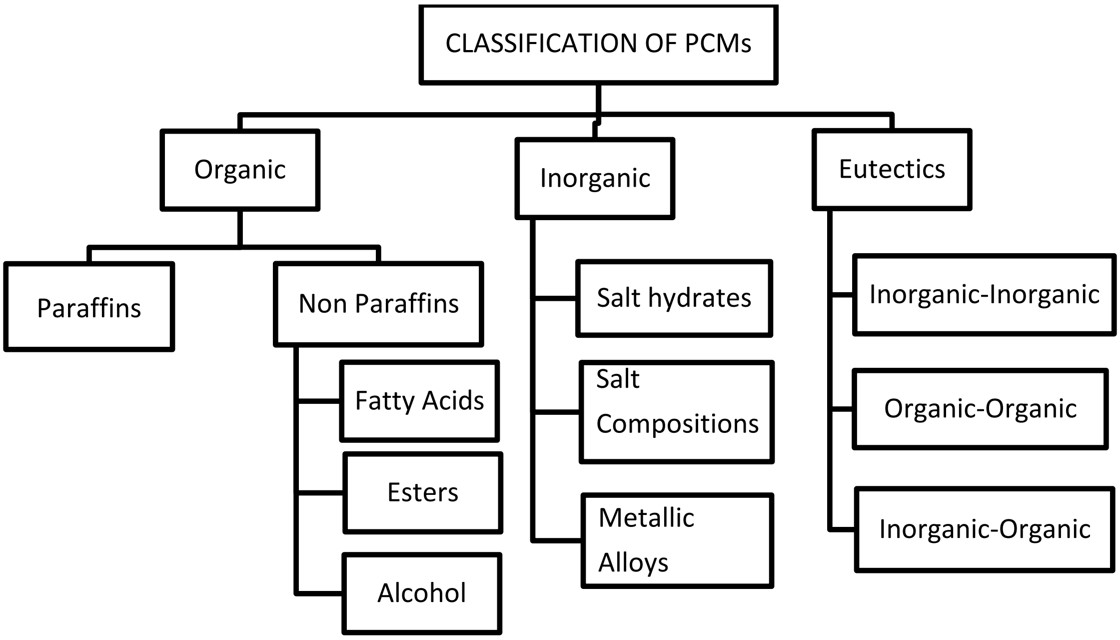


Figure 8: Classification of PCM materials. Based on [15, 17]

The main categories of PCM are organics, inorganics and eutectics. PCMs that contains a carbon atom are defined as organics. These are further divided into paraffines and non paraffines. They are available for a wide range of temperatures, and are stable up to 300°C [17], which gives them a wide range of use. Paraffin wax is cheap, has moderate thermal energy storage capacity and low density. Because of the energy storage and density, paraffin wax PCMs need a large surface area to be efficient [18].

Inorganic PCMs are products of either salt hydrates, salt compositions or metallic alloys. The hydrated salts have a large energy storage capacity and high thermal conductivity, which can be beneficial. On the other side they can be prone to supercooling and can be segregated during the phase. Generally the inorganic PCMs are great for thermal energy storage [15] especially for medium to high temperatures.

The last category, eutectics, is made by a combination of two or more components. It can either be a mix of two inorganic PCMs, two organic PCMs or an inorganic-organic mix.

Organics, inorganics and eutectics has different advantages and disadvantages. Some of these are summarized in Table 1 [15, 18-22]. The most suitable PCM depends on the application.

Table 1: Advantages and disadvantages with different PCMs

	Advantages	**Disadvantages**
Organics	Non-corrosive No segregation Low/none under-cooling Low/No supercooling Chemically stable Thermally stable Paraffin waxes are cheap Wide range of melting T Recyclable	Lower enthalpy for phase change Low thermal conductivity Need large surface to be efficient Can be flammable
Inorganics	High thermal conductivity High storage capacity Greater enthalpy of phase change High heat of fusion Low cost Availability Non-flammable	Corrosion Corrosive on metals Phase segregation Undercooling Lack of thermal stability
Eutectics	No segregation during melting and freezing Sharp melting point Higher volumetric storage capacity (than paraffines) Can customize properties	Limited data available on thermal and physical properties High cost

PCM for building purposes

Considering the benefits and drawbacks, some PCMs are better suited for application in buildings than others. For incorporation in buildings, inorganic salt hydrates, organic paraffin waxes or mixtures of these are mostly used [23]. PCM can be directly incorporated in interior surfaces like walls, ceiling or floors, or in the thermal envelope as external walls/roof or windows/shutters. Another alternative is implementation in ventilation systems or energy tanks for storing heat for peak shaving. The most recent experiments have been to enhance the insulation layer of buildings with PCM microcapsules, first started by Oak Ridge National Laboratory [24, 25].

PCMs can be made and incorporated into construction building materials in several ways. The normal ways are integration by immersion, direct incorporation and micro- or microencapsulation [26]. Immersion means that the building material is dipped into melted PCM, and that the building material absorbs the PCM by capillary action. For direct incorporation, the PCM is added directly in the construction material when it is produced. It can be done through mixing powder of PCM with gypsum powder when the gypsum board is manufactured, or by mixing it as an additive in concrete. Micro-encapsulation is the process where PCM particles are surrounded or coated by a film of another material (e.g. in an aluminium film) and macro-capsulation is where PCM is kept in large containers that are installed in the buildings.

One very important property for choosing PCM for buildings is that the phase change occurs close to the room temperature. In addition, good thermal conductivity, high latent heat by volume, and that the PCM gives low risk for occupants' health or the environment is important.

With increased study of PCM and their possible use, some commercial producers of PCM for building applications have entered the market. This includes Rubitherm, Climator, DuPont, InsolCorp, EPS Ltd, TEAP, Cristopia and PCM Products Ltd [27-32].

All papers studied conclude that PCM is efficient to limit temperature fluctuation in buildings, lower heating needs during the winter, or to lower or completely limit the cooling needs due to overheating in summer [20, 23, 26, 33-41]. Khadiran et al [22] are a bit sceptical to recommend PCMs. They concluded that the technology of PCM is promising, but also suggested that the installations and applications in buildings must be investigated further.

Reduction of temperature fluctuation has been investigated for various cubicles or buildings, and for different climates. Shilei et al. [39] concluded that for rooms with PCM in gypsum wallboards the max temperature fluctuation could be reduced by 1.15℃ during the Chinese winter. Another study done on cabins in New Zealand claims that indoor temperature fluctuation could be reduced by 4℃ [35]. Other studies have not quantified the temperature stabilization but agrees that PCM can smooth out daily temperature fluctuations for heavy-weight buildings [42, 43].

PCM application in a cold climate

The Viking Age Museum will be built in an area with cold winters, and mild summers. Most studies on PCM are conducted in warmer climates. Two studies done in similar climates to Norway is from the Netherlands and Sweden [40, 44]. These are done with focus on residential buildings. In the Dutch study, Entrop et al. had solar boxes with PCM in the floor. They found that the difference between min and max temperatures for the box without PCM was 6.2 ± 0.5℃, while the difference in the PCM box was 3.7 ± 0.5℃ on average. This shows that the temperature fluctuation could be reduced about 2.5℃ with PCM in the floor. A passive house was studied in the Swedish by Persson and Westermark. They did not quantify the fluctuation but concluded that the peak temperature could be reduced by 0.5 - 2℃ due to PCM.

In Norway, Vik et al. did an experimental study on PCM application for an office building by bio-based PCM [41]. The office room investigated had a floor area of 15m^2 and had 17m^2 exposed PCM for the maximum PCM scenario. They concluded that this amount of PCM could reduce the cooling significantly when directly exposed to the indoors.

Current implementation to real buildings in Norway is limited to storage tanks for cooling and load shifting. This has been implemented at the University of Bergen, Statoils' office in Bergen, as well as the new Bergen Airport [45]. Implementation of PCM wallboards, infused concrete slabs and other installations lack in Norwegian buildings.

Amounts of PCM in buildings

The heat that can be absorbed and released in building materials is dependent on the enthalpy at temperatures. Enthalpy is dependent on the density, which is related to the amounts of PCM that can be used. For some studies done at cubicles, the floor area is covered with PCM, and the possible effect is measured [44, 46]. Other studies have been done with PCM installed in the all internal walls [34, 47, 48], in internal walls and the ceiling [41, 47]. The amount and incorporation method of PCM varies.

2.2. Relative humidity stabilization

In this chapter the theory for relative humidity stabilization will be introduced. First some theory on humidity of air will be presented, before the humidity interaction between indoor air and building materials can be read. Then moisture buffering of various building materials can be found. At last, studies done on building materials and their effect of moisture buffering and dampening of relative humidity fluctuation will be presented.

2.2.1. Humidity of air

The air always contains water vapour. The water vapour content of the air can be specified in several ways, but a normal way to specify it is by the term “relative humidity”.

Relative humidity is defined as

$$\emptyset = \frac{v}{v_{sat}} = \frac{p_w}{p_{ws}}$$

Where

$p_w = vater\ vapour$

$p_{ws} = saturation\ vapour\ partial\ pressure,$

Usually presented in percent,

$$RH = \emptyset * 100\ [\%]$$

The air also has heat content, which is called Enthalpy. The amount of water vapour the air can hold is dependent on the air temperature, relative humidity, enthalpy and partial pressure. A way to represent the relation between these properties is the Mollier chart. The chart is often used in building physics and is a way to approximate changes in state for the air. An example of the simplified Mollier chart can be seen in Figure 9.

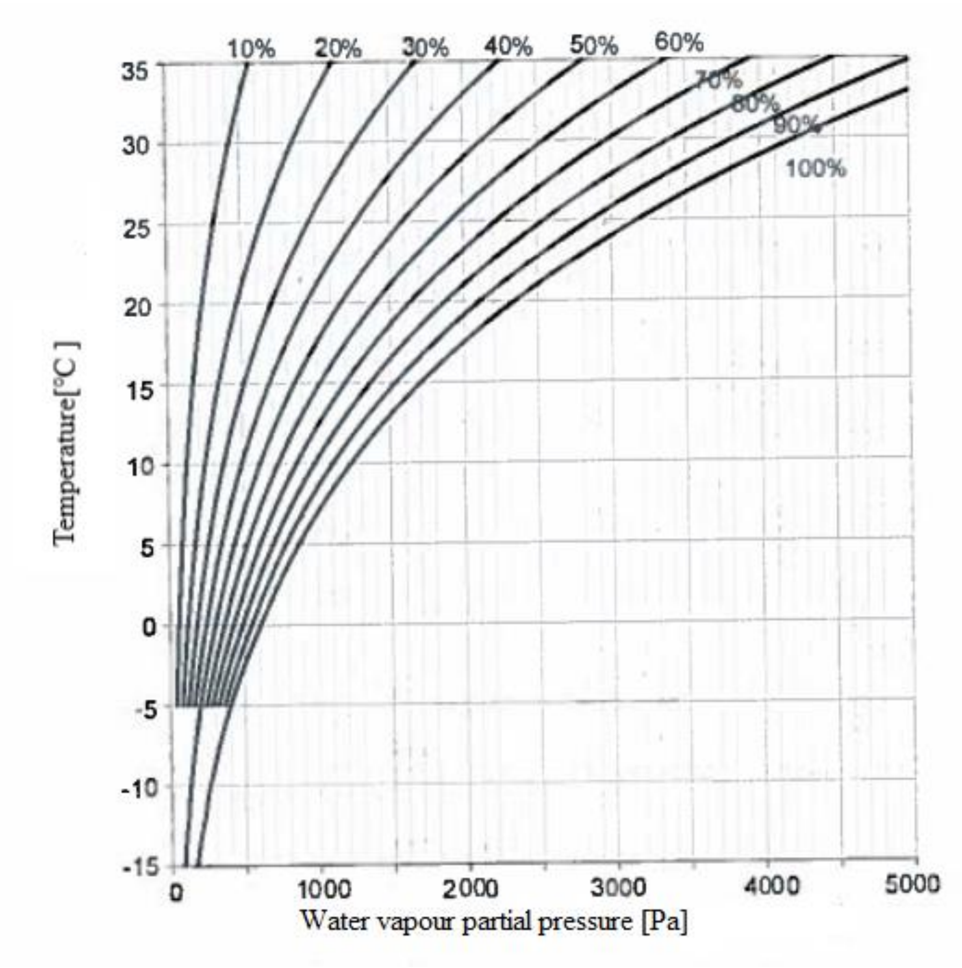


Figure 9: Simplified Mollier chart [49]

2.2.2. Interaction of air and moisture in building materials

When materials are in contact with humid air they will absorb some water vapour. The amount of moisture accumulation and the rate of absorption is dependent on the material, the pore structure and the way moisture is absorbed in the material. To have good moisture absorption possibilities, both pores and material should have a continuous structure, or the material can have a discontinuous structure, with continuous pore structure. These properties give space for water and water transport in the material. Materials with these kinds of pore structures are called hygroscopic materials, and are good for moisture buffering.

The water can be bound in the material either chemically or physically. For moisture buffering, the adsorptive and capillary condensation physical binding is the most import ones. In the beginning, adsorptive binding on the surface is the main source to moisture absorption, while the capillary condensation in the material takes over further into the material. [50]

Any material for building purposes have different properties for absorbing and releasing humidity. Porous materials can have moisture as water vapour, capillary-bound water and ice in their pores. The materials will absorb some of the water vapour in the room air, dependent on their capacity, and on the moisture load in the room. This capacity is dependent on their equilibrium moisture content [51]. A way to quantify the possible moisture absorption and desorption is to look at the moisture storage function for the material. An example can be seen in Figure 10 below. The equilibrium moisture content is when the humidity for the surrounding air is met. The material can absorb water until it reaches what is called the free water saturation, w_f. On the figure below this is when the relative humidity is 100%. It can also be seen that the w_f is less than w_{max}. At free water saturation, there is still pores inside the material that are filled with air, so the porosity of the material determines the w_{max}. w_{80} is also marked on the figure. This is called the practical moisture content, and is often used for estimations.

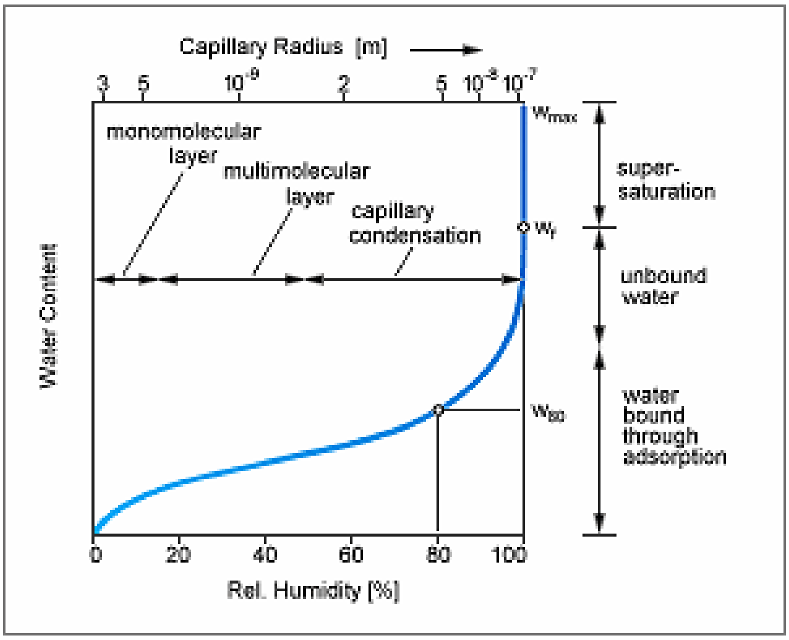


Figure 10: Example of a moisture storage function for a material [52]

Another important property for the uptake of water vapour is the water vapour resistance factor. It is denoted µ, and defined as the water vapour permeability of air, divided by the water vapour permeability of the specific material [53] . Since it is a relative quantity it does not have a specified unit. When materials are exposed to various levels of humidity, measurements have shown that the same material can obtain different values. This is since the surface diffusion is apparent at higher levels humidity [54]. Porous materials can have µ close to 1, and less permeable materials have higher values.

For a long time, no classification system existed to determine, compare and categorize the moisture buffering of materials. A new test method by NORTEST defines the Moisture Buffer Value (MBV) [55]. The test procedures consist of a typical exposure, like a daily variation. The MBV “*indicated the amount of water that is transported in or out of a material per open surface area, during a prescribed period of time, then it is subjected to specific variations in relative humidity of the surrounding air with a specified velocity”*[55]

Figure 11 shows a graphical representation of the ranges for classification of mositure buffering values (MBV). The materials that have good or excellent MBV could possible reduce the indoor humidity fluctiations.

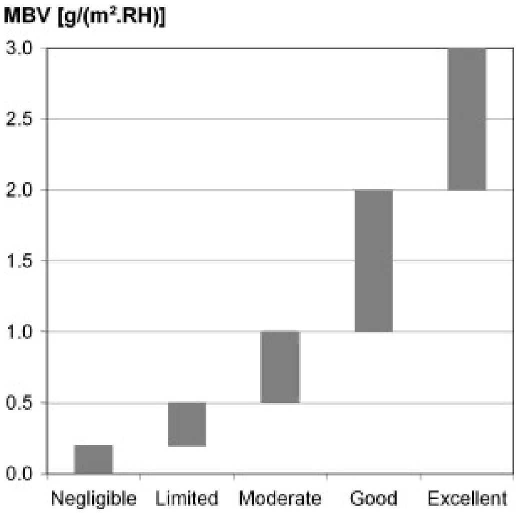


Figure 11: Ranges for classification of MBV [56]

Below in Figure 12 the measured MBV found through the NORTEST test can be seen. In this classification system, only sprayed hemp concrete seems to have a sufficient moisture buffering value.

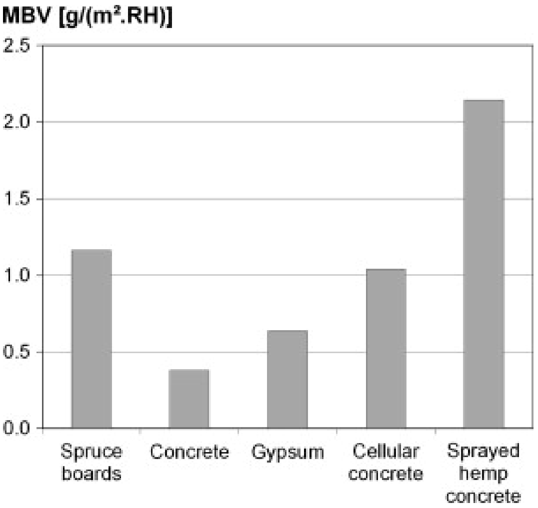


Figure 12: MBV for some regular construction materials [56]

2.2.3. Moisture buffering of materials for building purposes

For buildings with strict requirements for indoor relative humidity, the RH must be controlled. It is possible to install modern HVAC-systems that can fully control the environment, but this is very energy extensive, and also takes up a lot of volume for pipes. Therefore, it is needed to look at passive measures to help control the indoor humidity. Already from early years, passive measures were used. One of the earliest attempts found in literature is McIntyre who apparently reduced the relative humidity for the Hampton Court Palace in England in 1934. His invention was to buffer the moist in the ventilation ducts by putting old linen there [57].

Since then Moisture buffering of materials have been investigated by many researchers. To estimate at what conditions the material will degrade and lose their purpose, to estimate the moisture buffering capacity for materials, and to some extend reduce relative humidity fluctuation.

Padfield and Jensen [58] and Mitamura et al. [59] did studies on different porous materials and their moisture buffering capacity. While Padfield conducted the study on climate chambers, the studies of Mitamura et al. used a room sized cell for the tests. The conclusion for both studies was that wood panels had the best moisture buffering capacity, but that cellular concrete came second. Of commercial produced construction, Padfield and Jensen stated that cellular concrete with an additional gypsum board had the best capacity.

At the Technical University of Denmark, Mortensen et al. conducted full scale tests on moisture buffering of cellular concrete and plaster boards, with various finish materials [60]. Unfinished material seems to have the best moisture buffering effect, and this effect is strongly reduced when paint or other finish material is applied.

Another report from DTU by Rode et al. [60] summarized that building materials in contact with the indoor air can moderate the humidity fluctuations of the air. Materials tested were wood boards, gypsum, concrete, cellular concrete and bricks. Concrete had the lowest moisture buffering value, while spruce boards and cellular concrete had the highest values. The moisture buffering value definition defined in this study describe the materials ability to exchange vapour with the indoor environment of a room.

Ferreira et al. investigated how hygroscopic materials could dampen relative humidity when the museums are situated in old buildings [61]. The assessment concluded that changing the finishing materials of walls and ceilings to a highly hygroscopic material, spruce wood panels that were covered with mineral binders, could decrease the relative humidity stabilization index by 30%.

Holm et al. [62] did simulations for a dwelling with gypsum plaster on the interior side of the construction. Less fluctuation could be seen for the case with gypsum plaster, compared to the case with a vapour tight interior surface.

Studies mentioned above states that relative humidity swings could be dampened by hygroscopic materials. Simonson et al. [63] also concludes that increasing the ventilation has a stronger impact on the average indoor conditions than the hygroscopic materials can for most cases. Their results conclude that the ventilation rate can be decreased for a room when hygroscopic materials are used, without compromising on the relative humidity. Depending on criteria and variables, the peak could be lowered by 20 – 50%.

Museums have quite short amount of time with load from people, depending on the opening hours. This makes them suitable for absorbent walls. By installation of absorbent walls the moisture production produced by people during the operating hours can be stored in the structure, and then the climate system can neutralize the indoor climate when there's nobody present [57].

2.3. Norwegian building regulations

Norway has building regulations that everyone who wants to raise a building must follow. The abbreviation for this regulation is TEK. Energy efficiency requirements which are relevant for this study will be presented here. In addition to the building regulations, buildings can achieve the Norwegian passive house standard, which is stricter than the building regulations. The energy efficiency requirements for buildings that want to achieve passive house standard will also be presented here.

2.3.1. TEK - Regulations on technical requirements for construction works

Until 01.01.2017, new buildings in Norway had to fulfil the minimum requirements in the "Regulations on technical requirements for building works", TEK10. From 01.01.2017 the Norwegian government upgraded the building code to TEK17. The minimum requirements related to energy efficiency of public buildings did not change. Table 2 gives an overview of the minimum requirements for energy efficiency, specified in TEK. It is up to the contractors how these minimum requirements will be fulfilled.

Table 2: Minimum requirements for construction parts [64]

U-value, external wall [W/(m^{2}K)]	U-value, roof [W/(m^{2}K)]	U-value, floors on ground and facing open air [W/(m^{2}K)]	U-value, windows and doors including frames [W/(m^{2}K)]	Leakage figures at 50 Pa pressure differential [air change/h]
≤ 0.22	≤ 0.18	≤ 0.18	≤ 1.2	≤ 1.5

From NS3031 – Table A.4: Standardized normalized thermal bridge value: 0.12 W/(m^{2}K) [65].

This is only minimum requirements. By use of the energy frame method it is possible to have a higher thermal transmittance for some parts, and lower for other parts, as long as the net energy need is lower than the specified "frame".

2.3.2. Passive house standard

The passive house concepts originate from the Passive house institute in Germany founded in 1996 [66]. Through the foundation, the institute has gained considerable success in Germany and other European countries for energy efficient and environmental friendly buildings. A committee from Standard Norge has developed a Norwegian standard for requirements to passive houses. The passive house standard NS 3701:2012 was published in September 2012, and gives the official requirements for Norway. The passive house concepts originate from the Passive house institute in Germany founded in 1996 [66]. Through the foundation, the institute has gained considerable success in Germany and other European countries for energy efficient and environmental friendly buildings. A committee from Standard Norge has developed a Norwegian standard for requirements to passive houses. The passive house standard NS 3701:2012 was published in September 2012, and gives the official requirements for Norway.

The new part of the museum will have a big volume compared to the floor area. This makes it difficult to fulfil the strict passive house requirements for energy demand, and at the same time maintaining a sufficient indoor climate for the objects. Also, the old museum and the new one will be connected as one museum, making it even more difficult for the building in total to achieve passive house standard. Therefore, it is required that the separate building parts and leakage numbers will be in accordance with NS3701:2012, but not the net energy need. The minimum requirement for energy efficiency for building parts can be found in Table 3.

Table 3: Minimum requirements for energy efficiency of construction parts [67]

U-value, external wall [W/(m^2K)]	U-value, roof [W/(m^2K)]	U-value, floors on ground and facing open air [W/(m^2K)]	U-value, windows and doors including frames [W/(m^2K)]	Leakage figures at 50 Pa pressure differential [air change/h]
≤ 0.12	≤ 0.08	≤ 0.08	≤ 0.8	≤ 0.6

From NS3701:2012 – Table 9 – Standardized normalized thermal bridge value: 0.03 W/(m^2K) [67].

Passive houses will to a better extent than other buildings separate the indoor environment from the fluctuations of the outdoor conditions. Therefore, museums are appropriate buildings for passive houses, as it is easier to control the indoor environment, when the internal gains makes up most of the load for the HVAC-system [68].

3. Building performance simulation

Simulations in IDA ICE are the main method used for investigation in this thesis. An introduction to building performance simulation will be presented here, as well as current issue with interoperability between BIM and energy modelling.

3.1. Building Performance Simulation

Building performance simulation has gotten increased focus the previous years. With dynamic whole building simulation programs it is possible to investigate the effects of different design solutions before the building is built. This gives many opportunities for building designers, but also big requirements for knowledge about the building and how the simulation programs work. Their shortage and limitations must be known to the user, so right simulation tool can be used for the purpose of the simulation.

3.2. IDA Indoor Air and Climate

IDA Indoor Climate and Energy, IDA ICE, is a dynamic whole building simulation program that lets the user simulate the indoor climate and energy need of a building that can consist of several zones. The program is made by EQUA Simulation AB in Sweden, and the first version was released in 1989. IDA ICE can be used both for Early Stage design purposes, and for more detailed analysis with a standard level and an advanced level. The description of components in the program is based on a language called Neutral Model Format. Advanced users can use this to build their own advanced systems when needed. A benefit with IDA ICE is the open source code. This makes it possible for the user to understand the governing equations used for the simulation One of the major benefits of IDA ICE is the 3D-visualisation of the building. The 3D-view can be used for presenting simulation results, which makes it easier for designers, engineers and clients to visualize the consequences of design choices [69].

3.3. Challenges - BIM export for Energy modelling

When several companies are producing software for similar purposes, some issues are coming up. One of the current issues in the industry is the lack of communication between the programs. With a lack of communication and export/import possibilities, some work must be done twice, in two different programs. This is very time consuming, and several consultancy companies are working to make the import/export between programs more seamless. IFC is one of the formats that have been developed with seamless transaction of information in mind. Several programs have made it possible to export IFC-files, that contain extensive information about the building parts. The IFC-file can then be imported in Energy Modelling programmes, (e.g. IDA ICE), and be used to run energy- and indoor climate simulations. Even though IDA ICE is one of the programs that claims to be IFC-compatible, still some work is lacking to make the import seamless. Also, the people that are making the IFC-files, needs knowledge on how to make the files fit for export for energy modelling. Erichsen and Horgen is one of the companies that have tried to make a report on the prerequisites for import of IFC-models made in BIM-programs for energy simulations [70]. However, Hjellnes Consult claimed that some of these recommendations is conflicting with good BIM- practises. This points out the ongoing contradictions in the industry.

4. Simulation model of the Viking Age Museum

In this chapter the creation of the energy model in IDA ICE will be presented. To make detailed and accurate simulations a collection of input values and assumptions are required.

4.1. Localization and climate

One of the most important inputs in energy models is the chosen weather data. This is the boundary conditions for the building, and consist of information on solar gains, wind speed, radiation, relative humidity and temperature. In IDA ICE, it is possible to download weather data for various locations around the world. They are provided from ASHRAE, the American Society of Heating and Air-Conditioning Engineers. The Viking age museum will be built on the west side of Oslo, at Bygdøy. The weather file for Oslo, Gardermoen was downloaded from ASHRAE IW2 database provided inside IDA ICE [69], and Table 4 gives a shortlist of the data.

Table 4: Weather data for Oslo, Gardermoen from ASHRAE IWEC2 downloaded in IDA ICE [69]

	Variables						
	Dry-bulb temp, °C	Rel. humidity of air %	Direct normal rad, W/m^2	Diffuse rad on hor. Surface W/m^2	Wind speed, x-component m/s	Wind speed, y-component	Cloudness %
January	-7.2	85.3	59.0	9.0	0.1	-0.4	56.6
February	-4.9	81.0	103.7	24.2	0.5	-0.3	57.6
March	-1.8	77.1	154.3	51.1	0.1	1.2	55.2
April	2.8	73.6	133.3	87.8	-0.5	-0.3	63.1
May	10.7	56.9	201.1	115.2	0.1	-0.8	59.1
June	13.2	65.0	183.2	133.6	0.2	0.6	64.5
July	15.6	67.6	185.5	125.4	0.2	-1.0	60.8
August	14.8	74.4	152.8	100.7	-0.6	-0.6	64.7
September	9.8	77.0	121.1	65.3	-0.2	0.5	62.7
October	4.9	85.8	101.2	32.8	-0.4	0.9	59.0
November	0.7	87.7	63.2	13.4	-0.3	1.4	63.1
December	-3.2	93.5	37.4	6.3	0.0	0.3	60.5
January	-1.4	77.3	96	5.8	-0.5	-2.8	31.3
Mean	4.7	77.1	124.7	63.8	-0.1	0.1	60.5
Min	-7.2	56.9	37.4	5.8	-0.6	-2.8	31.3
Max	15.6	93.5	201.1	133.6	0.5	1.4	64.7

The information is adjusted with the latitude, longitude and elevation at the position of the museum at Bygdøy [71].

Latitude:	59.9 N
Longitude	10.68 E
Elevation	16.5m

4.2. Building body geometry and zones

In this chapter the process of making the building body and zones in IDA ICE will be presented.

4.2.1. Building body geometry

The model of the building body and zone in IDA ICE was made based on several sources. Emails from Hjellnes Consult, the BIM-model made in Revit, in addition to a report from Statsbygg [72] is what the information is based on. The model in Revit also consisted of several 2D floor plans and structural plans that were used.

For this project, a BIM- model made in Revit was shared by Hjellnes Consult. To be able to edit a BIM-file, the user needs editing rights which was not obtained. As mentioned in the chapter about simulation programs, the direct import of IFC-files from BIM to Energy Modelling programs are still under development and a big issue in the industry. The IFC-file of the Viking age museum contained excess information about building parts, while it was lacking essential information. E.g. the windows of the outer perimeter of the building was categorized as holes in the wall construction, and detailed information about construction materials were lacking. Direct import of the BIM-file to IDA ICE was not beneficial or possible. To make an energy model some modification had to be done in several computer programs. A float diagram of this process can be seen in Figure 13.

Figure 13: Float diagram of how the geometry of the model was made

The floor plans from the BIM-model in Revit was exported to AutoCad. In AutoCad all the irrelevant elements were deleted, and the rounded geometry was simplified. This process can be seen in Figure 14 – Figure 17.

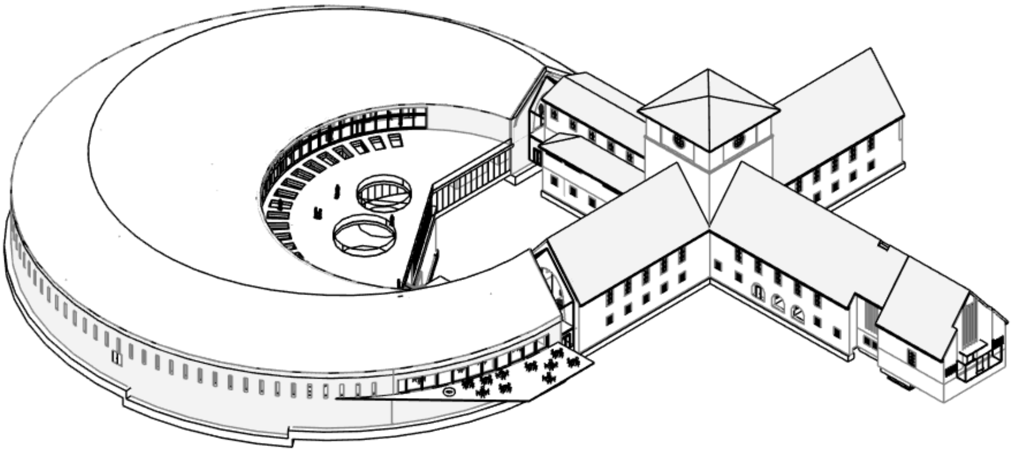


Figure 14: BIM-model screenshotted from Revit.

In Figure 15 the floor plan from Revit was imported in AutoCad. A lot of helping lines are used by the architect to make the model, but this is confusing and excess information when an energy model shall be made.

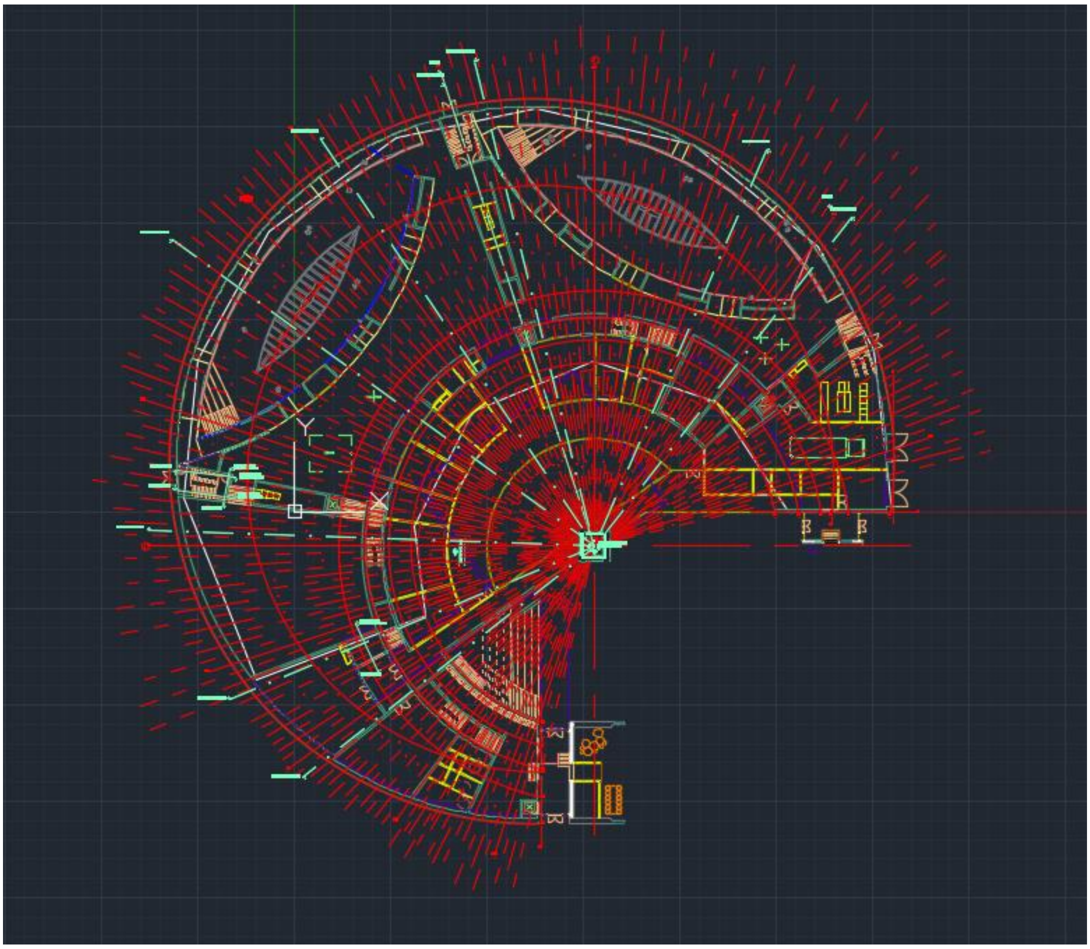


Figure 15: Floor plan of level U1, exported from Revit and imported in AutoCad

Figure 16 and Figure 17 shows the floor plans when a lot of the excess helping lines are removed, and the specification of the new external floors (Blue lines in Figure 17).

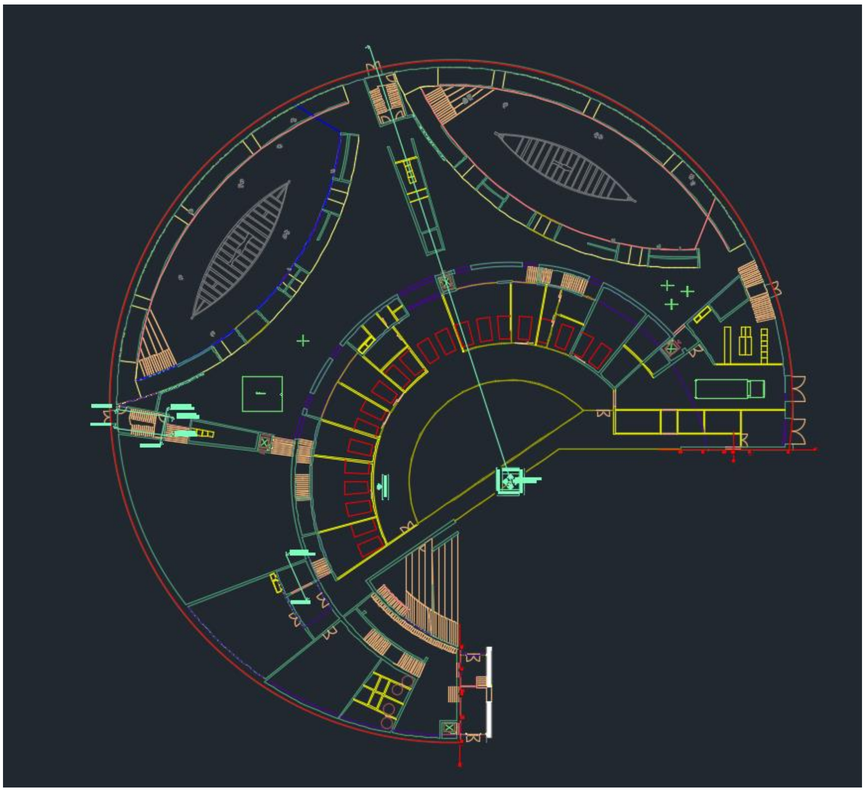


Figure 16: The floorplan without excess information.

Figure 17: Simplified floorplan made in AutoCad. The blue shining lines are the ones that are exported.

To make an Energy model in IDA ICE, a building body must be defined. The building body can be made directly in IDA ICE, or made in other programs and imported. The building body need to have specified points on the outer perimeter of the building, as well as heights to determine the air volume of the rooms. For an experienced AutoCad user who knows how to make 3D elements, it might be possible to make a 3D building body directly from the floor plans in AutoCad and export this (as an dxf, 3ds or skp file) to IDA ICE. For this thesis, two building bodies was made in SketchUp instead.

When the floorplans were imported in SketchUp, the building body was made by a push/pull tool to the accurate height of the zone. This can be seen in Figure 18. The heights of the zones were estimated from drawings in the Statsbygg report [72]. Level U1 has a height of 4.2 and level 1 3.9m. the height from where the curved roof starts till the top of the interior side of the ceiling is 5.43m.

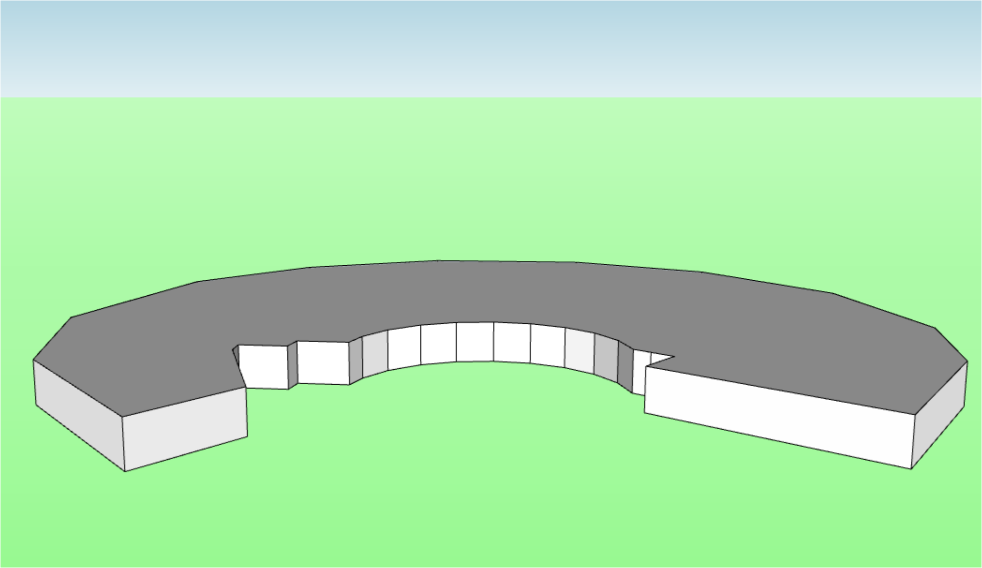


Figure 18: Illustration of building body of level U1 made in SketchUp

After the building bodies were made in SketchUp, they were imported in IDA ICE. Their surfaces define the boundary between the indoor and outdoor conditions. In IDA ICE the building body is defined as the interior side of the wall. To make the roof, the roof editor in IDA ICE was used.

4.2.2. Zones

In IDA ICE, the building must be divided into thermal zones. A thermal zone corresponds to the indoor air volume of a room. For simplification and to shorten down computational time, rooms with same internal gains, ventilation system, heating- and cooling setpoints as well as orientation can be defined as one thermal zone. Due to solar gains, rooms with different orientations, or far away from the perimeter should be simulated as separate zones [73].

To make thermal zones in IDA ICE, the simplified floor plans were imported as dwg-files from AutoCad, and moved to their respective heights. Zones were then added inside the drawing lines that corresponds to the rooms.

The building was divided into 13 zones. 7 zones for the lower floor, and 6 zones for the upper floor. The zones of interest, where the indoor conditions will be analysed, are called Gokstad and Oseberg. This is the name of two of the Viking ships that will be exhibited there. The other rooms in the building were included in the model because they will have an impact on the zones of Gokstad and Oseberg. The building was divided into two floors, called level U1 and the level 1. Since it is not possible to make zones over more than one floor level in IDA ICE, the open exhibition areas of Gokstad and Oseberg was made as two zones with a horizontal opening between them. Figure 19 shows an illustration of how the exhibition halls are illustrated by the architects, and Figure 20 shows how this is implemented in IDA ICE. Unfortunately, it is not possible with the current version of IDA ICE to rotate the openings to more accurately represent the open areas between the zones. This means that the area of the openings is smaller than the real case, and can lead to some disparities of the real airflow and temperature distribution. Another way to model the openings is to put two horizontal openings next to each other. This makes the area of the opening more accurate than implementing just one opening.

Figure 19: Illustration of open areas in the exhibition zone of Gokstad [72]

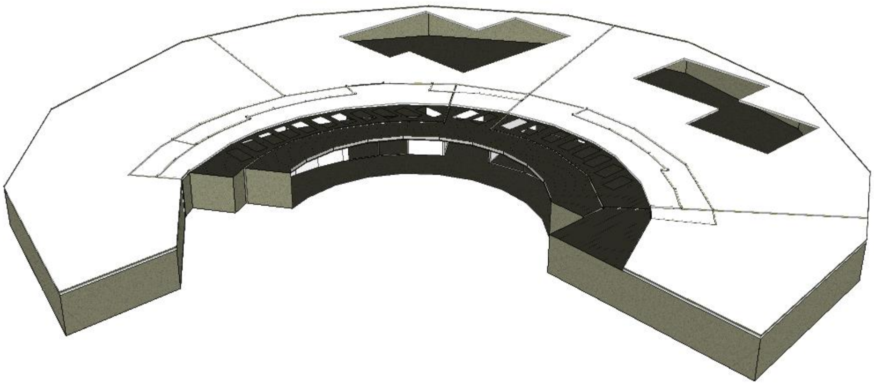


Figure 20:How the open areas are modelled in IDA ICE, view from level 1 to U1

Description of zones

Figure 21 and Figure 22 illustrates how the building was divided into thermal zones. The offices and common working areas is where the workers of the museum will be preparing the museum objects or rehabilitate them. Some of the offices have glazed walls towards Gokstad and Oseberg halls, so visitors can observe the workers in action. This was included in the model. The common working area has some glazed walls and doors towards the offices, and structural wall towards the inner courtyard that was implemented. In the common working area, the workers can either work, while visitors can watch through the windows or they can showcase temporary exhibitions.

The zones called Rooms are where the museum will receive goods, have toilets, cabinets for technical stuff or other needs. For simplification these rooms have been merged together. On level 1, there will also be a café, called cafeteria & exhibition on the figure.

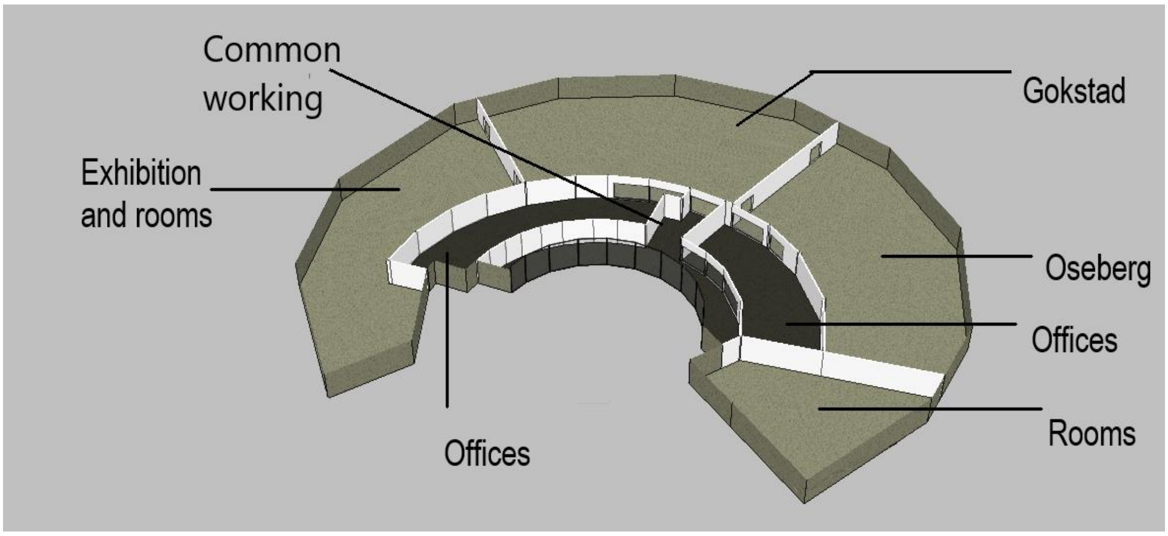


Figure 21:Illustration of the zones, level U1 (From IDA ICE)

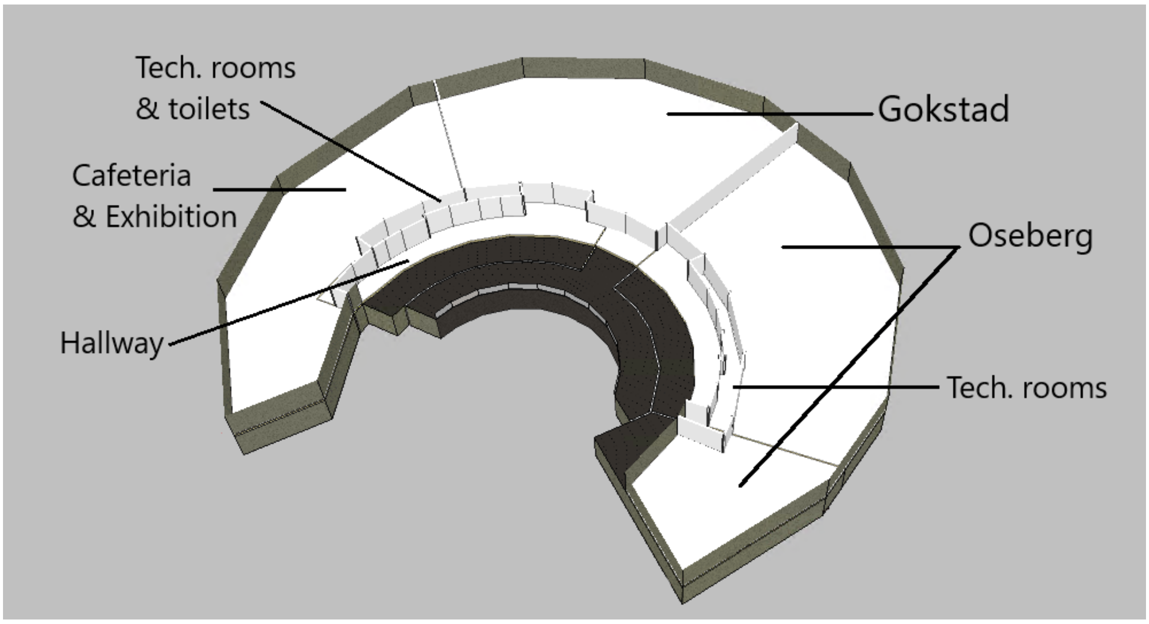


Figure 22: Illustration of the zones, level 1 (From IDA ICE)

4.3. Simplifications

Several simplifications were made, to shorten the computational time. As long as the simplifications are well thought through, and won't have a critical impact on the purpose of the investigation it is fine. This is called "fit for purpose", and a normal way to simplify and shorten down computational time of the simulations. In early stage design there's a lot of uncertainties, so simplifications are important. The simplification done for this study in IDA ICE will be presented here.

4.3.1. Windows

Daylight is not one of the objects of this study. The windows are in the model to give a prediction of the solar gains distributed to the different zones. Therefore, all windows on an external wall can be merged to one big window, with the same glazing area as the windows in total. The total area of the frame is also added here. This simplification can be seen in Figure 23 and Figure 24.

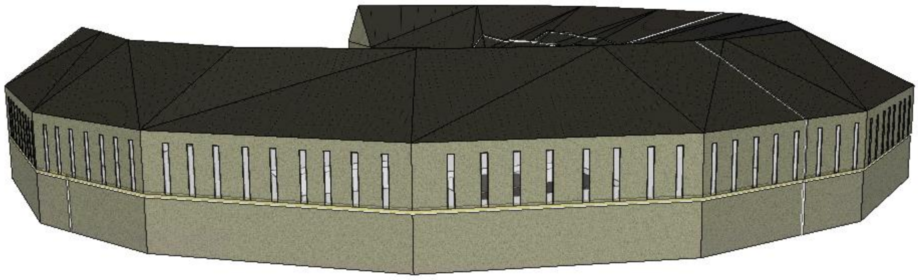


Figure 23: Windows on outer perimeter, as designed

⇩

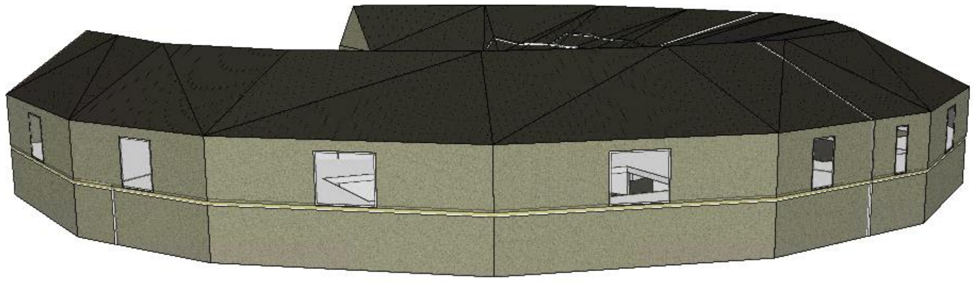


Figure 24: Windows after simplification

4.3.2. Geometry

The building has a rounded geometry with an inner perimeter towards the existing Viking Ship museum. As it was not possible to import and simplify the model in Revit as an IFC-file directly in IDA ICE, it was decided to use the floor plans and simplify the geometry of the curved external walls in AutoCad. This can be seen in Figure 25. The red curve is the actual inner surface of the building, while the blue lines are the simplified walls.

Figure 25: Simplification of the geometry of the building

4.3.3. Shading

Some trees will be planted that will give throw shadows on the building for some parts of the year. The trees were made in SketchUp, but when they were added in IDA ICE, the simulation wouldn’t run. Since there was no straightforward way to implement them after some attempts, they have been neglected. Especially two tall trees that are planned to be planted in the inner courtyard between the museum buildings, will provide shade to the curtain walls on both floors during the spring and summer. This will lower the solar gains in these zones. Figure 26 below shows gives an illustration of the building in IDA ICE when trees and the existing museum was added. The shadows from the old museum building and trees can be seen.

Figure 26: 3D model in IDA ICE with shading from trees and old museum building

4.4. Input data

In this chapter the input data in IDA ICE will be presented. As the output is dependent on the input values, a comprehensive overview of the model will be presented.

4.4.1. Areas

The net area and height of the different zones are:

Area of Gokstad level U1:	1261m^2
Area of Gokstad level 1:	1291m^2
Area of Oseberg level U1:	1094m^2
Area of Oseberg level1:	1406m^2
Floor height level U1:	4.2m^2
Floor height level 1:	3.9m^2

The height of level 1, is from the upper surface of the separating floors, till where the curved ceiling starts. From the curved ceiling till the highest point of the ceiling it is 5.43m.

4.4.2. Air handling unit

The air handling units is added with heat exchanger, heating coil, and cooling coil. Airflow for the zones were added as:

Gokstad & Oseberg:	$15m^3/(h \cdot m^2)$
Other rooms:	$10m^3/(h \cdot m^2)$

Corresponding to numbers received from Hjellnes and the Statsbygg report.

4.4.3. Shading and orientation

To calculate the solar gains correctly, nearby buildings and terrain must be considered. Since the surrounding terrain is flat [72], and the trees were too complex to model, only the current Viking Ship museum was included. The building body of was made in SketchUp, based on measurements of the BIM-file, and then imported as a CAD-object in IDA ICE. When imported in IDA ICE, the button “calculate shadows” was checked. Both the new Viking Age Museum, and the Viking Ship Museum were oriented 350° to have the right orientation. Figure 27 shows an illustration of shadows, orientation and both museum buildings.

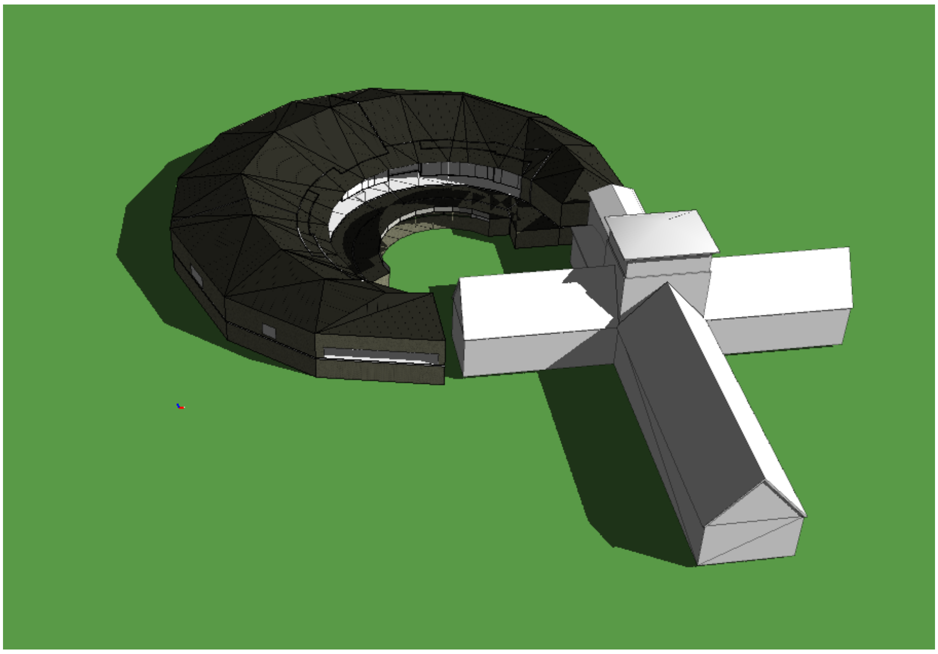


Figure 27: Model of the new and old museum building and illustration of shadows. The screenshot is at 10 AM on the 21st of July, seen from the south.

4.4.4. Construction materials

The museum will mainly consist of heavy materials. Since the project is in the early design phase, the correct material properties are uncertain. The standard values for heat conductivity, density and specific heat was taken from the IDA ICE database.

In the Statsbygg report it is defined that the external walls will have different structure, depending on where it will be situated. For simplifications the structure in Table 5 was assumed for all external floors. A figure that illustrates the structure can be seen in Figure 28.

Table 5: Structure of the external walls

Material
Natural slate
Ventilated gap w/wood spacers
Wind barrier
Metal frame + insulation
Concrete

Figure 28: Illustration of the external wall construction

For slab towards ground, the structure and materials can be seen in Table 6 and Figure 29

Table 6: Structure of the slab towards ground. From inside to outside

Material
Terrazzo tiles
Screed
XPS, insulation
Gravel, drainage layer
Concrete slab

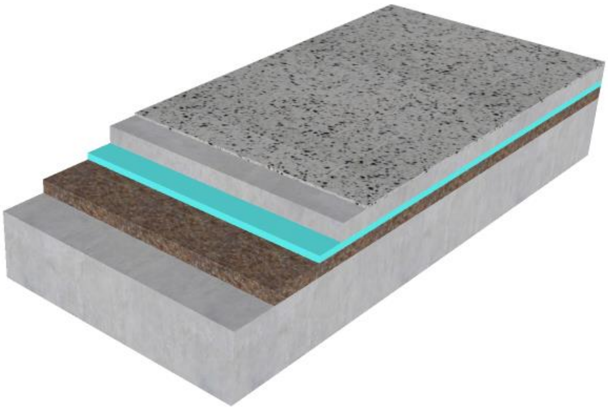


Figure 29: Structure of the slab towards ground

The roof is built up a little differently depending on where it is placed. The curved roof construction takes up most of the roof area. For simplification the roof was assumed to be the same everywhere. The materials and structure of the roof can be seen in Table 7 and Figure 30.

Table 7: Structure of the roof

Material
Natural slate
Wood spacers
Cardboard (wind barrier)
Ventilated gap
Mineral wool insulation + wood
Mineral wool insulation + wood
Concrete rib construction
Membrane

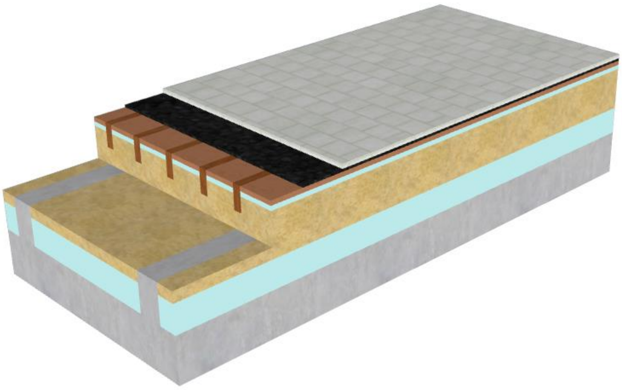


Figure 30: Structure of the roof construction

In Table 8 and Figure 31 the structure of the partition floors can be seen. Some parts of the museum will have suspended ceilings, but since there is no good way to implement this in IDA ICE, this structure is assumed for all partition floors.

Table 8: Structure of partition floors

Material
Terrazzo tiles
Screed
Concrete slab

Figure 31: Structure of partition floors

4.4.5. Glazing - Windows, curtain walls and skylight

The museum has a large area with windows, curtain walls and skylight. The windows on the outer perimeter of the building are high and narrow. Their dimension is 0.5m wide, and 3.85m high. How they were implemented can be seen in Figure 32. A standard window was chosen in IDA ICE database, and the U-values adjusted to the right values.

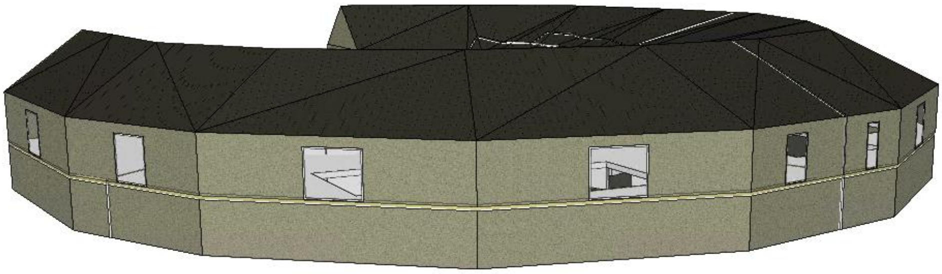


Figure 32: Illustration of the windows on the outer perimeter of the museum

The walls against the inner perimeter and courtyard are made of curtain walls for both floors. On level 1 the curtain walls are installed in between wooden beams, and on level 1 structural glass with be installed between aluminium frames. How this was implemented in IDA ICE can be seen in Figure 33.

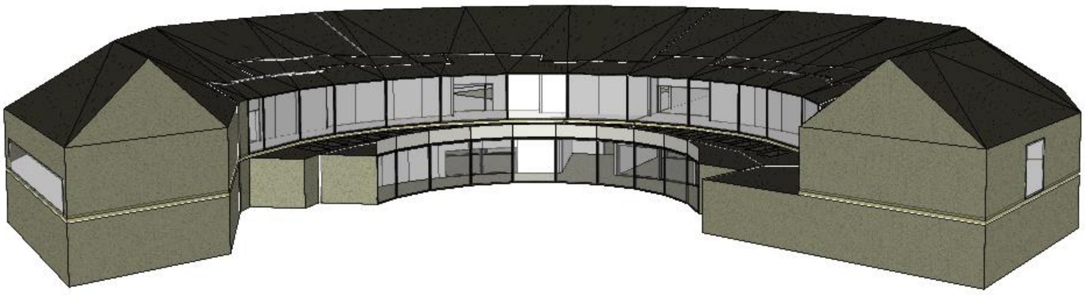


Figure 33: Illustration of the curtain walls on the inner perimeter of the building

The area of level U1 is larger than the area of level 1. A slab in between them will let the visitors walk outside in a courtyard, and will also have skylights. This can be seen as the black slab above the 1st floor on Figure 34. Rails that will be present on the slab can also be seen on the figure. These are added as they provide some shadows on the skylights.

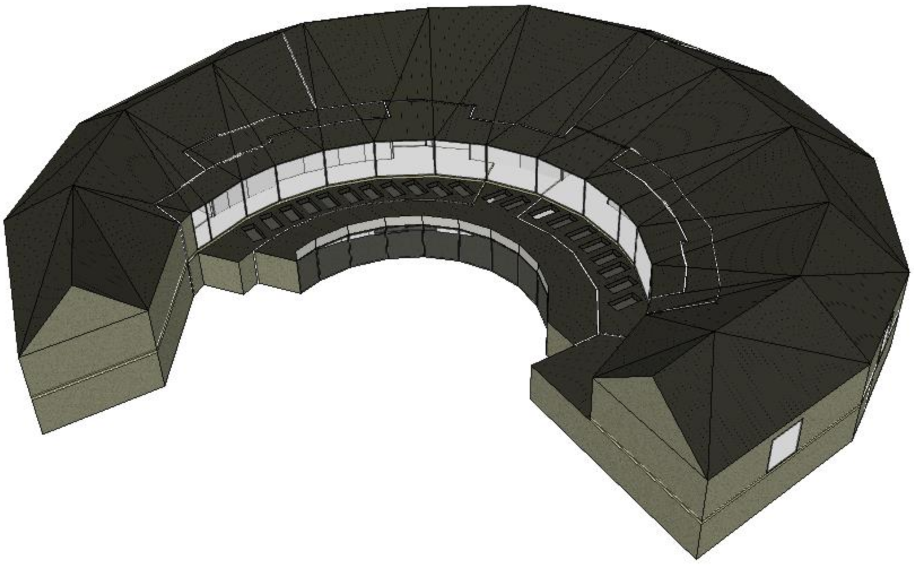


Figure 34: Illustration of the building with skylights and railing towards inner perimeter

Skylights on the slab will provide daylight to the offices at level U1, as well as they give visitors the possibility to watch workers in action. IDA ICE has models for skylight that were used. That was concluded to be important as the skylights will provide solar gains to the offices in level U1. An illustration of the illuminance from the skylight can be seen in Figure 35.

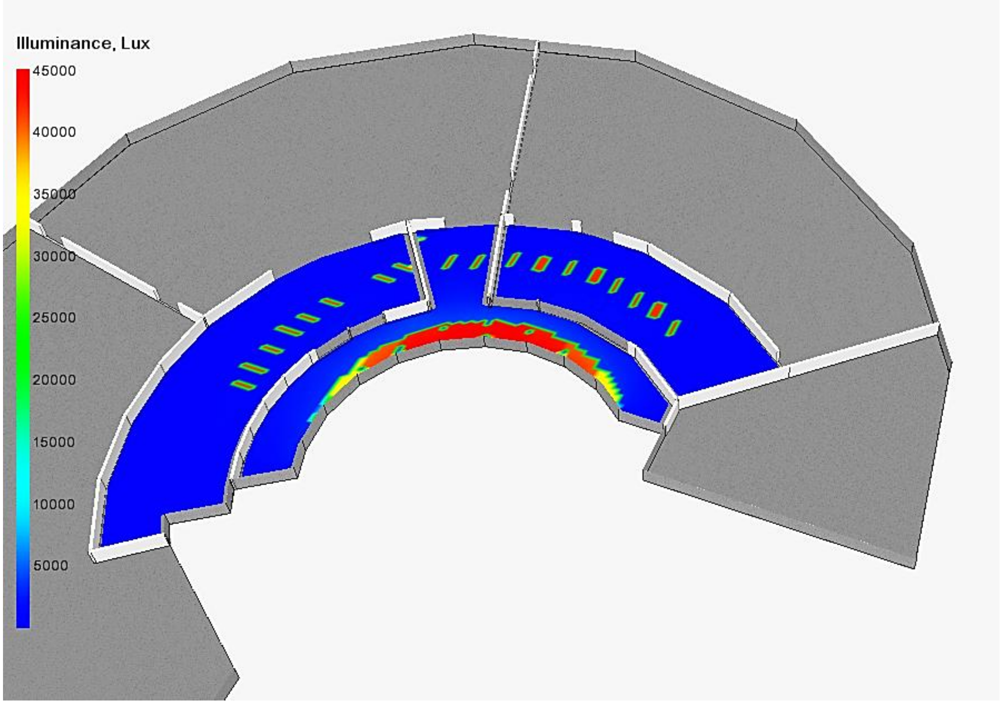


Figure 35: Illustration of the illuminance due to skylights

4.4.6. Opening hours and holidays

The occupancy and internal gains will depend on holidays and opening hours. The current museum is only closed on the 1st of January, New Year's Day. It also has different opening hours depending on the time of the year [74].

Summer	01st of May – 30th of November	9 AM – 6 PM
Winter	01st of October – 30th of April	10 AM – 4 PM

Holidays were added in IDA ICE, and opening hours used as schedules for internal gains, and for the air supply.

4.4.7. Equipment, lighting, Domestic hot water

The museum will have equipment and lights installed and use domestic hot water. In IDA ICE this numbers must be added to accurately estimate the energy need and heat supply. The numbers were obtained from NS3031:2014 Calculation of energy performance of buildings – Method and data [65]. In NS3031, numbers can be found for various building categories. The Viking age museum is defined as a cultural building, so the estimated values for cultural buildings was used. Table 9 gives information about the internal gains that were added to the model.

Table 9: Internal gains. Obtained from [65].

	During opening hours [W/m^2]	Outside opening hours [W/m^2]
Lighting	8	4
Equipment	1	0
Domestic hot water		10 Wh/(m^{2}year)

In IDA ICE the occurrence of the internal gains is added with a schedule of operating hours, corresponding to the opening hours.

4.4.8. People

People affect buildings by being present and releasing heat, vapour, CO_2 etc. as well as by their physical actions. It is therefore important to include them in simulations [73]. One of the biggest uncertainties of the project is the number of visitors. Today's number of visitors is known, but the area of the museum is already too small to host todays visitors. In addition, with the increased number of tv-shows and films based on Vikings, as well as a rise in tourists in Oslo, it is assumed that a new museum will attract even more visitors. Today, the Viking age museum is already one of the most visited tourist attractions in Oslo [75, 76].

Schedule

The number of visitors to the museum will not be evenly distributed throughout the day. An estimation of the distribution of occupants throughout the day was received in an email from Hjellnes Consult [77]. The occupancy schedule that was added in IDA ICE can be seen in Figure 36.

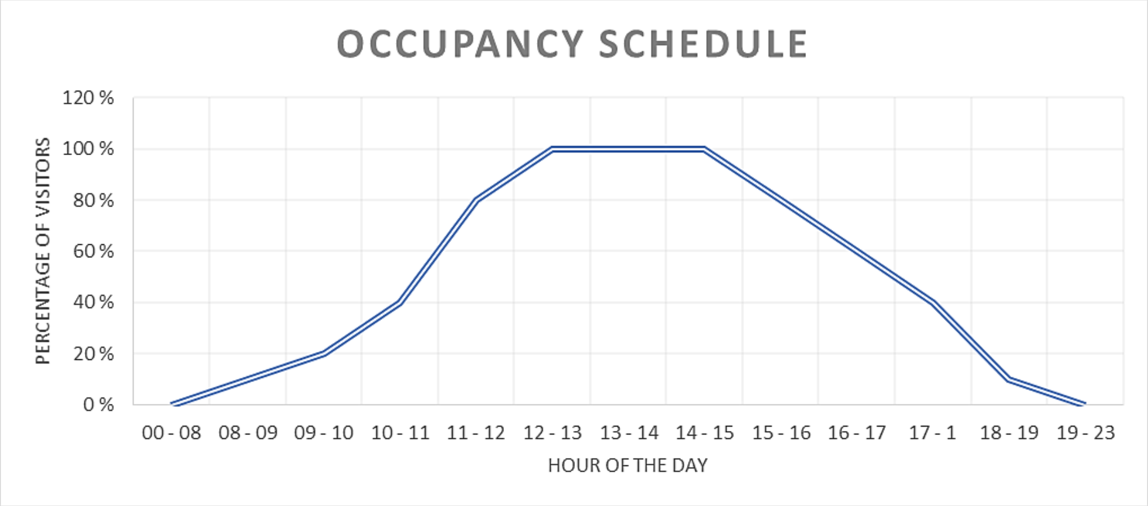


Figure 36: Percentage of occupancy dependent on the hour of the day [77]

Heat production

In addition to the occupancy schedule, an estimate of the number of people for each zone was added. This is the maximum number of people that will occupy the zone, and occurs when the schedule mentioned above is at 100%. The numbers are very uncertain, but for the main exhibition halls, Gokstad and Oseberg, it is estimated that in total 650 people should be able to be present at the same time for level U1 and 1. An overview of the number of visitors that were added in the model can be seen in Table 10 and Table 11. Figure 37 and Figure 38 shows the zones for a better illustration.

Table 10: Number of people added per zone in level U1

Zone	No. of people
Gokstad	325
Oseberg	325
Exhibition & Rooms	150
Offices	20
Common working area	15
Rooms	7

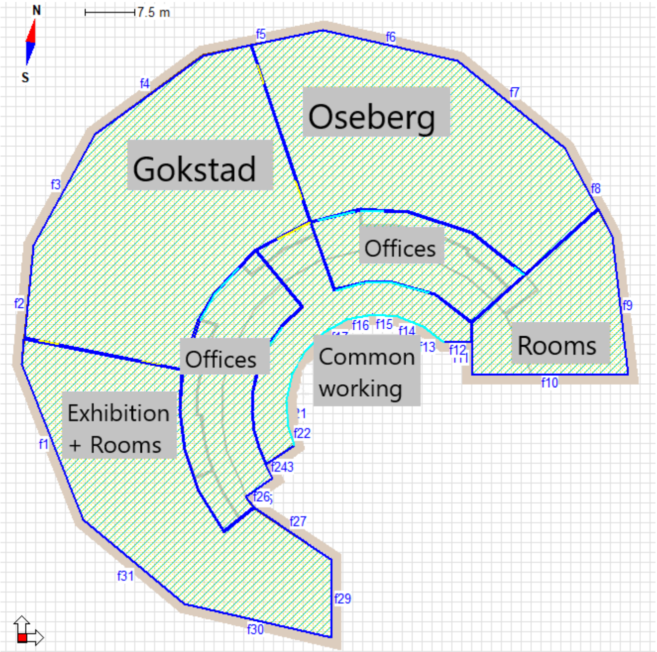


Figure 37: Overview of zones in level U1

Table 11: Number of people added per zone in level 1

Zone	No. of people
Gokstad	325
Oseberg	325
Exhibition & Café	200
Rooms (incl. toilet)	10
Hallway	60
Tech. rooms	0

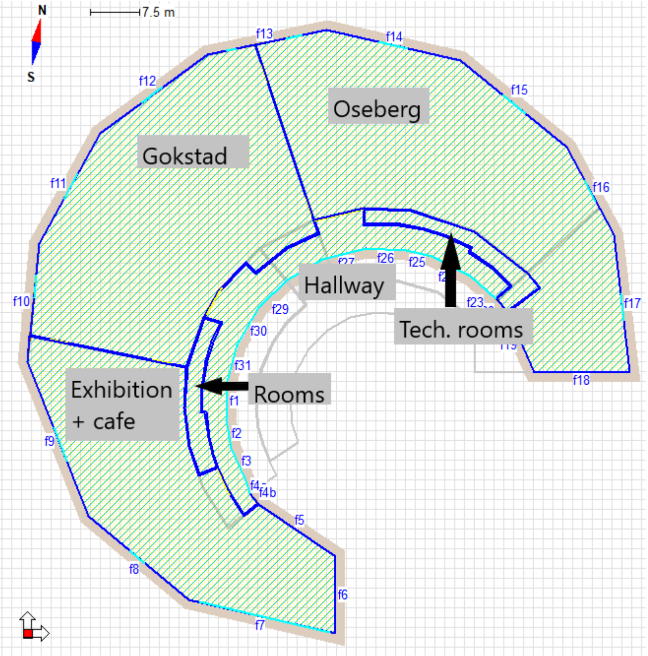


Figure 38: Overview of zones in level 1

Other input values that was added for people are their activity level, defined in MET, as well as their clothing level, defined in CLO. The estimated values can be seen Table 12.

Table 12: Input in IDA ICE for activity and clothing level

Activity level	2 MET
Clothing	0.85 ± 0.25

2 Met in activity level corresponds to slow walking. The CLO is automatically adjusted in IDA ICE to provide comfort. This means that the clothing level in the summer will be 0.85 – 0.25 = 0.6 CLO, and 0.85 + 0.25 = 1.1 CLO during winter.

Moisture production

When people are added in IDA ICE, only their emitted heat to the zone is calculated. However, for the protection of the Viking ships, the emitted moisture is very important to take into consideration. According to the sourcebook written by the International Energy Agency [78], the water vapour production of humans can be approximated depending on their activity level. The following numbers are suggested per person:

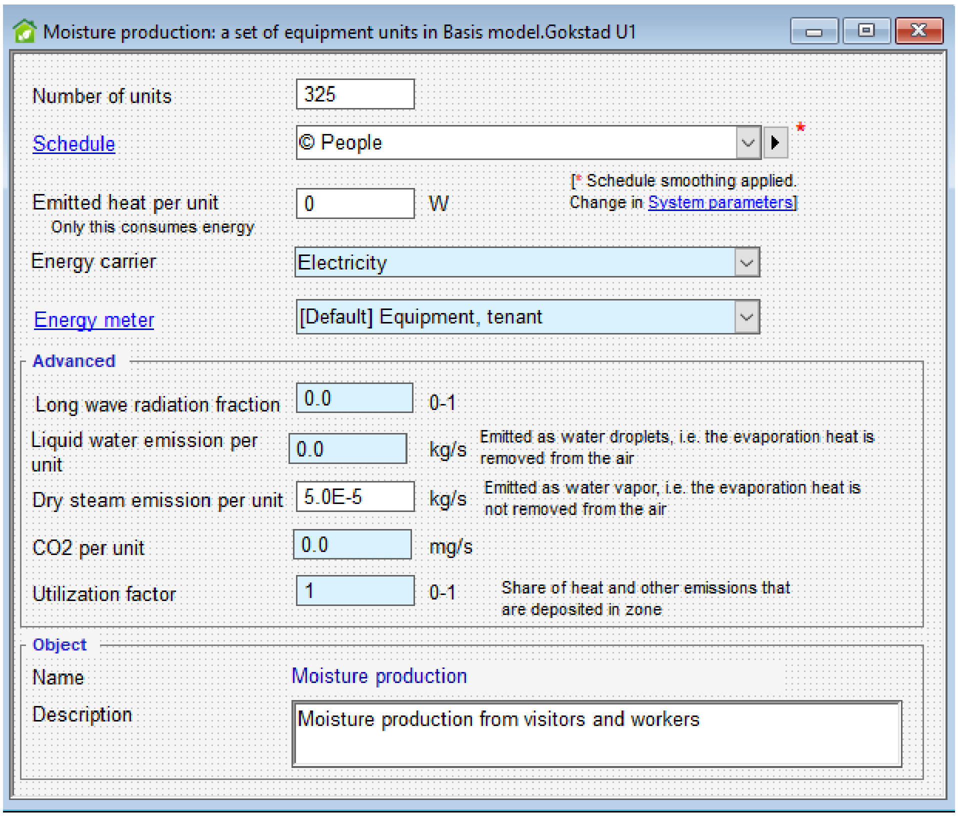
Light activity	30 – 60 g/h
Medium activity	120 – 200 g/h
Heavy activity	200 – 300 g/h

Moisture production was added to a zone in IDA ICE by adding it as “equipment”. Since the moisture production is estimated per person, the number of moisture units corresponds to the number of people in the zone. The schedule for occupancy was used for the moisture production. Since the emitted heat is already calculated through the internal gains of people, this was set to 0W here.

People will be walking around at different pace. Medium moisture production was decided to be a good estimation. This was added in IDA ICE through a form that can be seen in Figure 39, and estimated as:

Medium activity 180g/h $= 5 \times 10^{-5}$ kg/s

water vapour production per person.


Moisture production: a set of equipment units in Basis model.Gokstad U1

Number of units: 325

Schedule: © People *

[* Schedule smoothing applied. Change in System parameters]

Emitted heat per unit: 0 W

Only this consumes energy

Energy carrier: Electricity

Energy meter: [Default] Equipment, tenant

Advanced

Long wave radiation fraction	0.0	0-1	
Liquid water emission per unit	0.0	kg/s	Emitted as water droplets, i.e. the evaporation heat is removed from the air
Dry steam emission per unit	5.0E-5	kg/s	Emitted as water vapor, i.e. the evaporation heat is not removed from the air
CO2 per unit	0.0	mg/s	
Utilization factor	1	0-1	Share of heat and other emissions that are deposited in zone

Object

Name: Moisture production

Description: Moisture production from visitors and workers

Figure 39: Form for moisture production from people in IDA ICE.

3D-visualization of the final model in IDA ICE

In Figure 40 the final 3D-model of the Viking Age museum can be seen.

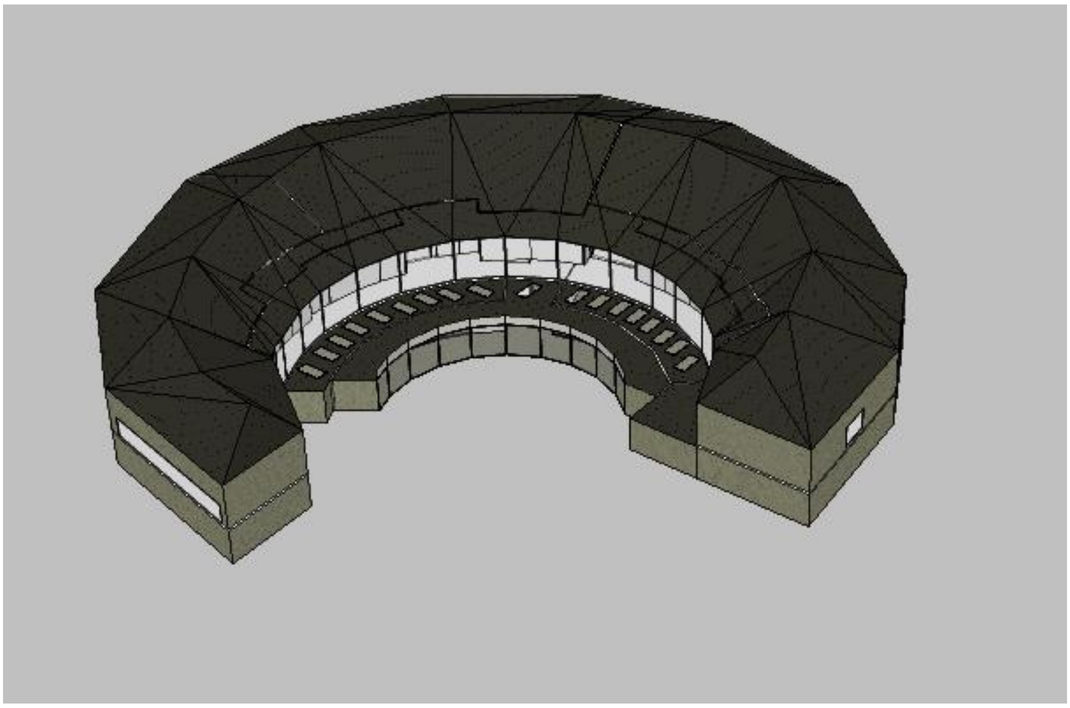


Figure 40: Illustration of the final IDA ICE model.

5. Simulation scenarios

To investigate the indoor environment for the Viking Age museum, some scenarios was decided to be simulated. Two reference models, one based on the minimum requirements for Norwegian buildings (TEK-house) and one based on the Norwegian Passive House standard (PAS-house) were made. The simulation scenarios were compared to these reference models. This way, the impacts of the techniques could be measured, quantified and compared.

5.1. Reference models

When running simulations for research it is important to have reference models. They work as a baseline, so the results from investigations can be compared and quantified with respect to a reference point. It was chosen to have two reference models, one for the minimum requirements (TEK-house), and one for a passive house standard (PAS-house). This was done to check whether the effect of the scenarios would have different efficiency depending on the standard it is based on. The reference models have the same input values as mentioned in chapter 4. Differences in input values are summarized in Table 13. The thicknesses of the construction elements were adjusted to reach the U-values in the table.

Table 13: Differences in input values between TEK and Passive house reference models [65, 67]

	TEK-house	**Passive house**
U-value, ex. Walls	0.22 W/(m^{2}K)	0.12 W/(m^{2}K)
U-value, slab towards ground	0.18 W/(m^{2}K)	0.08 W/(m^{2}K)
U-value, roof	0.22 W/(m^{2}K)	0.08 W/(m^{2}K)
U-value, windows and glazings	1.2 W/(m^{2}K)	0.8 W/(m^{2}K)
Heat exchanger, efficiency	70%	80%
SFP-factor, AHU	3 kW/(m^3/s)	1.5 kW/(m^3/s)
Leakage number, n_{50}	1.5 h^{-1}	0.6 h^{-1}
Normalized thermal bridge value	0.12	0.03 W/(m^2 ·K)

5.2. PCM implementation in IDA ICE

EQUA Simulation AB has developed an ad-in for IDA ICE, called “PCM-WALL”. It is available for research purposes on request, and results should be shared with EQUA for validation. The ad-in was received from NTNU professor Natasa Nord. “PCM-WALL” behaves like a layer of wallboard with PCM-material.

Modelling of PCM in buildings can be done in several ways [79]. In IDA ICE it is based on the enthalpy method, where the heat equation is solved by the enthalpy-temperature relationship of the material. The most important input is therefore the numbers for the partial enthalpies for each temperature step.

After contact with commercial PCM producers, Rubitherm SP21EK was chosen for simulations, as it has a suitable melting temperature of 21°C and their data sheet had sufficient information to implement in IDA ICE. Rubitherm SP21EK is based on mixture of salt water and additives, so it is categorized as a salt hydrate phase change material.

Information provided in the datasheet is based on experiments, which contains experimental errors. Figure 41 shows the enthalpy-temperature graph for Rubitherm SP21EK. Even though the material has a melting/solidifying temperature at 21°C, the phase change occurs in a temperature interval, called the transition zone. In this transition zone some of the material is solid and some is liquid. When surrounding air reach the main peak of the PCM melting area, the material will start to melt and it will follow the heating curve. When the material is cooled down again, it takes some time and before all the material is solid. This is called the hysteresis effect, and can be seen from the graph in Figure 41, where the cooling graph is shifted to the left compared to the heating graph.

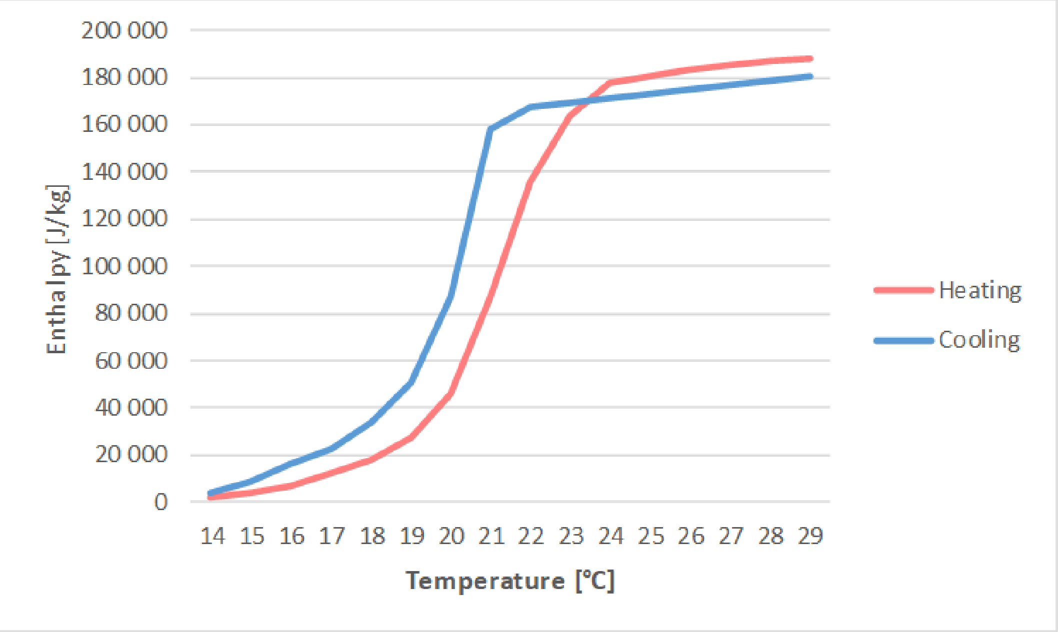
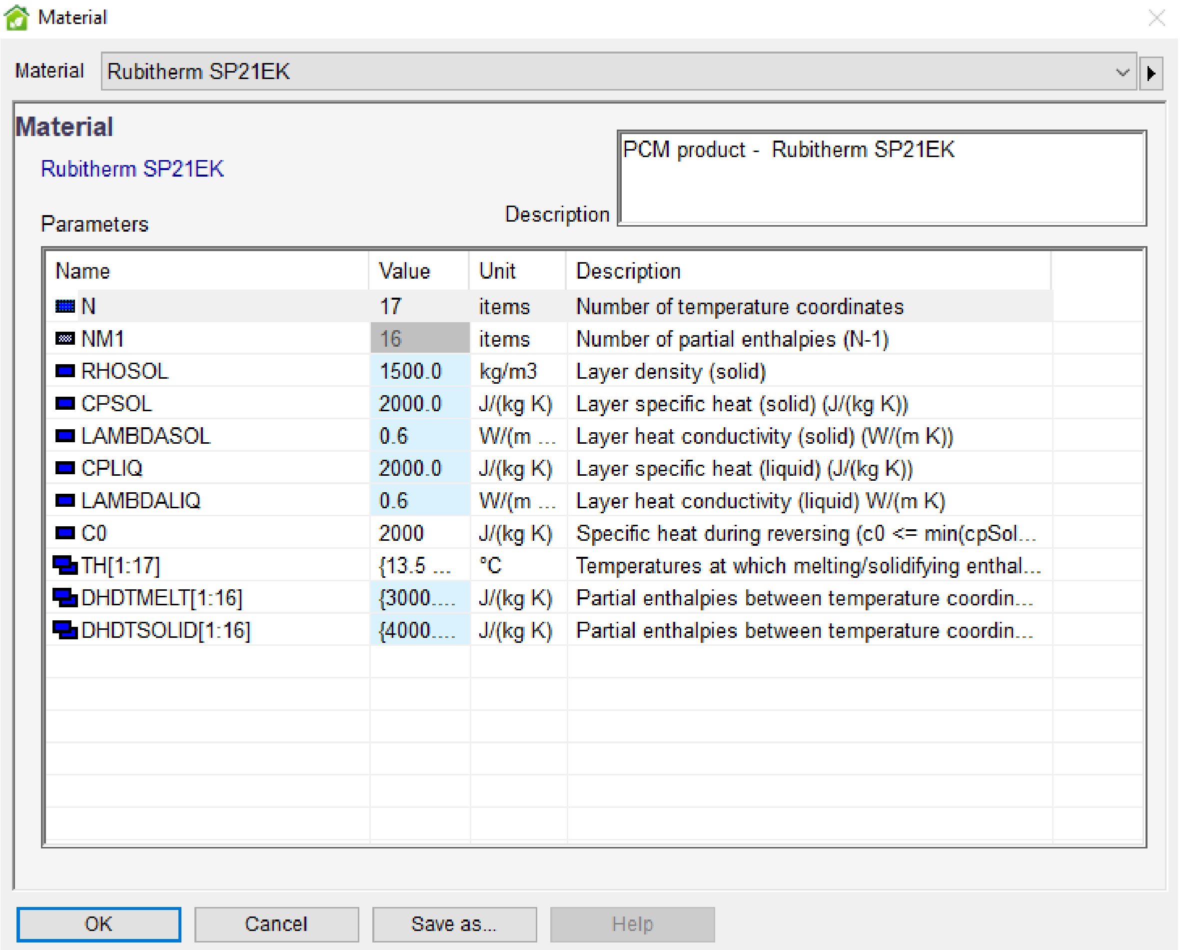


Figure 41: Enthalpy-temperature graph for Rubitherm SP21EK PCM

The graphs for solidifying and melting should meet at the tail points, as the PCM is either in complete solid or complete liquid state here. For Rubitherm SP21EK this means that when the temperature is 14°C all the material is solid, while at 29°C it is liquid. In IDA ICE it is a requirement that the total enthalpy for melting and solidifying is equal. Therefore, some modification of the provided data was necessary.

The modification will not result in any errors or affect the simulation results. Cristina Cornaro et al. have done this and verified the results against experimental studies [46, 80] . The studies conclude that the ad-in for PCM in IDA ICE has a good correlation with experimental data. Their set-up was received by email and compared with the setup for this thesis.

Figure 42 shows how the input values were added in IDA ICE. For other construction materials only the density, thermal conductivity and specific heat are required input values. While the enthalpy-temperature relations must be added for the PCM ad-in.



Material: Rubitherm SP21EK

Material

Rubitherm SP21EK

Description: PCM product - Rubitherm SP21EK

Parameters

Name	Value	Unit	Description
N	17	items	Number of temperature coordinates
NM1	16	items	Number of partial enthalpies (N-1)
RHOSOL	1500.0	kg/m3	Layer density (solid)
CPSOL	2000.0	J/(kg K)	Layer specific heat (solid) (J/(kg K))
LAMBDASOL	0.6	W/(m ...	Layer heat conductivity (solid) (W/(m K))
CPLIQ	2000.0	J/(kg K)	Layer specific heat (liquid) (J/(kg K))
LAMBDALIQ	0.6	W/(m ...	Layer heat conductivity (liquid) W/(m K)
C0	2000	J/(kg K)	Specific heat during reversing (c0 <= min(cpSol...
TH[1:17]	{13.5 ...	°C	Temperatures at which melting/solidifying enthal...
DHDTMELT[1:16]	{3000....	J/(kg K)	Partial enthalpies between temperature coordin...
DHDTSOLID[1:16]	{4000....	J/(kg K)	Partial enthalpies between temperature coordin...

Figure 42: Form for input values of the PCM-WALL ad-in.

The input values were taken from the modification of the PCM, where the tail points were adjusted. Figure 43 shows these values on the graph for each temperature point.

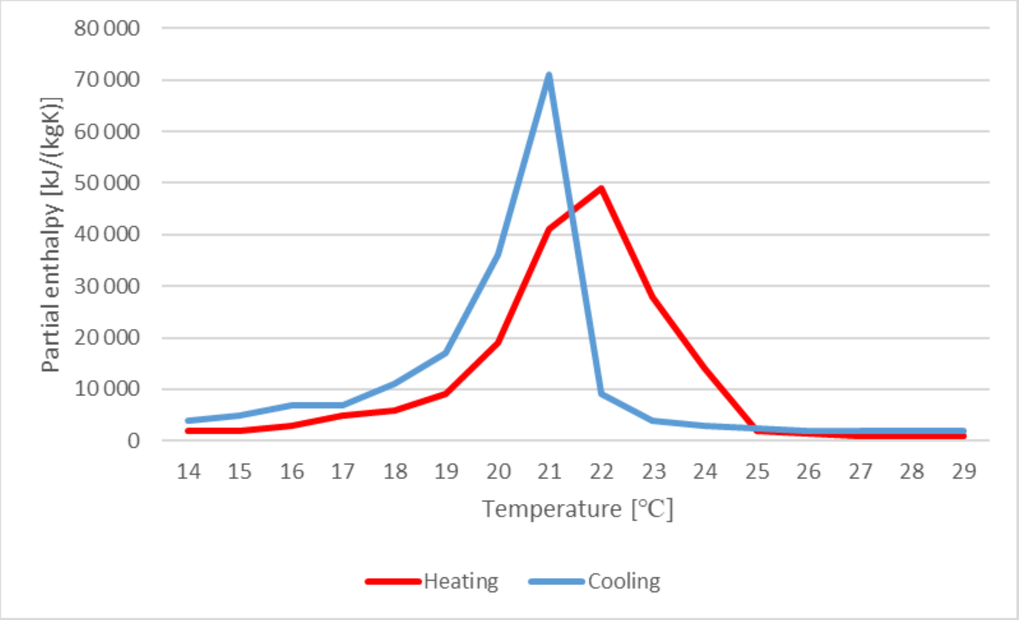


Figure 43: Partial enthalpies for heating and cooling of Rubitherm SP21EK after modification

The PCM ad-in is intended to be used as a wall layer in IDA ICE. However, due to the complexity of the model, the simulations failed to complete the simulation period due to numerical problems when this was implemented. The solution was therefore to add PCM as internal mass walls in each zone. Internal wall masses are added as two-sided, so the areas for each scenario that was simulated are the total area of both sides of one wall.

5.3. Simulation scenarios of PCM

PCM is supposed to lower peak temperatures during summer, and early autumn time. Therefore, the simulation period was set from the 15th of June – 30th of September to cover the peak time of efficiency for PCMs.

Various amounts of PCM surface areas were chosen, to check how much the temperature could be stabilized in the zones. Papers on these topics have very variated amounts of PCM. Some have only the ceiling or floor incorporated with PCM, while others have almost covered all internal surfaces. It was therefore chosen to simulate PCM application to only half on the internal walls as a minimum amount, and to cover the floors and all internal walls as a maximum amount. PCM was only added to the zones of Gokstad and Oseberg. The amount of PCM for each zone was estimated based on the areas of the walls, floor or ceilings for that specific zone.

In Table 14, the amounts of PCM for each of the scenarios can be seen.
Scenario A corresponds to the reference cases. In Scenario B, half of the internal walls of each zone are covered with PCM. Scenario C has all internal walls with PCM. For Scenario D, the amount of PCM corresponds to the same area as the internal floors. The last scenario corresponds to the same amount of PCM as if the whole floor and internal wall area of the zone would have PCM.

Table 14: Amounts of PCM for each of the simulation scenarios

	Scenario A: No PCM [m^2]	Scenario B: Half. Int walls [m^2]	Scenario C: All int. walls [m^2]	Scenario D: Int. floors [m^2]	Scenario E: Int walls + floors (max) [m^2]
Gokstad U1	0	133	267	1261	1783
Gokstad 1	0	276	553	916	1702
Oseberg U1	0	121	241	1094	1601
Oseberg 1	0	213	426	1160	1914

5.4. Moisture buffering in IDA ICE – HMWall

As the use of building simulation programs have increased the past years in addition, many programs have been made to simulate the coupled heat and moisture transfer through walls. The Canadian mortgage and housing corporation made a review of available hygrothermal models on the market in 2003. Already then, 45 different programmes were available. The humidity transport can be calculated in 1D, 2D or 3D [81].

Kurnitski and Vuolle developed in 1999 a 1-D model for the coupled heat, moisture and air transport calculations for walls in IDA ICE [82]. They have now continued the work at EQUA with the model called HMWall. The HMWall is available as an "Extend IDA application" by request to EQUA, and still under development [83]. EQUA sends an explanation of how it works, and the physical equations behind the model when they share the model. To replace the standard wall model with the HMWall, the advanced mode with schematic view in IDA ICE must be used. Normally only the density, thermal conductivity and specific heat are required input values. For simulations with HMWall more material parameters are required. They are listed in Table 15.

Table 15: Material parameters required as input for HMWall

Material parameters	Nomenclature and unit	
Heat capacity	C_o	J/(kg K)
Bulk density, dry material	ρ_0	kg/m^3
Thermal conductivity, dry material	λ_0	W/(mK)
Thermal moisture conductivity supplement	b_λ	-
Free water saturation	w_f	kg/m^3
Water content at 80% relative humidity	w_{80}	kg/m^3
Vapour diffusion resistance factor, dry-cup	μ_D	-
Vapour diffusion resistance factor, wet-cup	μ_W	-

For this thesis, simulation of different moisture buffering surface materials and their stabilizing effect on the relative humidity in the museum was done. Chosen materials were based on the findings from the theory presented in chapter 2. The materials were added on the interior of the walls, in addition to the existing structure. An exception was done for the cellular concrete, which replaced the regular concrete. The material properties were found in the German Masean database [84] as suggested by EQUA, in Künzel’s report [85] that EQUA has referred to, and from the material database in WUFI Pro [86].

Previously published studies conducted with HMWall in IDA ICE are not many, but includes three papers on simulation of historical churches [87-89], one for a museum building [90], and an Austrian study of flats in low energy buildings [91].

5.5. Simulation scenarios of moisture buffering

Simulations of HMWall and moisture buffering capacity has been done for one month during the winter, from the 15th of January – 15th of February.

Before the HMWall was implemented in the model, a control system that could control the humidity was implemented. Free-floating temperature is not relevant to look at, as it is highly important to control the humidity to range from 35 – 55%. The transfer value of free-running RH investigations would be low, and therefore chosen to not be of interest.
A separate air handling unit with humidifier and dehumidifier was added for Gokstad and Oseberg, while a standard one was added for the rest of the rooms in the museum building. The setup of the air handling unit for Gokstad and Oseberg can be seen in Figure 44. It was based on tips from the IDA ICE forum.

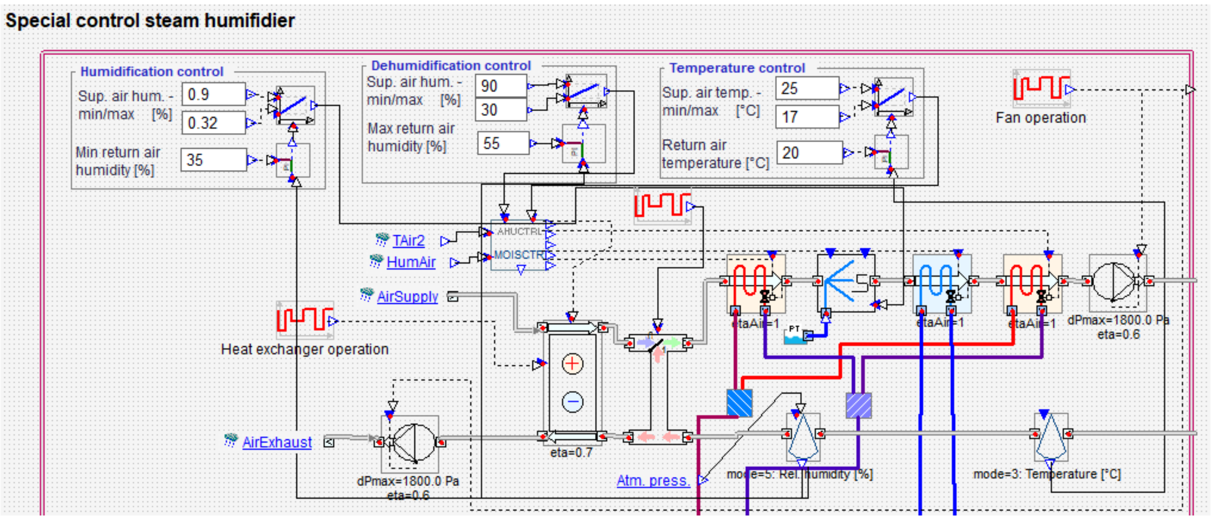


Figure 44: Air Handling Unit for humidification and dehumidification of Gokstad and Oseberg

5.5.1. Description of simulation scenarios

The same materials are used for the reference models (scenario A) as explained in the chapter of input values, and the additional material parameters that are required can be seen in Table 16 below.

Table 16: Material parameters for the reference models: TEK-house and PAS-house

Material parameters	Concrete w/c = 0.5	Insulation
C_p	850	850
ρ	2300	60
λ	1.6	0.04
b_λ	8	-
w_f	150	44.8
w_{80}	85	1.79
μ_D	180	-
μ_w	220	1.3

The materials that were chosen for simulation scenarios were found to show a good moisture buffering effect during previous studies presented in the theory chapter, and having moderate to good MBV. A simulation scenario of hemp concrete, that has a very high MBV was planned. However, it could not be conducted as input values were missing.

For scenario B, the concrete of the external walls was replaced with cellular concrete, which through studies has shown a better moisture buffering capacity compared to regular concrete. Lime cement plaster have been highlighted as a good moisture buffer material of several researchers, simulated as scenario C. Scenario D was simulated with gypsum panels, and Scenario E had spruce wood panels on the interior surface, which through the study of Ferreira et al. [61] proved to be very efficient for moisture buffering.

The material parameters for the simulation scenarios are presented in

Table 17.

Table 17: Material parameters for the simulation scenarios

Material parameters	Scenario B: Cellular concrete	Scenario C: Lime plaster	Scenario D: Gypsum panels	Scenario C: Spruce wood panels
C_p	415	850	1000	1810
ρ_0	850	1900	850	533
λ_0	0.1	0.8	0.3	0.075
b_λ	4	8	-	-
w_f	381	210	400	47
w_{80}	8.4	45	6.3	40
μ_D	7.7	7.3	8.3	3.2
μ_w	7.1	6.4	7.3	1.1

Only the model for external walls have been replaced with the HMWall for calculations in IDA ICE. It is expected that not all walls can consist of the moisture buffering material as thermal mass, acoustics and other criteria also must be met.

5.6. Data analysis

Some requirements are set for the museum, and this will provide the basis for the analysis of the results. The temperature range must be 16 – 25°C over the year. The relative humidity has to be within the range of 35 – 55% during winter time, defined as from the 1st of October – 30th of April. For the summer time, 1st of May – 30th of September the relative humidity must be in the range of 45 – 65%.

For simplifications, the simulations have been done for representative summer and winter months. 2 months during summer time was simulated to investigate the effect of incorporating PCM in the exhibition areas of the museum, from 15th of June – 15th of August. The simulations for moisture buffering was done during the winter, from the 15th of January – 15th of March. In this way it is possible to say something about the potential effect of the concepts, but to avoid the issues when the seasons go from summer to winter, and the requirements are changed.

The analysis of the indoor environment was done for the exhibition halls of Gokstad and Oseberg. This is where the ships will be located, and where the consultancy company is most worried about the indoor conditions. The other zones are implemented in the model because they will have an impact on the indoor conditions for the exhibition zones. E.g. solar gains in the hallway will heat up the concrete partition walls towards the exhibition halls. Heat flows from areas with the highest temperature, to lower temperatures, and therefore the heat will flow from the concrete internal walls and to the exhibition areas and have an impact.

In addition, two simple index TS (Temperature Stabilization RHS (relative humidity stabilization) were defined to quantify the stabilizing effect of the measures on the temperature or relative humidity fluctuations.

The average temperature for each of the simulation scenarios were calculated. The TS index was then quantified as the absolute value of the sum of the difference between the average temperature for the scenario and the hourly mean air temperature [61].

$$\text{TS} = \sum_i |\overline{T} - T_i|$$

The Relative Humidity Stabilization index was quantified in the same way:

$$\text{RHS} = \sum_i |\overline{RH} - RH_i|$$

6. Simulation results

In this chapter the results from the simulations in IDA ICE will be presented. In the first subchapter the results from the simulations of PCM will be presented. First the results from PCM application in each of the reference buildings, and then a comparison of the two buildings with same amount of PCM.

The second subchapter contains the results from the moisture buffering investigation. The results from the reference models are presented with comparison to the models simulated with various surface materials.

6.1. PCM – Temperature stabilization

6.1.1. Effect of different amounts of PCM

Here the simulation results of different amounts of PCM in each of the houses will be presented. The graphs for the temperature distribution is for one week within the simulation period (31.07-2017 – 06.08.2017), while the calculations of stabilization are done for the whole period (15.06.2017 – 15.08.2017).

TEK-house temperature results

The temperature results for the building based on minimum requirements is presented below, for Gokstad and Oseberg.

Gokstad floor U1

In Figure 45 the temperature distribution from one representative week during the simulations can be seen. The blue graph is the temperature from the model with no PCM (Scenario A), and the green graph is the temperature for the model with PCM on floors and ceiling (Scenario E). It shows that the fluctuation of the air temperature is lower for the all cases with PCM compared to a solution with no PCM.

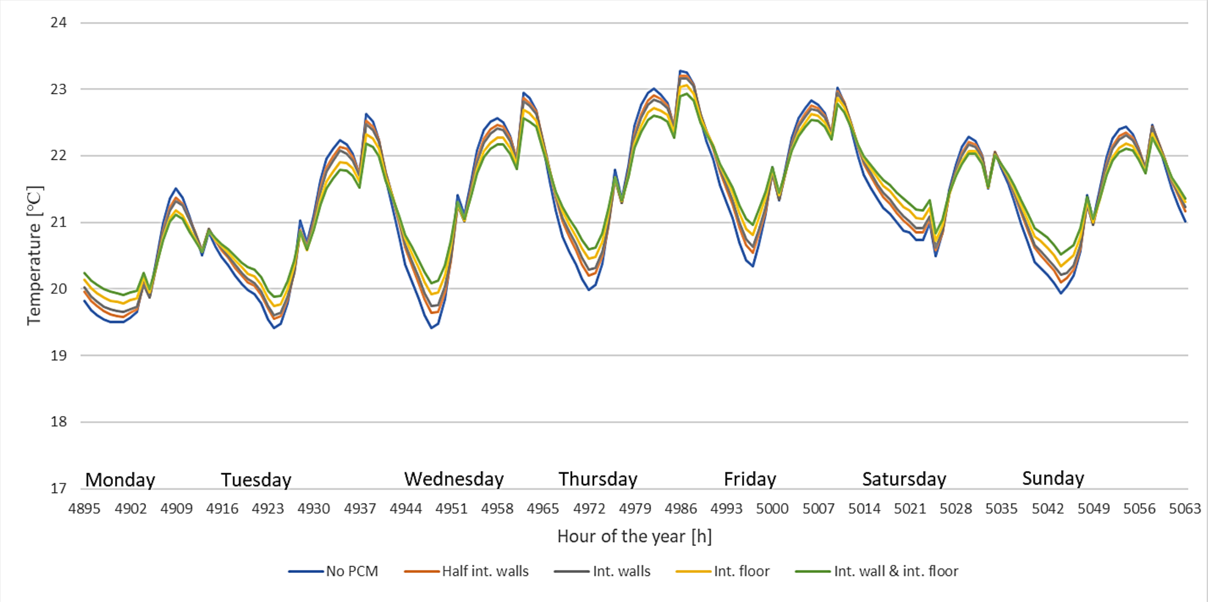


Figure 45: Mean air temperature distribution in Gokstad floor U1 for one week

In Table 18 the minimum, maximum, average and standard deviation of the temperature for each of the simulation scenarios is presented. The stabilization index, TS, can also be seen here. From the results one can see that the minimum temperature for all scenarios are the minimum temperature that are allowed for the museum, 16℃. It can also be seen that depending on the PCM-amount, the peak temperature can be dampened with 0.17 – 0.97℃. The temperature stabilization index can be reduced with 2.96%, 5.63%, 14.74% 17.6% for the respective scenarios. The standard deviation, which is a measure for the amount of variation, is also reduced by increasing amount of PCM.

Table 18: Results of PCM temperature stabilization for Gokstad floor U1

	A: No PCM	B: Half int. walls	C: Int. walls	D: Int. floor	E: Int. walls & floor
Minimum	16,04	16,04	16,05	16,05	16,04
Average	18,69	18,71	18,73	18,80	18,82
Standard deviation	1,93	1,88	1,83	1,67	1,61
Maximum	23,84	23,67	23,57	23,07	22,87
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	2433,92	2361,79	2296,86	2075,06	2005,38

Gokstad Floor 1

In Figure 46 below, the temperature distribution Gokstad floor 1 for one week can be seen. It shows a similar behaviour as the lower floor of the same zone.

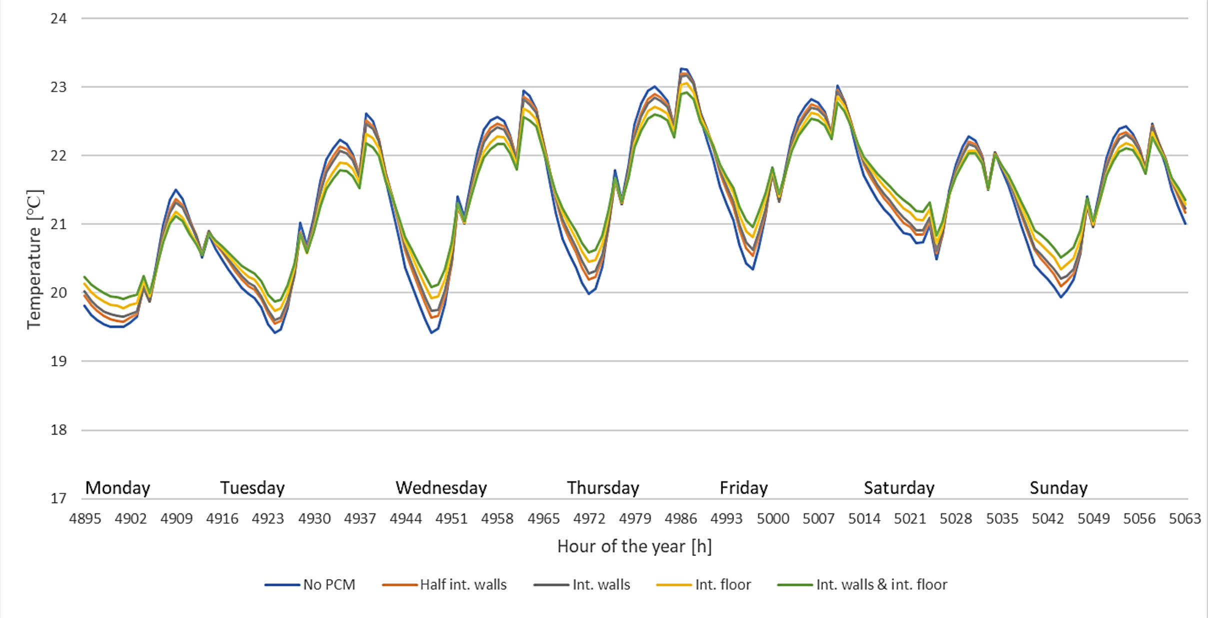


Figure 46: Mean air temperature distribution in Gokstad floor 1 for a representative week

The minimum, maximum and average temperature for each scenario can be found in Table 19 below, as well as the standard deviation for the fluctuation. According to the simulations, the PCM can reduce the maximum temperature by 0.22 - 0.81℃. The temperature stabilization index can be reduced by 3 – 12%

Table 19: Results of PCM temperature stabilization for Gokstad, floor 1

	A: No PCM	B: Half int. walls	C: Int. walls	D: Floor	E: Int. walls & floor
Minimum	16,04	16,01	16,00	16,02	16,02
Average	18,70	18,71	18,72	18,74	18,75
Standard deviation	1,95	1,90	1,87	1,79	1,73
Maximum	24,44	24,22	24,09	23,87	23,63
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	2438,64	2373,69	2322,38	2213,17	2150,68

Oseberg floor U1

Figure 47 shows the temperature for the lower level of Oseberg, floor U1, during the chosen week. Also for this zone the blue curve for the scenario of no PCM is swinging more than the scenarios with PCM.

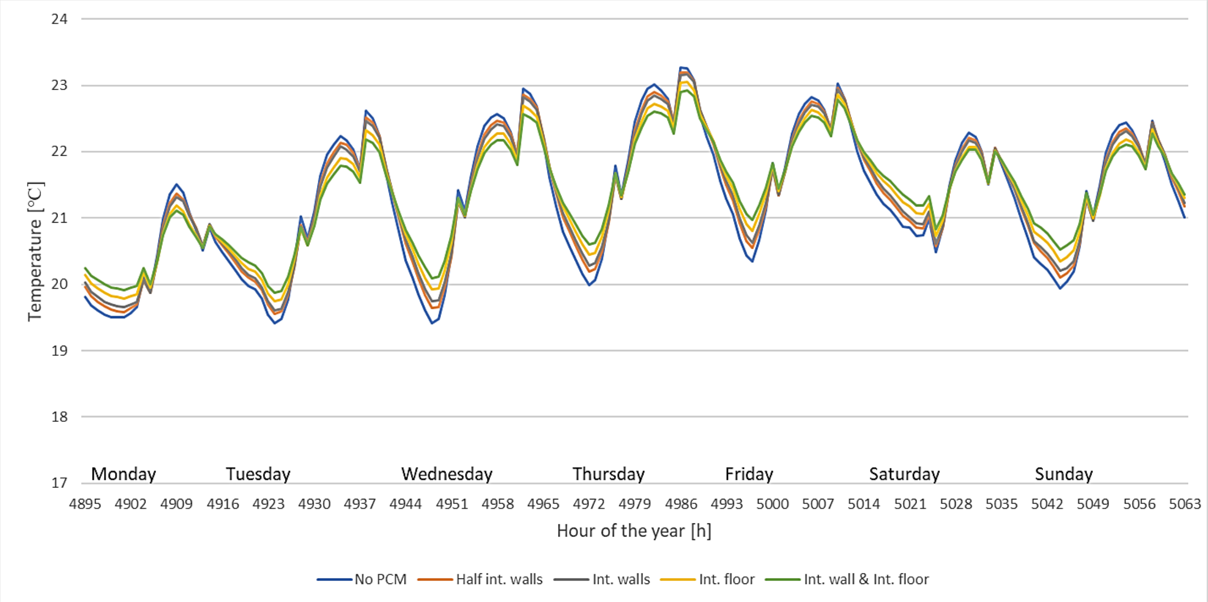


Figure 47: Mean air temperature distribution in Oseberg floor U1 for the chosen week

The resulting minimum, average and maximum temperature for Oseberg U1 can be found in Table 20. The temperature stabilization index is reduced by 3.1%, 6.2%, 16.5 and 19.5% respectively by implementing PCM. Reduction of the peak temperature are 0.2℃ - 1.07℃.

Table 20: Results of PCM temperature stabilization for zone Oseberg floor U1

	A: No PCM	B: Half int. walls	C: Int. walls	D: Floor	E: Int.Walls & floor
Minimum	16,02	16,05	16,04	16,07	16,05
Average	18,57	18,60	18,62	18,70	18,72
Standard deviation	1,88	1,83	1,78	1,60	1,54
Maximum	23,65	23,43	23,33	22,81	22,58
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	2377,61	2302,98	2231,06	1986,31	1914,28

Oseberg floor 1

Figure 48 below shows the temperature distribution for the scenario cases in Oseberg 1st floor. As can be seen in the figure, the temperature stabilization is visible.

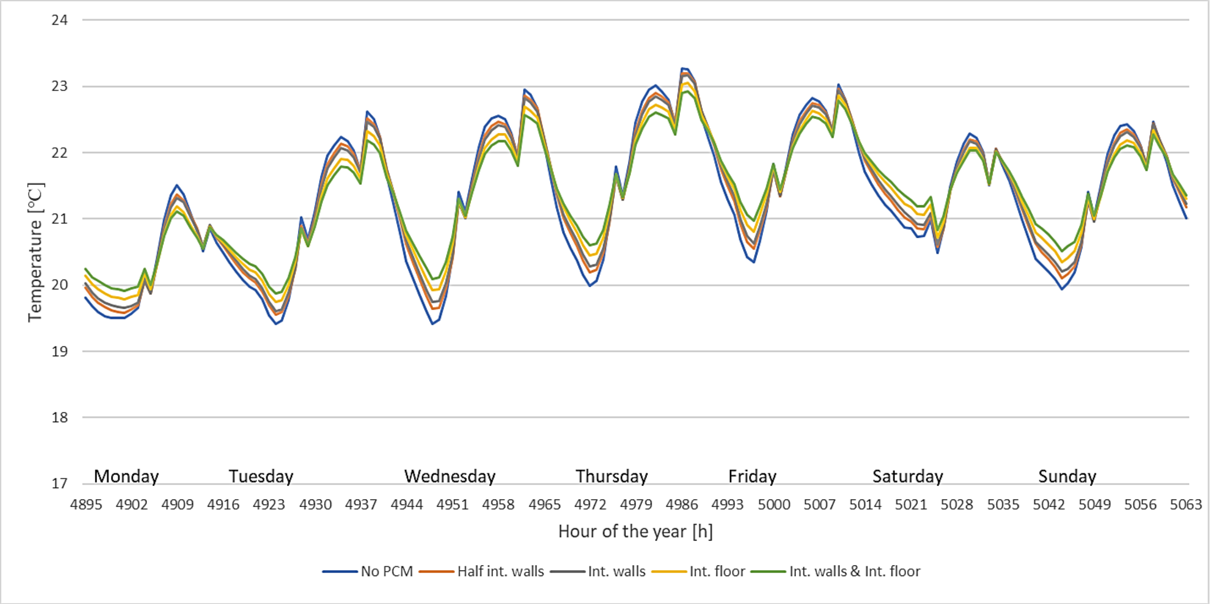


Figure 48: Mean air temperature distribution in Oseberg floor 1 for the chosen week

In Table 21 the data for the 1st floor in Oseberg can be seen, with the resulting minimum, average, standard deviation and maximum temperature. The peak temperature in this zone is reduced by 0.2-0.7℃ in the simulation scenarios. A reduction of 2 - 10.10% can be seen for the temperature stabilization index.

Table 21: Results of PCM temperature stabilization for Oseberg floor 1

	A: **No PCM**	**B:** **Half int. walls**	**C:** **Int. walls**	**D:** **Floor**	**E:** **Int. walls & floor**
Minimum	16,00	16,00	16,00	16,02	16,03
Average	18,62	18,63	18,64	18,66	18,68
Standard deviation	1,92	1,89	1,86	1,78	1,74
Maximum	24,19	24,02	23,93	23,68	23,49
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	2405,71	2357,25	2315,73	2210,83	2162,61

Passive house temperature results

In this chapter the results from the PCM simulations for the museum based on the passive house requirements will be presented.

Gokstad floor U1

Figure 49 shows the temperature of the zone Gokstad U1 for a week during the simulation period. It gives an indication of the temperature stabilization effect by installation of PCM. Scenario D and E, with PCM on the floor or internal walls in addition to the internal floor (yellow and green curves), shows a good dampening effect on the night minimum temperature compared to the other solutions.

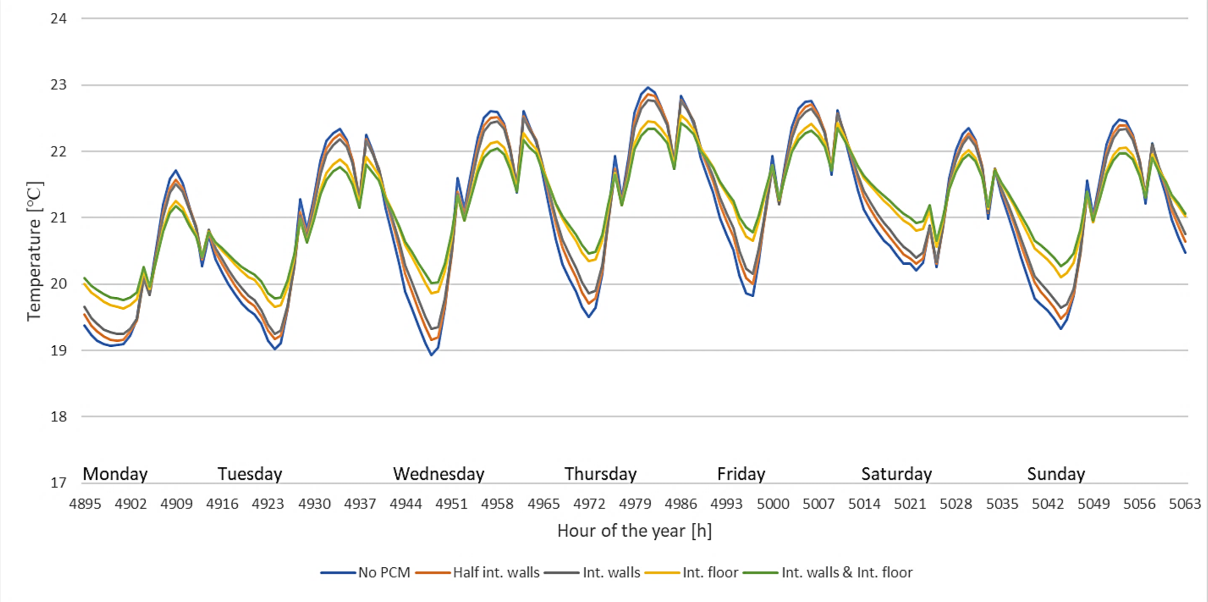


Figure 49: Mean air temperature distribution in Gokstad floor U1 for one week

Results for minimum, maximum, average and standard deviation of the temperature in Gokstad U1 can be seen in Table 22. The minimum temperature can be raised by up to 1°C, while the peak temperature for the simulation period can be reduced by maximum 0.54°C. For the whole simulation period, the temperature stabilization index can be reduced by 5 - 27.09%. The difference between the minimum and maximum for scenario A is 6.17°C, and 4.69°C for scenario E. This is a reduction of 24%.

Table 22: Results of PCM temperature stabilization in Gokstad floor U1

	A: No PCM	B: Half int. walls	C: Int. walls	D: Floor	E: Int. walls & floor
Minimum	17,05	17,16	17,29	17,83	17,99
Average	20,10	20,15	20,19	20,32	20,35
Standard deviation	1,38	1,31	1,26	1,06	1,01
Maximum	23,22	23,11	23,07	22,80	22,68
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	1722,37	1633,00	1564,16	1322,74	1255,71

Gokstad floor 1

Figure 50 shows the temperature distribution of Gokstad floor 1. It can be seen that the temperature fluctuation is less for the models with PCM, however this is not to a great extent. The reduction of peak temperatures, as well as the increased minimum temperatures seems to be less for this 1st floor, than for floor U1.

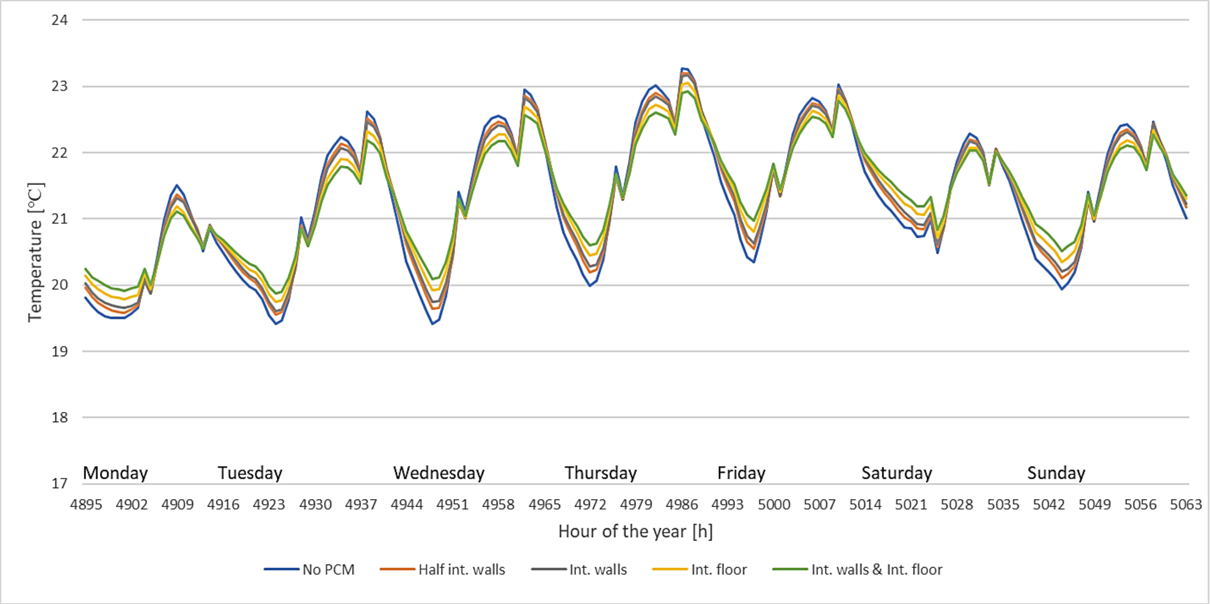


Figure 50: Mean air temperature distribution in Gokstad floor 1 for one week

Minimum, maximum and average temperatures for zone Gokstad floor 1, can be seen in Table 23 below. The reduction of peak temperatures is 0.13 – 0.47°C, and the minimum temperatures raised by 0.13 – 0.68°C, depending on the amount of PCM. For the temperature stabilization index, a reduction of 4.32 – 16.46% can be seen.

Table 23: Results of PCM temperature stabilization for Gokstad floor 1

	A: **No PCM**	**B:** **Half int. walls**	**C:** **Int. walls**	**D:** **Floor**	**E:** **Int. walls + floor**
Minimum	17,23	17,36	17,45	17,75	17,91
Average	20,24	20,29	20,31	20,36	20,39
Standard deviation	1,36	1,31	1,28	1,18	1,13
Maximum	23,75	23,62	23,57	23,42	23,28
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	1688,33	1615,43	1579,38	1470,28	1410,48

Oseberg floor U1

Figure 51 shows the temperature distribution for zone Oseberg at level U1. The graphs show the same tendency as for level U1 of Gokstad. PCM incorporation in the floor, or in the floor and the internal walls at the same time, gives a better stabilization effect, that is very clear from the figure.

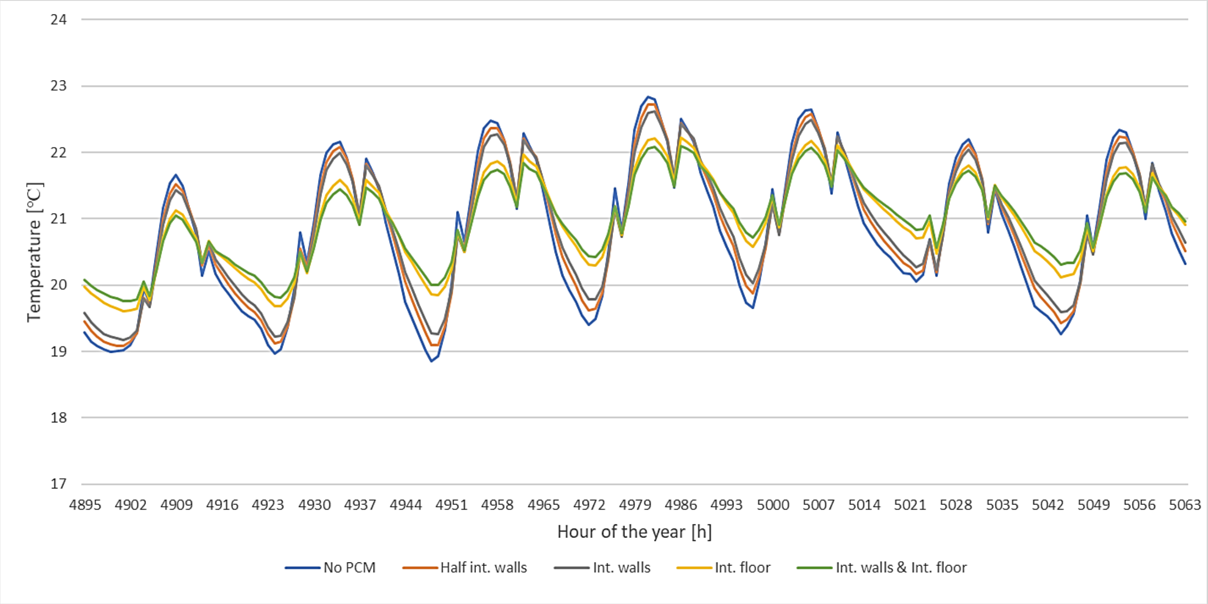


Figure 51: Mean air temperature distribution in Oseberg floor U1 for one week

In Table 24 the minimum, maximum and average temperature for each of the simulation scenarios can be seen. The minimum temperature is raised by up to 1.05°C when PCM is incorporated in the building, and the maximum temperature is reduced by up to 0.57°C. The difference between minimum and maximum temperature for scenario A is 5.87. It can be reduced to between 5.36 to 4.25 depending on the amount of PCM. The temperature stabilization index for the scenario with no PCM is 1674, and can be reduced by 5.5 – 31.7% by PCM.

Table 24: Results of PCM temperature stabilization for Oseberg floor U1

	A: **No PCM**	**B:** **Half int. walls**	**C:** **Int. walls**	**D:** **Floor**	**E:** **Int. walls + floor**
Minimum	17,06	17,15	17,27	17,92	18,11
Average	19,94	19,99	20,03	20,18	20,21
Standard deviation	1,34	1,27	1,21	0,98	0,92
Maximum	22,93	22,78	22,75	22,49	22,36
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	1674,00	1581,20	1499,26	1217,21	1143,30

Oseberg floor 1

Figure 52 shows the temperature distribution for Oseberg floor 1. It can be seen that the temperature is more stable when there's PCM installed, even though the difference for this case is less than for level U1.

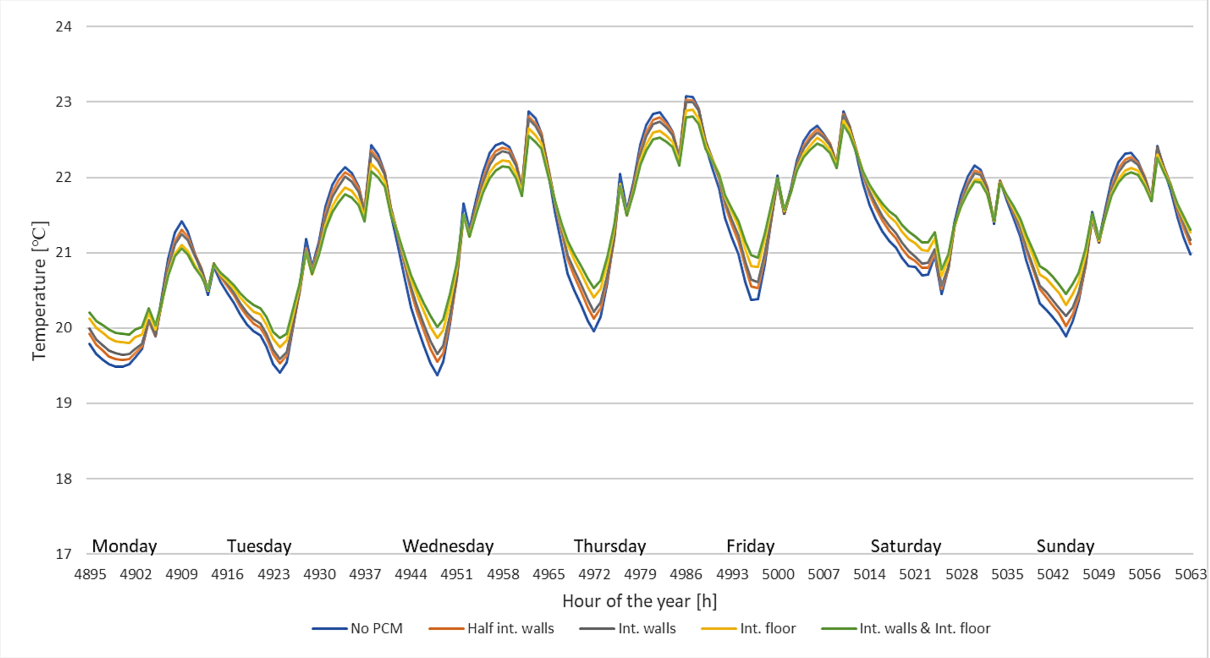


Figure 52: Mean air temperature distribution in Oseberg floor 1 for one week

Table 25 below gives the data for minimum, average and maximum temperatures occurring for the simulation scenarios. The minimum temperature is raised by 0.12 – 0.72°C, and the maximum temperature decrease by 0.09 - 0.36°C. A reduction of 3.43 – 14.89% can be achieved for the temperature stabilization index, depending on the PCM-amount.

Table 25: Results of PCM temperature stabilization for Oseberg floor 1

	A: **No PCM**	**B:** **Half int. walls**	**C:** **Int. walls**	**D:** **Floor**	**E:** **Int. walls + floor**
Minimum	17,27	17,38	17,47	17,82	17,99
Average	20,19	20,24	20,26	20,31	20,35
Standard deviation	1,33	1,29	1,26	1,17	1,12
Maximum	23,50	23,41	23,38	23,25	23,14
TS = $\sum_i \lvert \bar{T} - T_i \rvert$	1650,44	1593,89	1558,29	1456,31	1405,07

6.1.2. Comparison of same PCM-amounts for TEK-house and PAS-house

In this chapter the same amounts of PCM for the houses built based on TEK-regulations or Passive house regulations will be compared. This is done to check if the incorporation of PCM has a better attenuation depending on which regulations the house is fulfilling.

Gokstad floor U1

In Table 26 the comparison of the temperature stabilization index for the passive house, and TEK-house for zone Gokstad U1 can be found. The reduction of temperature fluctuation is higher for the passive house for all scenarios. Already at scenario B, a reduction of 5.2% in the TS can be seen. In addition, the TS index is already reduced by building a passive house, compared to a TEK-house. For the reductions of minimum and maximum temperature over the whole period, almost the same reduction can be seen for the TEK-house and the PAS house for scenario B and C. For scenario D a reduction of 0.8°C is visible for the TEK-house and 1.2°C for the passive house. To add even more PCM in scenario E does reduce it further to 1°C for TEK-house and 1.5°C for the PAS-house.

Table 26: Comparison of results from Gokstad floor U1

	TEK-house			PAS-house		
	TS	%-change TS	ΔT [°C]	TS	%-change TS	ΔT [°C]
A	2433.9	0	7.8	1722.4	0	6.2
B	2371.8	2.9	7.6	1633.0	5.2	6.0
C	2296.9	5.6	7.5	1564.2	9.18	5.8
D	2075.1	14.7	7.0	1322.7	23.2	5
E	2005.3	17.6	6.8	1255.7	27.1	4.7

Gokstad floor 1

Table 27 shows the temperature results for Gokstad floor 1. The temperature stabilization by PCM is also greater for the passive house, than for the TEK-house. The TS-index is reduced more when a passive house has PCM in just the floors (12.9%), compared to a TEK-house with PCM on all internal walls and the floor (11.8%). A reduction of fluctuation 0.2-0.4°C is visible for both houses for scenario B and D. Scenario D reduces the fluctuation for TEK-house and PAS-house with 0.6°C and 0.8°C respectively. A reduction of 0.8°C and 1.1 can be found for scenario E. The dampening effect of PCM is for all cases higher for the PAS-house than for the TEK-house.

Table 27: Comparison of results from Gokstad floor 1

	TEK-house			PAS-house		
	TS	%- change TS	ΔT [°C]	TS	%-change TS	ΔT [°C]
A	2438.6	0	8.4	1688.3	0	6.5
B	2373.7	2.6	8.2	1615.4	4.3	6.3
C	2322.3	4.8	8.1	1579.4	6.5	6.1
D	2213.2	9.2	7.8	1470.3	12.9	5.7
E	2150.7	11.8	7.6	1410.5	16.4	5.4

Oseberg floor U1

The data for Oseberg floor U1 is summarized in Table 28. Also for this zone, the stabilization for the passive house is better than the TEK-house. As for the other zones, a small reduction in the temperature fluctuation can be seen for scenario B and C. Scenario D and E can reduce temperature fluctuations with 0.9 – 1.1℃, which is the highest for the zones in the TEK-house. For the Passive house are reduction of 1.3℃ and 1.6℃ can be found.

Table 28. Comparison of results from Oseberg floor U1

	TEK-house			PAS-house		
	TS	%-change TS	ΔT [℃]	TS	%-change TS	ΔT [℃]
A	2377.6	0	7.6	1674.0	0	5.9
B	2302.9	3.1	7.4	1581.2	5.5	5.6
C	2231.1	6.2	7.3	1499.3	10.4	4.6
D	1986.3	16.4	6.7	1217.2	27.3	4.3
E	1914.3	19.5	6.5	1143.3	31.7	4.3

Oseberg floor U1

Table 29 summarize the stabilization in Oserberg floor 1. Compared with the other zones, this one has the lowest %-change of TS for the passive house, with between 3.4-14.9%. The same effect can be seen for the TEK-house. The difference in maximum and minimum temperatures for scenarios B and C follows the same pattern as for the other zones with decrease of 0.2℃ and 0.3℃ for the TEK-house, and the same for the PAS-house. Scenarios D and E reduce the fluctuation for the TEK-house of 0.5℃ and 0.6℃, and 0.8℃ and 1℃ for the passive house.

Table 29: Comparison of results from Oseberg floor 1

	TEK-house			PAS-house		
	TS	%-change TS	ΔT [℃]	TS	%-change TS	ΔT [℃]
A	2405.7	0	8.2	1650.4	0	6.2
B	2357.2	2.1	8.0	1593.9	3.4	6.0
C	2315.7	3.7	7.9	1558.3	5.6	5.9
D	2210.8	8.1	7.7	1456.3	11.8	5.4
E	2162.6	10.1	7.6	1405.1	14.9	5.2

In general, the temperature fluctuations are higher for the TEK-house than for the PAS-house. However, the PCM incorporation of the buildings seem to have the same dampening effect of the temperature fluctuations for both houses for scenario B and C. For Scenario D, however the maximum dampening effect for the TEK-house is 1℃, and a reduction of the TS-index of 17.6%. With the minimum amount of PCM the TS-index can be reduced by 2.6% and temperature fluctuation lowered by 0.2℃. The maximum reduction of the TS-index for the Passive house is 31.7%, and a temperature fluctuation reduction of 1.6℃. With scenario B, the minimum reduction of the TS-index is 3.4%, and a reduction of temperature fluctuation of 0.2℃.

6.2. HMWall – Relative humidity stabilization

In this chapter the results from the scenarios with different moisture buffering materials on the resulting relative humidity of the zones, will be presented.

6.2.1. TEK-house

In this chapter the results from simulation scenarios based on the TEK-house will be presented.

Gokstad floor U1

Results from the relative humidity in zone Gokstad floor U1 can be seen in Table 30. The scenarios B-E has variative effect on the relative humidity stabilization. Scenario B seems to have no effect on stabilization, C and D decrease the fluctuation by 0.4% and 0.5% respectively. The best stabilizing effect is from scenario E with 2.3%.

Table 30: Results for relative humidity for Gokstad floor U1

	A: Regular concrete	B: Cellular concrete	C: Lime finish	D: Gypsum	E: Spruce wood
Minimum	36,08	36,08	36,09	36,09	36,10
Average	41,86	41,86	41,85	41,85	41,81
Standard deviation	5,58	5,58	5,55	5,55	5,43
Maximum	56,76	56,76	56,65	56,61	56,00
RHS = $\sum_i \lvert \overline{RH} - RH_i \rvert$	3747,14	3749,05	3733,22	3729,51	3660,09

Gokstad floor 1

In Table 31 the results of the simulation for floor 1 of Gokstad can be seen. Scenario B shows no result in lowering the RH fluctuations. Scenario C, D and E also have a low possible dampening effect, decreasing the RHS by 0.1%, 0.1% and 0.8% respectively.

Table 31: Results for relative humidity for Gokstad floor 1

	A: Regular concrete	B: Cellular concrete	C: Lime finish	D: Gypsum	E: Spruce wood
Minimum	33,58	33,58	33,57	33,58	33,57
Average	40,92	40,92	40,91	40,91	40,87
Standard deviation	7,16	7,16	7,15	7,15	7,08
Maximum	58,81	58,81	58,71	58,68	58,07
RHS = $\sum_i \lvert \overline{RH} - RH_i \rvert$	4865,60	4867,41	4860,59	4861,60	4825,78

Oseberg floor U1

In Table 32 the results for the relative humidity for floor U1 of Oseberg can be seen. Scenario B and C reduce the relative humidity fluctuation in Oseberg U1 by 0.5 and 0.8% respectively, while Scenario E is reducing the indicator by 5%. The biggest reduction can be seen for scenario D with reduction of 11.8%.

Table 32: Results for relative humidity for Oseberg floor U1

	A: Regular concrete	**B: Cellular concrete**	**C: Lime finish**	**D: Gypsum**	**E: Spruce wood**
Minimum	38,03	38,02	38,05	38,12	38,20
Average	45,06	45,04	45,04	44,28	44,97
Standard deviation	5,78	5,76	5,74	5,13	5,47
Maximum	58,10	57,99	57,91	55,85	56,90
RHS = $\sum_i\lvert\overline{RH} - RH_i\rvert$	3828,60	3810,53	3797,75	3376,73	3633,85

Oseberg floor 1

In Table 33 the relative humidity results from Oseberg U1 can be seen. Scenario B shows no reduction in RH fluctuation. Scenario C and D decrease the fluctuation by 0.3% and 0.2% respectively, while scenario E decrease the fluctuation by 2.2%.

Table 33: Results for relative humidity for Oseberg floor 1

	A: Regular concrete	**B: Cellular concrete**	**C: Lime finish**	**D: Gypsum**	**E: Spruce wood**
Minimum	37,15	37,15	37,13	37,15	37,18
Average	43,49	43,49	43,48	43,48	43,43
Standard deviation	7,18	7,18	7,16	7,15	6,98
Maximum	60,07	60,02	59,90	59,82	58,89
RHS = $\sum_i\lvert\overline{RH} - RH_i\rvert$	4831,38	4831,68	4819,12	4820,30	4722,80

6.2.2. Passive house

In this chapter the results from the simulations based on the passive house standard will be presented.

Gokstad floor U1

Table 34 summarizes the results for relative humidity in Gokstad floor U1 for the different simulation scenarios. For simulation scenario C there’s no dampening effect. Scenario D, has a very small reduction of 0.3%. Some reduction of 2.1% and 2,9% can be seen for scenario B and E respectively.

Table 34: Results for relative humidity for Gokstad floor U1

	A: Regular concrete	**B: Cellular concrete**	**C: Lime finish**	**D: Gypsum**	**E: Spruce wood**
Minimum	35,42	35,29	35,41	35,39	35,30
Average	40,29	40,20	40,29	40,28	40,19
Standard deviation	5,23	5,13	5,23	5,21	5,09
Maximum	54,26	54,20	54,14	54,26	53,99
RHS = $\sum_i\lvert\overline{RH} - RH_i\rvert$	3536,88	3463,53	3534,36	3525,54	3435,84

Gokstad floor 1

Table 35 shows the results for relative humidity in Gokstad floor 1. The results have almost the same distribution as for floor U1. No reduction in the RHS for scenario C. A reduction of 0.3% for scenario D, and a reduction of 2.5% for scenario E. Scenario B has a lower reduction impact here than on the first floor. The RHS is reduced by 1.7%.

Table 35: Results for relative humidity for Gokstad floor 1

	A: Regular concrete	B: Cellular concrete	C: Lime finish	D: Gypsum	E: Spruce wood
Minimum	36,48	36,32	36,47	36,44	36,33
Average	41,22	41,13	41,22	41,21	41,12
Standard deviation	5,53	5,44	5,52	5,51	5,39
Maximum	55,55	55,51	55,43	55,55	55,28
RHS = $\sum_i \lvert \overline{RH} - RH_i \rvert$	3733,78	3670,56	3731,75	3724,48	3638,71

Oseberg floor U1

The results for zone Gokstad U1 can be seen in Table 36 below. For this zone, the stabilization is higher than for the previous zones. Scenario C is reducing the RHS by 0.4%, while Scenario D is reducing it by 0.8%. For scenario B the reduction of RHS is 3.3%, and scenario E with spruce wood has the best stabilizing effect with 5.5% reduction.

Table 36: Results for relative humidity for Oseberg floor U1

	A: Regular concrete	B: Cellular concrete	C: Lime finish	D: Gypsum	E: Spruce wood
Minimum	36,53	36,52	36,54	36,53	36,66
Average	41,48	41,38	41,49	41,48	41,41
Standard deviation	5,77	5,59	5,74	5,72	5,44
Maximum	55,08	54,95	54,94	55,06	54,55
RHS = $\sum_i \lvert \overline{RH} - RH_i \rvert$	3859,48	3732,87	3845,38	3827,91	3647,86

Oseberg floor 1

For Oseberg floor 1, the results can be seen in Table 37 below. Scenario C and D has the lowest impacts on RHS, reducing it by 0.4% and 0.8% respectively. Scenario B with cellular concrete reduce the relative humidity fluctuation by 3%, and scenario E reduce the fluctuation by 5.8%.

Table 37: Results for relative humidity for Oseberg floor 1

	A: Regular concrete	B: Cellular concrete	C: Lime finish	D: Gypsum	E: Spruce wood
Minimum	37,51	37,47	37,52	37,51	37,66
Average	42,42	42,31	42,43	42,42	42,35
Standard deviation	5,77	5,60	5,74	5,717	5,42
Maximum	56,39	56,02	56,28	56,16	55,28
RHS = $\sum_i \lvert \overline{RH} - RH_i \rvert$	3844,74	3729,51	3831,14	3815,68	3622,52

6.2.3. Comparison between TEK-house and PAS-house

In this chapter a comparison of the relative humidity stabilization by moisture buffering on the reference cases will be presented

Gokstad floor U1

Table 38 below shows the comparison of the relative humidity stabilization index between the TEK-house and the PAS-house. The stabilization is quite low for all scenarios. Spruce wood, in scenario E is the best performing for humidity stabilization reducing RHS 2.3% for the TEK-house and 2.9% for the PAS-house. The other scenarios have little or none effect on the RHS.

Table 38: Comparison of relative humidity stabilization for Gokstad floor U1

	TEK-house		PAS-house	
	RHS	%-change RHS	RHS	%-change RHS
A	3747.1	0	3536.9	0
B	3749.1	0	3463.5	2.1
C	3733.2	0.4	3534.4	0
D	3729.5	0.5	3525.5	0.3
E	3660.1	2.3	3435.8	2.9

Gokstad floor 1

Table 39 below shows the results for the relative humidity stabilization index for Gokstad floor 1. The RHS is low for all scenarios in the TEK-house, while scenario B and E has some dampening effect on the PAS-house. They reduce the RHS by 1.7% and 2.5% respectively.

Table 39: Comparison of relative humidity stabilization for Gokstad floor 1

	TEK-house		PAS-house	
	RHS	%-change RHS	RHS	%-change RHS
A	4865.6	0	3733.8	0
B	4867.4	0	3670.6	1.7
C	4860.6	0.1	3731.8	0
D	4861.6	0.1	3724.5	0.3
E	4825.8	0.8	3638.7	2.5

Oseberg floor U1

Table 40 is a comparison of the relative humidity stabilization for Oseberg on floor U1. It can be noticed that scenario D and E suddenly seems to reduce the RHS for the TEK-house, by 11.8% and 5% respectively, while the same results for the passive house shows reductions of 0.8% and 5.5%. Scenario B and C has almost no reduction for the TEK-house, while scenario B reduce the RHS with 3.3% for the PAS-house.

Table 40: Comparison of relative humidity stabilization for Oseberg floor U1

	TEK-house		PAS-house	
	RHS	%-change RHS	RHS	%-change RHS
A	3828.6	0	3859.5	0
B	3810.5	0.5	3732.9	3.3
C	3797.8	0.8	3845.4	0.4
D	3376.7	11.8	3827.9	0.8
E	3633.9	5	3647.9	5.5

Oseberg floor 1

Table 41 below shows the results for the TEK-house and PAS-house with respect to relative humidity stabilization. Scenario B shows no effect on the TEK-house, while a reduction of 3% on the RHS can be seen for the PAS-house. The PAS-house experiences a reduction of the RHS of almost 6% with scenario E, while only a reduction of 2.2% can be seen for the TEK-house. The other scenarios don’t really have any stabilizing effect on either of the houses.

Table 41: Comparison of relative humidity stabilization for Oseberg floor 1

	TEK-house		PAS-house	
	RHS	%-change RHS	RHS	%-change RHS
A	4831.4	0	3844.7	0
B	4831.7	0	3729.5	3
C	4819.1	0.3	3831.1	0.4
D	4820.3	0.2	3815.7	0.8
E	4722.8	2.2	3622.5	5.8

The simulations of moisture buffering on the TEK-house and PAS-house shows that spruce wood (scenario E) can to a certain extent reduce the fluctuation of the relative humidity. A reduction of 2.5 - 5.8% can be seen for the passive house, while the effect for the TEK-house ranges from 0.8 – 5%. It can also be noticed that cellular concrete (scenario B), has close to no reducing effect on the RHS index for the TEK-house, while it shows a stabilizing effect up to 3.3% for the PAS-house. Generally, none of the materials show a great reduction of the relative humidity fluctuations for all zones.

7. Discussion

In this chapter the simulation model, the PCM-ad in and the HMWall model is discussed. Then the results from the simulation scenarios will be discussed and compared with to literature.

7.1. Energy model

The energy model was built up for this thesis specifically. In the subchapters below the setup of the energy model will be discussed, as well as the models used for investigation, PCM ad-in and HMWall.

7.1.1. Input values

At the early design phase, simplifications and assumptions must always be made. The energy model of the Viking Age museum is based on information, mainly from the documents in the BIM-file in, a report found on Statsbygg's web pages and documents shared by Hjellnes Consult. The collected input values are from reliable sources, and should be trustable. However, some of the information from the different sources were contradicting, and assumptions had to be made. Since the project is in the early stage, some data might be subject to changes later on.

The model was made by the writer of this thesis alone, with minor help from the supervisor. When only one person is making a complex energy model, some errors of implementing the input data might happen, that could produce errors in the output from the simulations. In complex energy models these errors can be hard to find, even if the model is assessed carefully by the maker. Therefore, at least one additional person should look critically at the model. Errors can also occur if the maker has a wrong understand of the governing equations of the simulation program. These errors caused by the fact that humans are making the models is hard to get rid of.

One of the most critical and uncertain input values, are the number of visitors. For this study, the same number of people and occupancy schedule are assumed every day. This means that every day Gokstad and Oseberg will have 625 visitors that will release both heat and water vapour. This heat and vapour will still be present in the building model for the next day, if it is not removed by the room units, or techniques installed. Since many periods of the year will have a lower number of visitors, the efficiency of the techniques to the dampening of relative humidity and temperature can be too high, compared to the real situation.

A detailed heating and cooling system has been neglected, as it was important to see how the techniques chosen for the master thesis was functioning. However, it is planned to have thermal wells for energy storage and 800m^2 solar panels. If all of this were to be added to the model, the way these systems work together with the techniques proposed could change the results of the simulations.

The net area of the building in IDA ICE is higher than what was expected from information from Hjellnes, even though their floor plans were used as a reference point for making the model. In an email from Hjellnes, it was estimated that the total floor area of Gokstad will be about 2250m^2 in total. The total floor area in the IDA ICE model is 2553m^2. This is an error of ~13.5%, that could cause deviation from the real case. When the PCM was applied, the estimation for some of the scenarios was based on the floor area of the zones. This PCM solutions will then have more m^2 area of PCM than would be the case for the real building. On the contrary, the energy model has more air volume where the temperature fluctuation has to be reduced. For the simulation cases with PCM on internal walls, or HMWall, the area of the walls compared to the volume of the building will be too little. This means that if the net area was more accurate, the measures could have a higher efficiency on stabilizing the indoor environment.

7.1.2. The PCM model

The PCM model is still under development, and are only available from EQUA AB by request. IDA ICE is a well validated and trusted program. No equations have been changed or added, so the results from the models should be trustable. Cornaro et al. have validated the modelling of PCM through a comparison of experimental data to simulated data. This is the only paper found that has validated the PCM ad-in. Hence, there could be issues with the equations on the program, compared to how the PCMs would work. The enthalpy-temperature method of calculating the effects of PCM is used by several other simulation programs that have validated their PCM models. Therefore, the results should give somewhat trustable indication of the possible effects of the PCM.

Even if the PCM ad-in is trustable, the simulations in IDA ICE failed during simulations due to numerical failure. This happened when the PCM was added as an internal wallboard of the wall It might be due to the complexity of the model, which makes it complicated for the simulation program to solve the equations. Since the PCM was added as an internal mass instead, it was not succeeded to find the heat fluxes to and from the material. This output can then not be compared to the ones done by e.g. Cornaro et al., and to check how the PCM is absorbing the heat during daytime, and releasing it at night time. This could have given valuable results.

Even though several programs have implemented their own PCM models, not all specialists are impressed by the work. In a 2014 meeting of the IEA (International Energy Agency), members revealed that their confidence in building simulation modelling of PCM was low [92]. The experience was that actual thermal behaviour of PCM was not well known, extensive testing of PCM models were lacking, and modelling parameters were very simplified.

The PCM ad-in for IDA ICE is new, and still under development. Only two published studies were found, both conducted by Cornaro et al. This makes it impossible to directly compare the results of the simulations to gain confidence in the simulation model and the results.

7.1.3. The HMWall model

The HMWall model is also still under development. Some studies were found with implementation of the HMWall, but none provided their set up and no papers with discussion of the equations for the HMWall was found. When EQUA sends out the HMWall extension, some example files are attached. They were tested out to confirm that the exchange of the regular wall with the HMWall was done in the right way. Correct simulation results were achieved for the examples. EQUA does not provide any support for extensions that are not finished, even though they are eager for people to try them out and get results in return.

One of the most important aspects of moisture buffering in building materials is the pore structure. The pores of the material structure are where the moisture is absorbed to, and hence the availability of pores in the material is one of the important parameters. The HMWall does not have porosity as one of the input values of the program. Other simulation programs seem to have a separate parameter that indicates the porosity of the materials. This could possibly be a source to unexpected results.

An issue with implementing the HMWall is that for a lot of materials, not all input values that are required by the HMWall can be found, or have been estimated through experimental studies [84]. When no parameter data is found for a material, even inserting 0 or 1 could have an impact on the simulation results.

Another challenge that could cause incorrect results is the Maesan database where most of the input data was collected from. It has a wide variation of options for the same product. For cellular concrete, 16 varieties can be found in the database. The material parameters do distinguish to some extent, and which product that was chosen could influence the result.

7.2. Simulation results

The results from the simulations presented in the previous chapter will be discussed in the following subchapters.

7.2.1. Temperature stabilization by PCM

The results show that the temperature fluctuation is reduced for all simulation scenarios with PCM. Both the difference between the minimum and maximum temperature occurring in the period (ΔT), and the temperature stabilization index (TS) was reduced. The total surface area of PCM determines the possible stabilization of the fluctuations.

As the passive house already separates the indoors more from the outdoor conditions than a TEK-house, it could be expected that the reduction of the fluctuation would be greater for a TEK-house. When low amounts of PCM is installed, corresponding to the area of half the internal walls or all the internal walls, there’s a small difference for the two buildings. However, with increased amount of PCM, a higher reduction of the temperature fluctuations can be observed for the PAS-house compared to the TEK-house. This effect could be due to a slower response of the PAS-house with change of temperatures.

For practical and economic reasons, it would not be possible to fill all the internal walls and the floor of the zones with PCM, even though this scenario had the best stabilizing effect. PCM products are often based on hard surfaces that have bad acoustic absorption properties. Also, the price of PCM products for building applications is still high, so to buy large amounts of PCM would blast the budget. Incorporating PCM in just internal floors, had a very good stabilizing effect of 0.9% for the TEK-house and 1.1% for the PAS-house. This could be a possible measure to reduce the indoor temperature fluctuations. The PCM could then be blended with the concrete, and used in the floor Viking Age museum. However, studies done on large scale buildings, like the Viking Age museum lacks.

In Table 42 an overview of some and their results for stabilizing temperature fluctuations can be seen. Their main results and comparison to this research is listed. All of the papers claim that PCM can reduce temperature fluctuations. Not all of the papers have stated the amount of reduction, but several papers have concluded that the reduction can be up to 1°C. This agrees with the results of this study.

Table 42: Comparison of previous research and this studiy with respect to stabilization effect of PCM

Other research		This research		Comments
Ref. No	Statement	Agree	Disagree	
[39]	Max temp. fluctuation 1.15°C lower.	X		Test room Gypsum wall board w/PCM Chinse winter Normal indoor temp
[44]	Temp. fluctuation could be reduced by 2.5°C		X	Test boxes Dutch study PCM in concrete floor Netherlands
[35]	Reduce indoor temp. fluctuation with 4°C		X	Cabins in New Zealand Gypsum wallboard Summer
[42]	Reduce peak T up to 1*C Smooth out daily fluctuations	X		Mediterranean climate Brick construction
[43]	Smooth temperature fluctuations	X		Three different climatic conditions in China

A direct comparison between this study and other studies can give some indication of the effect of PCM. However, the studies have different ways of incorporating PCM (gypsum boards/encapsulation in concrete), different PCM producers, different PCM products (salt hydrates/paraffines), different peak melting temperatures, different climatic conditions, allowance for free-running temperatures etc. which makes it difficult to compare results directly. For most studies, a somewhat free-floating temperature has been allowed. This of course gives a higher resulting effect as more heat can be stored, especially when the test rooms are experiencing high temperature over a time-range, so all of the material can be exploited.

One of the crucial issues of PCM application in buildings, is the lack of quantifiable data in literature of the effect of PCM for buildings in use. Very many papers praise PCM as a measure to dampen temperature fluctuation, and reduce heating- and cooling needs. However, most of these studies are either state-of-the art reviews, laboratory work, or experiments done on cubicles, test cells or small family houses. In these studies, no cooling is applied, and fre running temperature often allowed. Even though some literature [93, 94] mention case studies, no measurable data can be found to compare with the findings in this study. The transfer value of these studies is therefore limited. In this way this thesis can provide knowledge of possible effects of incorporating PCM on a large-scale building for temperature stabilization in a Nordic climate.

7.2.2. Relative humidity stabilization by moisture buffering materials

By looking at the results in chapter 6 it is clear that the moisture buffering did not provide as great stabilizing effect on the relative humidity as expected. Some reduction of the RHS could be seen for the spruce wood panel for the TEK-house and the passive house. The cellular concrete could also have some reduction on the RHS for the passive house, while it had no effect at all for the TEK-house. The rest of the materials had no stabilizing effect on the relative humidity.

When comparing to the information provided in the theory section, it is not likely that exchanging regular concrete for cellular concrete would not give any dampening effect at all. Neither the simulation results for the other materials. As some moisture buffering could be seen from the scenario with spruce wood panels, it is not clear why the rest of the materials lack any effect on the relative humidity fluctuation of the room.

A possible explanation for why the moisture buffering might not work is due to the small area of moisture buffering materials. For all simulation scenarios the HMWall, and moisture buffering materials were only added at the internal side of the external walls. Compared to the large volume of the exhibition rooms, these small areas with moisture buffering material, might not be sufficient to efficiently absorb the water vapour released from visitors and equipment.

Another possible reason for the lack of expected results, could be that the control system somehow conflicts with the effects of the moisture buffering materials. The air handling unit had to be applied in order for the study to have any transfer value for the museum, but this can also have caused the lack of expected results.

There’s a lot of studies on moisture buffering of materials that provide moisture buffering values of specific materials. However, few studies are quantifying the stabilizing effect on relative humidity. They claim relative humidity fluctuations can be stabilized, and it is visible on graphs in their papers, but no values are defined for comparison. In addition, information on how much the HVAC-system of air flows, humidification and dehumidification can be reduced by use of the passive moisture buffering of materials is not provided. In this way it is difficult to compare the results from this study, to other studies.

Based on the results, it is not easy to conclude with anything about the tested moisture buffering materials and their ability to stabilize the indoor environment with confidence. Especially the suddenly effect of gypsum on reducing the RHS for Oseberg U1 in the TEK-house. It is assumed that this specific result must come from an error in the input of the simulation model, even though it could not be found by examining the model carefully.

8. Conclusion

In this thesis the stabilization of the indoor environment using building technologies was studied. Two techniques found in literature, that are claimed to have a stabilizing effect on the indoor environment, was implemented and evaluated. Phase change materials were looked at for stabilizing temperature, while moisture buffering in building materials was tested to reduce fluctuations in relative humidity for the museum. Two reference cases were made, one based on the minimum requirements for buildings (TEK-house), and one based on the Norwegian passive house standard (PAS-house). The indoor environment of exhibition halls of Gokstad and Oseberg were analysed.

The simulations of incorporation of PCM into the exhibition halls, showed that PCM can stabilize the temperature fluctuations, and lower the peak temperature in the exhibition halls. The possible stabilizing effect is increasing with increased amounts of PCM, and the effect was higher for the PAS-house than the TEK-house. For a PAS-house, a reduction of the temperature fluctuation up to 1.6°C could be seen. For this case all internal walls and the floor were covered with PCM. The TEK-house can achieve a reduced temperature fluctuation up to 1.1°C with the same amount of PCM. A more realistic amount of PCM, covering the floor, showed a possible reduction of fluctuation of up to 0.9°C for the TEK-house and 1.3°C for the PAS-house.

Although the study found evidence that PCM can stabilize the temperature fluctuations through stimulations, it is not possible to determine if the same effect would be present in an operating building. The study has given some data on simulation of PCM in a complex energy mode, and proved that the PCM can have a positive effect on reducing the temperature fluctuation in a cold climate during the mild summer time.

Simulations of moisture buffering materials did not provide results that could prove that moisture buffering by materials can be an efficient way to reduce the relative humidity for the Viking Age museum. An HVAC system must be installed to ensure stabilization of the humidity fluctuations to avoid violation. Through simulations it was shown that the stabilization effects, quantified by the RHS index, was reduced more for moisture buffering materials in a PAS-house, than for the TEK-house. For the PAS-house a reduction of up to 3.3% was achieved by exchanging the concrete of the external walls with cellular concrete. For the TEK-house, the same exchange did not show any effect. The best reduction of the RHS-index was achieved when spruce wood board was applied to the interior side of the external walls. For the TEK-house the RHS was reduced by up to 2.3%, while the PAS-house experienced reductions up to 5%. Reduction of the RHS for both gypsum boards and lime plaster were less than 1 % for both cases. The simulation results were not as good as expected, and is assumed to be due to errors in the model, conflicts between the air handling unit and the moisture buffering materials, or that the surface area of the moisture buffering materials for each zone were too small, compared to the large air volumes of the zones.

Further studies on PCM incorporated in real buildings should be done, especially to investigate how implementation of PCM in a building affects the HVAC-system, and how people, internal gains and HVAC-system affects the PCM efficiency in return. Also, more studies on quantification of relative humidity stabilization for the indoor environment are required to determine the possible effects moisture buffering.

9. Further work

In this work IDA ICE was chosen for simulations, as it's a validated and trusted program for simulations of the indoor environment. Simulations for moisture buffering and relative humidity was done with HMWall in IDA ICE. This is still under development from EQUA AS, and more validations of the set up should be made. It is recommended that someone take a deeper look into stabilization of the moisture in the museum in a simulation program that is more fitted for this specific use e.g. WUFI. Then extreme situation of a rainy day with a maximum of visitors could be simulated, and how this would affect the museum objects and the HVAC-system.

In IDA ICE PCM can only be implemented as a wallboard or internal wall mass. However, many studies have concluded that PCM applied in the air condition system could smooth the temperature variation. This could be investigated further in another software

This work has a narrow focus, as one measure was looked at for temperature stabilization, and another one for relative humidity stabilization. An investigation on the implementation of all measures, and how the building, occupants and building systems will work together should be looked at.

The requirements achieved in this work was a range of indoor air temperature between 16℃ - 25℃, and relative humidity fluctuation of 35 – 55%. In addition to this, requirements from Statsbygg is that the fluctuation of relative humidity should not exceed 5% during an interval of 24h. Many museums must fulfil these requirements, so a study on how this range can be fulfilled can be interesting.

A review of measured data for the indoor environment from other buildings that have successfully installed PCM in building materials should be made. This could give both clients and designers better grounds to consider if PCM could be applicable for their buildings.

Another interesting aspect is the one of climate change. Due to global warming it is expected that the future climate in Norway will be wetter, wilder and warmer. Most simulation programmes today use historical climate data to predict the behaviour of buildings. This is also the case for this thesis, where weather data from (years etc), have been used to make the climate file. As the climate file is one of the most important boundary conditions for the building simulation, the future climate is assumed to affect the results of the simulations to a high degree, and should be investigated. It is not sufficient to know that the building will be able to handle today's climate, it must be fit for the future and able to maintain good preservation of the museum objects with a changing climate.

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Attachments

1. Copyright notice – Lundqvist

2. Digital attachment: Model of the Viking Age Museum

The IDA ICE model of the Viking Age museum is attached as a digital file. The model can be obtained from the supervisor, Mohamed Hamdy, at the Department of Civil and Environmental Engineering at NTNU.