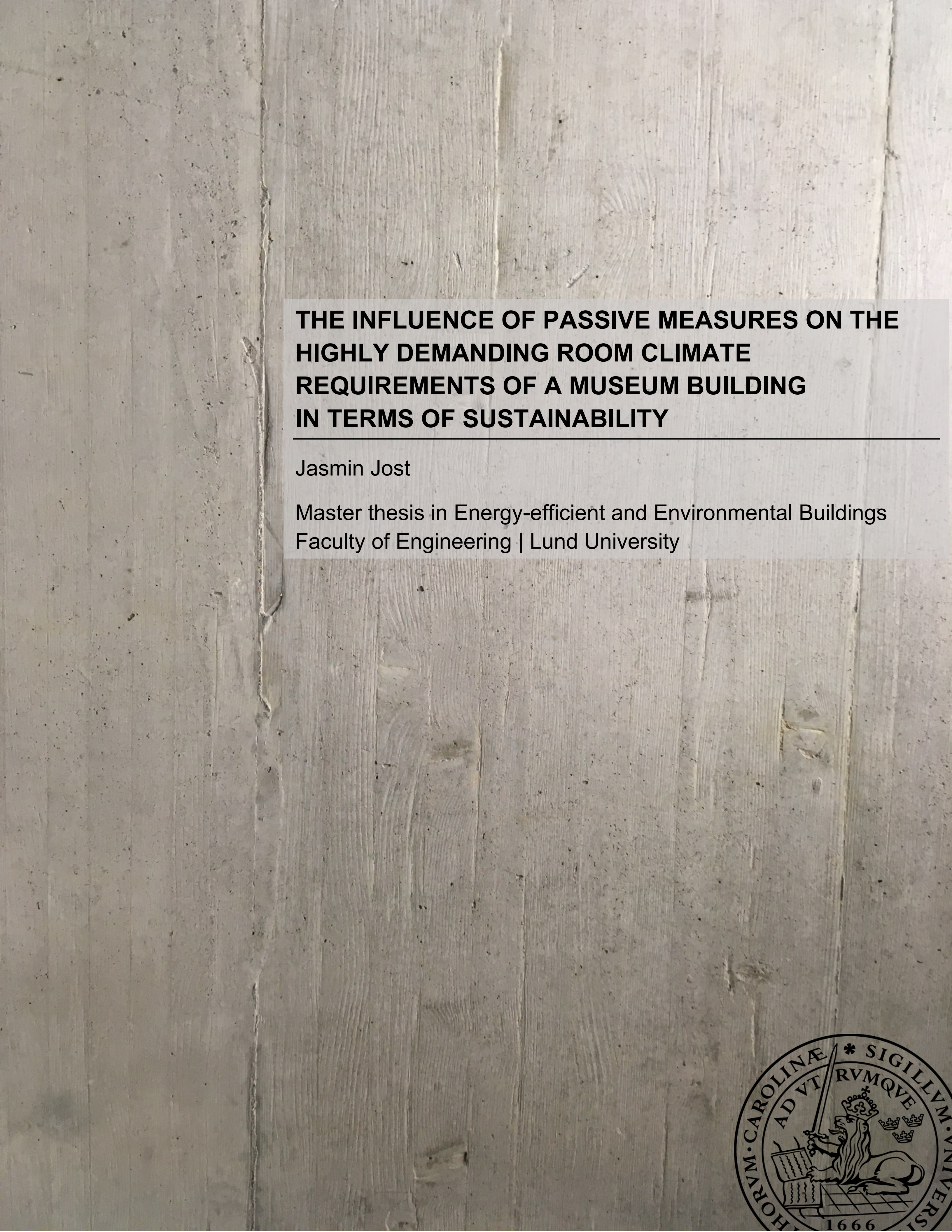

# THE INFLUENCE OF PASSIVE MEASURES ON THE HIGHLY DEMANDING ROOM CLIMATE REQUIREMENTS OF A MUSEUM BUILDING IN TERMS OF SUSTAINABILITY

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Master thesis in Energy-efficient and Environmental Buildings
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## Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

### Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: museum, museum climate, conservation requirements, climate risk assessment, indoor environment, thermal comfort, thermal mass, moisture buffering, hygroscopic materials, life cycle assessment (LCA)

Publication year: 2021

## Abstract

In the exhibition space of a museum, a compromise between the requirements for the preservation of cultural goods and thermal comfort criteria for visitors has to be applied. Such a high level of control without allowing fluctuations in temperature and relative humidity poses a big challenge to the air conditioning systems to maintain these very specific hygrothermal conditions.

This study presents a simulation-based parametric study of passive measures implemented to reduce the energy demand and thereby also the environmental impact of the building. The changes were limited to the interior walls and surfaces, keeping the main type of construction of the investigated reference building intact. The effect of thermal mass by wall thickness and moisture buffering capacity of clay plaster were assessed.

The simulation results showed that the biggest increase of thermal mass could lower the cooling demand by 1.8 % while the thickest layer of clay plaster reduced the dehumidification demand by nearly 2 %. These effects confirmed the general hypothesis but the improvement was rather minor. In terms of life cycle assessment, the applied changes amortized in less than two years due to the low initial environmental impact of the measures. By implementing a specific climate risk assessment method it was possible to investigate the impact of changed setpoints while still maintaining conservation requirements. This resulted in a reduction of the cooling demand by a third. In general, a critical review of the current standards and practices on museum air conditioning and individual risk assessment could lead to a considerable mitigation of environmental impacts currently caused by museums.

## Acknowledgements

I would like to express my gratitude towards my thesis supervisor Saqib Javed for his continued advice and support. By offering constructive feedback he helped me to achieve the goals of this study.

I would like to thank my company supervisor Michael Wengert, who provided all the necessary project information and helped with suggestions and critical questions throughout the process.

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# List of Abbreviations

DBT – Dry Bulb Temperature [°C]

EPD – Environmental Product Declaration

EPS – Expanded Polystyrene

ICCROM – International Centre for the Study of the Preservation and Restoration of Cultural Property

ICOM – International Council of Museums

ICOM-CC – International Council of Museums – Committee for conservation

IEA – International Energy Agency

IAQ – Indoor Air Quality

GHG – Greenhouse Gases

LCA – Life Cycle Assessment

MBV – Moisture Buffering Value [g/($m^2$ % RH) @ 8/16h]

PMV – Predicted Mean Vote [-]

PPD – Predicted Percentage Dissatisfied [%]

RH – Relative Humidity [%]

RMOT – Running Mean Outdoor Temperature [°C]

TABS – Thermally Activated Building Systems

UV – Ultraviolet (Light)

# 1 Introduction

In 2018, the building and construction sector caused 36% of final energy use and 39% of energy-related $CO_2$ emissions worldwide, being thereby the sector with the biggest impact (Global Alliance for Buildings and Construction et al., 2019). Museum buildings are often of high architectural value and are therefore being operated for a much longer time than other types of buildings. Over their lifespan, this results in an even higher environmental impact on their energy consumption (Huckemann et al., 2014, p. 3). However, due to the highly demanding air conditioning requirements for conservation purposes they usually have extremely high energy demands. As soon as the technological progress allowed for more specific air conditioning, these technologies were applied to the museum context. As one of the first museums, the Boston Museum of Fine Arts already installed air conditioning systems in 1908 (Erhardt et al., 2007). The improving air conditioning technology resulted in ever more ambitious architectural designs. Before its temporary closure in 2015, the, by Ludwig Mies van der Rohe designed, 'Neue Nationalgalerie' (New National Gallery) in Berlin had an annual energy demand of 12.5 million kilowatt-hours, which equals the energy use of 3 500 two-person households in Germany (Reinhardt, 2021).

The rising energy prices and financial difficulties compel municipalities to operate their buildings more cost-effectively (Huckemann et al., 2014, p. 3). Not only economic but also environmental aspects are becoming more and more relevant for museum operators. Art and artists have been addressing the topics of climate change and environmental issues for some time now. But there is a gap between the artworks and the spaces that they are displayed in (Reinhardt, 2021). In 2008 the International Institute for Conservation of Historic and Artistic Works' dialogue '*Climate Change and Museum Collections'* sparked the conversation on climate change and its impact on collections (Kirby Atkinson, 2014).

The European Standard on Conservation of Cultural Heritage already includes sustainability as the first of its principles and strategies for collections:

> "…*buildings intended to house them shall be designed to have a long life. Whether planning a new building or the refurbishment of an existing building, the Whole Life Cost (WLC) shall be evaluated and used as a basis for decision-making. (…) Planning for any new or refurbished building or space shall be directed at determining whether collections can be protected through passive or low energy means wherever possible.*" (SS-EN 16893, 2018, Chapter 4.1).

The aim of this thesis work is to investigate the impact of passive measures on a museum climate and the involved energy demand. The second aim is to critically review the room climate requirements of museums and how to provide these conditions as energy-efficiently as possible. Therefore, several passive measures and their impacts have been investigated and analysed in terms of their sustainability.

In a first step, a literature review on the status quo of museum buildings, the specific requirements for preservation of artwork and historic artefacts and examples of contemporary solutions was conducted. The next step included a review of possible passive measures and their influence on indoor climate and energy demand. Based on these findings a hygrothermal simulation was performed with the software WUFI Plus.

A construction project for a new museum building in Germany served as an exemplary building for the simulation setup. The results of these simulations were evaluated in terms of energy need, climate risks, comfort and LCA.

This study investigated the effects on one specific reference exhibition space. The findings and conclusions might not be fully applicable to other cases. Several assumptions about the construction type as well as the collection requirements were made, which would have to be critically reviewed to transfer the results to another project. It should be mentioned, that one of the assessment methods used in this study is not part of the current industry standard and should therefore only be used carefully. The results for the energy demand of the air conditioning systems does not include the processes that would be necessary within the mechanical systems. These results should therefore rather be considered as a relative indicator.

# 2 Literature Review

The following chapter gives an overview of museums in general, their specific climate requirements and climate risk assessment methods. A review of different passive measures in terms of construction materials and the process of life cycle assessment of such materials is also provided.

## 2.1 Museums

To be able to evaluate the impact of passive measures on museum climate conditions, the relevant parameters have to be established and understood. For this understanding, the purpose of a museum has to be clear. The International Council of Museums (ICOM) defines a museum as follows (*ICOM*, 2007):

> *“A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment.“*

In combining all the efforts to safeguard a collection, the term ‘preventive conservation’ was established by the ICOMs committee for conservation, describing “all measures and actions aimed at avoiding and minimizing future deterioration or loss.” (ICOM-CC, 2008).

To successfully operate a museum the collections need to be sufficiently protected against any impact that could harm the exhibits. The different standards define threats (ASHRAE, 2015), ‘agents’ of deterioration (Pedersoli Jr. et al., 2016) or hazards (SS-EN 16893, 2018). All three standards include the hazards visualised in Figure 1.

The most energy-intensive part of building operations is usually the air conditioning systems. These systems have the biggest influence on air temperature and humidity. Incorrect temperature or relative humidity of the indoor environment can pose considerable threats to collections (Michalski, 2017c).

In the next sections, the relevant climate risks, specifically the ones caused by incorrect temperature or relative humidity will be explained and general conditions which can lead to deterioration of exhibits will be presented.

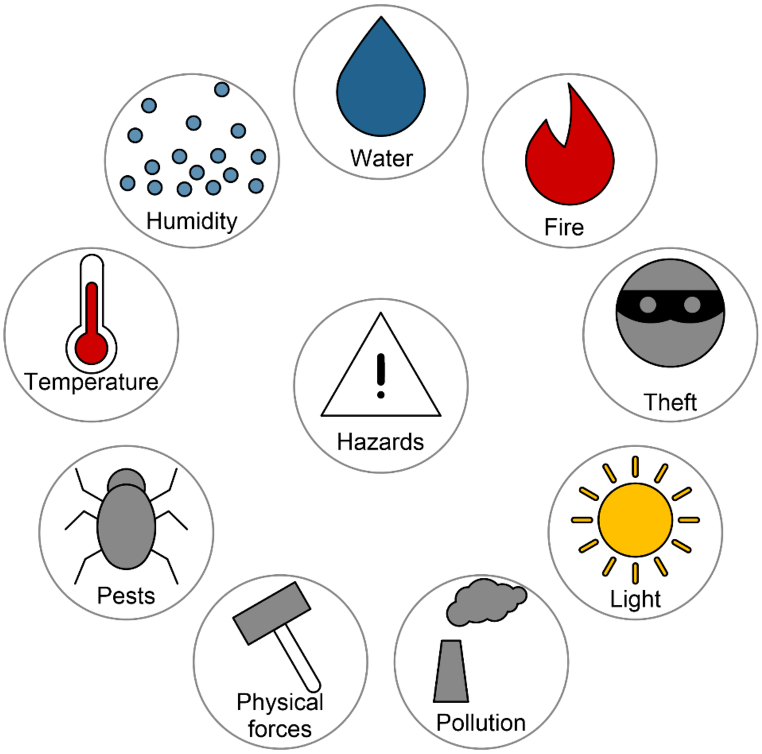


*Figure 1: Hazards to collections*

### 2.1.1 Climate Risks

(Schito, 2016) highlighted, that the relevant indoor air quality (IAQ) parameters to monitor in a museum are the mean temperature and relative humidity including their daily and seasonal fluctuations. He also includes illuminance as a critical factor.

A report by the ICOM Committee for Conservation suggests that the degree of light-induced damage on textiles or paints is dependent on the proportion of UV radiation of the light source (Saunders & Kirby, 2008). The higher the amount of UV radiation the bigger the damage. In terms of visual performance, daylight would be ideal for displaying artwork due to its excellent colour representation. However, the colour temperature, as well as its intensity, vary depending on the time of day and weather conditions (Dubois et al., 2019, Chapter 1.4-1.5). It also includes a considerable amount of UV radiation. While window glass does filter shortwave UV radiation, it does not filter enough for museum standards. Additional UV filters would have to be applied to provide sufficient protection for exhibits (Michalski, 2017a).

### Temperature

Temperature influences cultural materials principally in two ways: mechanical stresses or chemical processes. The deterioration of materials can be accelerated by high temperatures due to increased chemical processes. Exposing materials to low temperatures or high temperature fluctuations can result in cracks or deformation due to mechanical strains (Mecklenburg, 2007). Generally, the temperature should be kept as low as possible, the lower limits are usually set due to comfort criteria rather than conservation aspects (DBU, 2017).

Materials have different sensitivities to high temperatures. As displayed in

Table 1, a material with low temperature sensitivity might remain intact for over 500 years in a room with 25 °C, while another with very high sensitivity would probably deteriorate within 15 years. Examples of low sensitivity materials would be wood, cotton or leather. Stable photographic materials are considered medium sensitive, acidic paper or film as highly sensitive and magnetic media like videotapes as extremely sensitive to high temperatures (Michalski, 2017c Table 1a). According to Michalski the majority of exhibits in a mixed collection usually belong to the low-sensitivity category (2017c, sec. 3).

*Table 1: Lifetime of materials by temperature sensitivity (RH assumed to be 50%) (based on Michalski, 2017c Table 1b)*

| Temperature | Low sensitivity | Medium sensitivity | High sensitivity | Very high sensitivity |
|---|---|---|---|---|
| Heat treat, sun ~60°C | ~4 years+ | ~1 year | ~6 months | 2 months |
| Hot room ~30°C | ~250 years+ | ~75 years | ~25 years | ~7 years |
| Warm room ~25°C | ~500 years+ | ~150 years | ~50 years | ~15 years |
| Normal room ~20°C | Millennia ~1,000 years+ | A few centuries ~300 years | One human lifetime ~100 years | One human generation ~30 years |
| Cool store ~ 10°C | ~5,000 years+ | ~1,500 years | ~500 years | ~150 years |
| Cold store ~ 0°C | 20,000 years+ | ~ 6,000 years | ~2,000 years | ~600 years |

### Relative Humidity

Different kinds of relative humidity levels can be harmful to collections. As defined by Michalski (2017b, sec. 1) there are four types: Damp (over 75 % RH), RH above or below a critical value (object-specific), RH above 0 % and RH fluctuations.

One of the most common issues is dampness. It can lead to several different effects of deterioration. The most common ones are mould growth on organic materials and the corrosion of metals. Nevertheless, even highly sensitive materials like leather or parchment would need around 100 days at 70 % RH to show mould growth. The period shortens rapidly with rising relative humidity (around 2 days at 90 %). Some rather new materials are highly vulnerable even at rather low relative humidities (Rh above 0 %). Examples are old black and white negatives, videotapes or floppy discs. Here, the lifetime at 50 % RH is around 5 times lower than at 10 % RH (Michalski, 2017b Table 1).

In terms of RH fluctuation, Michalski distinguishes between the same four sensitivity groups (Table 2). While for a material with low sensitivity to humidity changes, an RH fluctuation of up to ± 40 % would probably lead to none or small damage, for a very high sensitivity material small to severe damage could already be expected with ± 10 %. In most material groups (paper, wood or paintings) the most critical objects are the ones that are either layered or restrained or include different kinds of materials with high differences in humidity-induced expansion (Michalski, 2017b Table 1).

*Table 2: Assumed damage depending on humidity fluctuations (based on Michalski, 2017b Table 1)*

| Humidity Fluctuations | Low sensitivity | Medium sensitivity | High sensitivity | Very high sensitivity |
|---|---|---|---|---|
| ± 40 % | None to small damage | Small to severe damage | Severe damage | Severe damage |
| ± 20 % | None to tiny damage | None to small damage | Small to severe damage | Severe damage |
| ± 10 % | No damage | None to tiny damage | None to small damage | Small to severe damage |
| ± 5 % | No damage | No damage | None to tiny damage | None to small damage |

### 2.1.2 Room Comfort

Since the purpose of a museum is not only to acquire and conserve human heritage but also to communicate and exhibit it, a compromise between the room climate conditions needed for conservation and comfort criteria for visitors has to be found.

It is not possible to exactly calculate room comfort. It is object to subjective sensations and preferences. An individual might perceive certain climate conditions as comfortable while someone else would consider similar conditions as uncomfortable (Schild & Willems, 2011, p. 267).

In order to provide a comparable evaluation method of the thermal environment the SS-EN ISO 7730 standard was developed (equivalent to ASHRAE standard 55). This standard seeks to determine comfort based on the heat balance of the human body. The standard uses the predicted mean vote (PMV) as an index that predicts how a large group of people would classify the climate conditions on a thermal sensation scale (Table 3).

*Table 3: Seven-point thermal sensation scale (as defined in SS-EN ISO 7730, 2006)*

| | |
|---|---|
| + 3 | Hot |
| + 2 | Warm |
| + 1 | Slightly warm |
| 0 | Neutral |
| - 1 | Slightly cool |
| - 2 | Cool |
| - 3 | Cold |

With the PMV, the predicted percentage dissatisfied (PPD) can be calculated. This index describes the percentage of people that feel thermally dissatisfied (vote hot, warm, cool or cold) on the thermal sensation scale (SS-EN ISO 7730, 2006, p. 4).

## 2.2 Risk Assessment

In this section, two different risk assessment methods are presented. The first one is the Classes of Control method specified in the ASHRAE handbook (2015) on Museums, Galleries, Archives and Libraries. The second one is a method developed by Martens (2012) which focuses on the different deterioration mechanisms on specific objects.

### 2.2.1 ASHRAE Classes of Control

The ASHRAE handbook includes five different classes of control (AA, A, B, C and D) with different bandwidths on short time and seasonal fluctuations of temperature and relative humidity, as can be seen in Table 4. In the highest class (AA) an extremely narrow humidity and temperature window of ± 5 % and ± 2 K is allowed. The setpoints are usually 50 % RH and between 15 °C and 20 °C DBT but can vary depending on collection specifications (ASHRAE, 2015, p. 23.13).

*Table 4: Temperature and Relative Humidity Specifications for General Museums, Art Galleries, Libraries and Archives (based on ASHRAE, 2015, Table 3)*

| **Maximum Fluctuations and Gradients in Controlled Spaces** | | | **Collection Risks/Benefits** |
|---|---|---|---|
| **Class of control** | **Short fluctuations plus space gradients** | **Seasonal adjust-ments in system setpoint** | |
| **AA**<br>Precision control, no seasonal changes | ± 5 % RH<br>± 2 K | RH: no change<br>up 5°C; down 5°C | No risk of mechanical damage to most objects and paintings. Some metals and minerals may degrade if 50% RH exceeds a critical RH. Chemically unstable objects unusable within decades. |
| **A**<br>Precision control, some gradients or seasonal changes, not both | ± 5 % RH<br>± 2 K | up 10 % RH, down 10 % RH<br>up 5°C; down 10°C | Small risk of mechanical damage to high vulnerability objects, no mechanical risk to most objects, paintings, photographs, and books. Chemically unstable objects unusable within decades. |
| | ± 10 % RH<br>± 2 K | RH: no change<br>up 5 °C; down 10 °C | |
| **B**<br>Precision control, some gradients plus winter temp. setback | ±10 % RH<br>±5 K | up 10% , down 10% RH<br>up 10°C, but not above 30°C down as low as necessary to maintain RH | Moderate risk of mechanical damage to high vulnerability objects, tiny risk to most paintings, most photographs, some objects, some books and no risk to many objects and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods will double life. |

| | | |
|---|---|---|
| **C**<br>Prevent all high risk extremes. | Within range 25% RH to 75% RH year-round<br>Temperature rarely over 30°C, usually below 25°C | High risk of mechanical damage to high vulnerability objects, moderate risk to most paintings, most photographs, some objects, some books and tiny risk to many objects and most books.<br>Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods will double life. |
| **D**<br>Prevent damp. | Reliably below 75% RH | High risk of sudden or cumulative mechanical damage to most objects and paintings due to low humidity fracture, but high humidity delamination and deformations, especially in veneers, paintings, paper and photographs will be avoided.<br>Mould growth and rapid corrosion avoided.<br>Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods will double life. |

### 2.2.2 Specific Climate Risk Assessment Method

To implement the impact of different climate conditions on individual exhibits, Martens (2012, p. 51) has developed a method focusing on different mechanisms causing deterioration on typical objects that represent a mixed collection.

The response of different materials to certain RH or temperature levels as well as changes of those parameters might vary greatly. This makes it difficult to specify requirements for museums in general. Instead the specific requirements of certain materials or objects should be taken into account (Erhardt et al., 2007). When looking at paper-based materials, the deterioration increases with higher temperatures. Fluctuating temperature does have an effect but the strongest expansion and contraction takes place with changes in RH. High RH also has a negative effect as it promotes mould growth and chemical reactions (NBS, 1983). For book storage, a relative humidity around 50 % and the lowest possible temperature are recommended. In most libraries and museums, the temperature (especially the lower limits) are set by comfort criteria rather than conservation considerations (NBS, 1983). The mechanisms that cause harm to exhibits are biological, chemical and mechanical degradation.

Biological degradation happens due to fungal growth. Germination only happens in damp conditions and with the availability of compostable materials. The compostable material can either be the exhibit itself or due to surface pollution. Generally, the risk of mould growth can be neglected at an RH below 60 % (Michalski, 1993, p. 625).

Mechanical degradation occurs when materials are stressed beyond their yield point. This happens especially with restricted materials and mixed materials with different expansion behaviour (Martens, 2012, p. 53).

Chemical degradation happens due to chemical processes within the material. The reaction speed of these processes is accelerated by high temperatures and the availability of water. The higher the relative humidity, the more moisture is absorbed by the material and hence the higher the reactivity (Erhardt & Mecklenburg, 1994).

Martens (2012, pp. 95–97) chose four typical pieces that have been well researched in the past to represent objects susceptible to degradation due to climate conditions. The objects are paper, a panel painting, a lacquer box and a wooden sculpture. For these materials, empirical data in terms of their deterioration behaviour at different RH and temperature levels was available. To assess the risk of fungal growth Martens implemented a study by Sedlbauer (2001), differentiating between biologically recyclable materials and materials with porous structure (allowing pollutant accumulation).

Chemical degradation was assessed with the Lifetime Multiplier Method, as described in Michalski (2002), comparing the lifetime of an object relative to its expected lifetime at 20 °C and 50 % RH. Two processes are leading to mechanical degradation. One is the difference in RH of the bulk and surface area of a material or in itself over time. The other one is the difference in volume expansion between the base material and the pictorial layer, as in the case of a panel painting (Martens, 2012).

### 2.2.3 Considerations on current Assessment Methods and Regulations

The ASHRAE classes of control should be chosen carefully. The highest class does not necessarily lead to the best result in terms of conservation of the exhibits. In historic buildings, a class B climate control is usually considered appropriate and also saves a lot of energy compared to higher classes. Generally moving up a class results in a considerable increase in energy demand (Kramer et al., 2015, sec. 3).

The “proofed” fluctuation as introduced by Michalski (2017b) is the largest RH fluctuation that an object has experienced. Any fluctuation smaller than that will result in much smaller new damage than usually anticipated for that kind of object and fluctuation. This can also be assumed for fluctuations in temperature. According to Michalski, a majority of objects in Canada has been exposed to at least ± 20 % RH, many ± 40 % RH. If an object has already been exposed to such high changes in relative humidity and they have not been restored in the meantime such humidity changes should not cause any further damage in the future either. The historic climate the artefacts have been exposed to should therefore be included in considerations concerning the climate requirements of collections (2017b).

## 2.3 **Status Quo**

This section shows several examples of museums in operation, best practices and simulation-based insights.

### 2.3.1 Examples

The following Table 5 presents a collection of room climate set points, bandwidths and energy demands of different European museums as found in current literature.

*Table 5: Examples of Setpoints and Energy Demands in European Museums*

| **Museum** | **Setpoints & Band-withs** | | **Floor Area** | **Energy demand** |
|---|---|---|---|---|
| | **T** | **RH** | | |
| Maritimes Museum Hamburg, Germany (DBU, 2017, p. 7) | Temperature subordinate as long as changes are only gradually happening | Min. 45 % rel. humidity (during winter for all materials) max. 65 % (during summer; for textiles, papers and metals) | ~ 12 000 $m^2$ | ~ 80 kWh/($m^2$a) |
| Museum Hermitage Amsterdam, Netherlands (Kramer, Maas, et al., 2015) | 21 °C; -3/+2 K | 55 % ± 5 % (paintings, furniture, wood);<br>45 - 50 % ± 5 % (mixed collections);<br>40- 50 % ± 5 % (metal collections) | ~ 2 200 $m^2$ (exhibition area) | 115.5 MWh/a (for one exhibition hall)<br>~ 250 kWh/($m^2$a) |
| Emil-Schumacher-Museum Hagen, Germany (Mueller, 2013, p. 235) | No data | No data | ~ 2 600 $m^2$ | 304 000 kWh/a<br>~ 117 kWh/($m^2$a) |
| Museum of Modern Art Kristinehamn, Sweden (EULEB, 2006c) | 20-25 °C in summer;<br>19-20 °C in winter | - | ~ 1 500 $m^2$ (330 $m^2$ exhibition area) | 107 kWh/($m^2$a); (Before improvements 210 kWh/($m^2$a)) |
| Bardini Museum Florence, Italy (EULEB, 2006a) | 20 °C | - | ~ 3 200 $m^2$ | ~ 150 kWh/($m^2$a); (Before improvements ~ 280 kWh/($m^2$a)) |
| Ethnographic Museum Canary Islands, Spain (EULEB, 2006b) | 25 °C in summer | 40-60 % | ~ 1 350 $m^2$ | ~ 120 kWh/($m^2$a) |

The six museums shown in Table 5 are set in different climates, have different qualities of envelope and mechanical systems. But overall, they show a correlation between the level of control and energy demand. The very specific requirements of Museum Hermitage result in an annual energy demand of 250 kWh/($m^2$a) while the lower level of control in the Maritimes Museum Hamburg has less than half of the energy demand per square meter floor area.

### 2.3.2 Best Practices

A very well-known example of a new-built museum in Germany is the Kunstmuseum Ravensburg. The building has few and small openings and surpasses the airtightness requirements for the passive house standard by 50%. It is noteworthy that this is despite it being the first passive house building with a revolving door in the exterior façade (*Deutsche BauZeitschrift*, 2014). It is the first museum in Germany that has been DGNB-certified (Pre-certificate in Silver) (Huckemann et al., 2014, p. 6). It improved its energy balance by using recycled bricks for the roof vaulting and the façade (DETAIL 6, 2013). The ventilation system includes heat and moisture recovery. The air is supplied via displacement ventilation. The 40 centimetre thick ceilings include TABS (Thermally Activated Building Systems) which are connected to a reversible geothermal heat pump with eight 100 meter boreholes (*Deutsche BauZeitschrift*, 2014).

A simulation-based study by Kramer et al. (2015) on the museum Hermitage (Table 5) suggests that fixed RH and temperature setpoints without any fluctuations, are not only highly energy-intensive but also increase the risk for chemical deterioration as well as discomfort. By implementing a temperature setpoint based on the RMOT, 100 % of recirculation and free-floating temperature during closing hours, the energy demand could be reduced considerably while also improving on the collection preservation. The best solution for relative humidity was a set point of 45 % with a band-with of ±5 %, this resulted in 98 % of hours in compliance with ASHRAE category A (see Table 4).

## 2.4 Passive Measures

As described in section 2.1.1 temperature and humidity fluctuations can cause considerable harm to collections. To lower the occurring fluctuations of the interior climate, the application of thermal mass and hygroscopic materials can be beneficial.

### 2.4.1 Thermal Mass

Thermal mass is the ability of a material to absorb and store heat. High thermal mass provides thermal inertia which can buffer the heat gains that occur during the day. By releasing the heat gains that occur during the day by solar irradiation and occupancy a phase-shifting can be achieved. This effect can be enhanced by night ventilation (Balaras, 1996).

In a study of a lightweight skeletal and a traditional masonry construction the average indoor temperature and cooling energy demand during a hot summer period was compared. In the masonry construction with higher thermal mass the average indoor temperature during a hot summer period could be reduced by nearly 3 K, while the cooling energy demand could be reduced by up to 75 % (Kuczyński & Staszczuk, 2020).

### 2.4.2 Moisture Buffering Capacity

A hygroscopic material has the ability to attract and hold water from its surrounding atmosphere. Such materials can therefore be used to buffer moisture changes of the surrounding climate. In an example of a bedroom, the peak indoor humidity could be reduced by up to 35 % RH by using exposed wooden structures (Simonson et al., 2002).

In 2006, a quantity to describe the capacity of materials to exchange moisture with the indoor environment was developed. The Moisture Buffering Value (MBV) specifies how much moisture can be released or absorbed by materials during humidity changes in their surroundings (Rode et al., 2006). The measurements were conducted with repeated diurnal variations of high humidity (75 % RH, 8h) and low humidity (33 % RH, 16h). The classification of MBV values can be seen in Table 6. Gypsum for example has an MBV of around 0.6 [g/(m$^2$ % RH) @ 8/16h] and is therefore considered as moderately moisture buffering. Another study by Nutt & Kubjas (2020) investigated the ability of clay plasters, which reached results between 2.18 and 3.1 [g/(m$^2$ % RH) @ 8/16h], and are considered to have excellent moisture buffering capacities.

*Table 6: Practical Moisture Buffer Value classes (based on Rode et al., (2006) Table 4.1)*

| **$MBV_{practical}$ class** | **Minimum MBV level** | **Maximum MBV level** |
|---|---|---|
| | **[g/(m$^2$ % RH) @ 8/16h]** | |
| Negligible | 0 | 0.2 |
| Limited | 0.2 | 0.5 |
| Moderate | 0.5 | 1.0 |
| Good | 1.0 | 2.0 |
| Excellent | 2.0 | … |

A simulation-based study by Liuzzi (2017) showed that the usage of clay-based plaster, instead of gypsum plaster, could reduce the hours of discomfort in summer. It also proved, a positive effect on the cooling demand. The cooling energy demand of the investigated living room was reduced by nearly 9 %.

## 2.5 **Life Cycle Assessment**

In LCA, the entire life cycle of a product is being assessed. This includes the extraction of the raw materials, production, usage and final disposal. By doing so, the environmental impact of certain stages and products should be made evident. This allows for adjustment and changes to happen to reduce the environmental impact of these stages and products (ISO 14040, 2006). To change towards a sustainable society, methods that make it possible to quantify and compare the environmental impact of products are needed. The earlier the life cycle assessment is taking place in a production process the higher the possible mitigation of environmental impacts (Rebitzer et al., 2004). In Figure 2, the different phases of life cycle assessment can be seen. In the goal and scope definition phase, the system boundaries and functional units are set, in the inventory analysis the resource and emission consumptions are estimated. The impact assessment gives an evaluation of the product life cycle. In every stage, the results are interpreted and assessed to be able to evaluate specific impacts and potentially already improve elements within this process (Rebitzer et al., 2004).

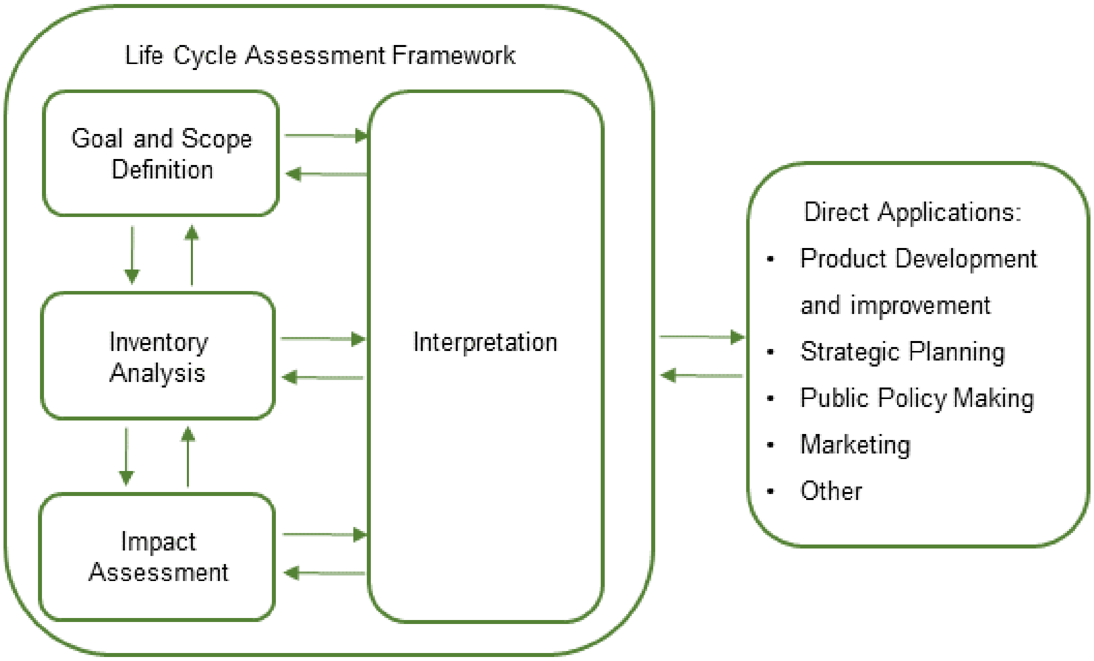


*Figure 2: LCA stages (based on ISO 14040, 2006)*

# 3 Methodology

In this chapter the method of this study is explained. In a first step the Reference Building and the modelling in the software is presented. Then follows an overview of the cases being investigated in the parametric study. The final part is the assessment of the result and a detailed presentation of the methods used for the different criteria.

## 3.1 Reference Building

The reference building is a new construction project of a museum in Germany. It has multiple basement floors with archives, depots and restoration workshops. The exhibition space is situated on the four upper floors. These upper floors have a square footprint with a gross floor area of 35 meters by 35 meters and a storey height of 6 meters. Expanded polystyrene (EPS) insulation on the exterior is combined with a solid construction with concrete walls and ribbed concrete floors. The building is projected to comply with passive house standard (Grobe, 2020).

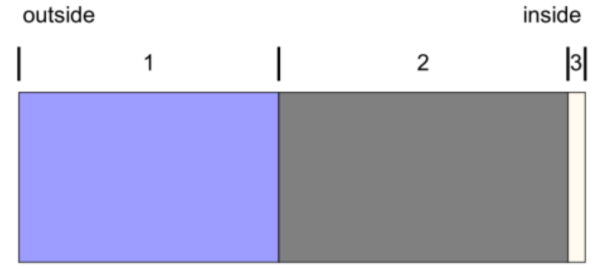
The architectural concept includes exterior glass-and-steel façade elements which are dissociated from the thermal envelope. Due to conservation requirements, specifically, the impact of UV-radiation (see 2.1.1) the building only has few openings. Windows are only sparsely placed around the entrance area and on the northern façade. The different exhibition floors are interconnected by multiple two-story voids. Heating and cooling is provided via a TABS system. To comply with the required climate specifications the air handling unit includes heating, cooling, humidification and dehumidification components. The energy source for heating is a district heating system while cooling and lighting are covered by an electricity mix of renewables and fossil fuels.

### 3.1.1 Simulation Setup

To model the effects of thermal mass and hygroscopic materials, the software WUFI Plus was used. This tool has been developed by the Fraunhofer IBP and allows to investigate the effect of heat and moisture on the indoor environment in interaction with the building components.

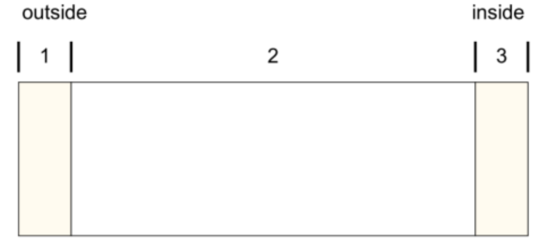
The climate file of Freiburg was used since these climatic conditions were the most fitting for the actual location of the museum. To focus on the effects of the passive measures described in 2.1.1 several simplifications have been applied to the building. The upper floor was modelled as a single zone without any windows or openings to the floor below. The exterior walls have a heat transfer coefficient of 0.15 W/(m$^2$K), the detailed assembly is shown in Table 7.

*Table 7: Assembly of exterior wall (U-value: 0.15 W/(m$^2$K))*

| Nr. | Material/Layer (from outside to inside) | Thickness [m] |  |
|---|---|---|---|
| 1 | Expanded Polystyrene Insulation | 0.225 | |
| 2 | Concrete, C35/45 | 0.25 | |
| 3 | Interior Plaster (Gypsum Plaster) | 0.015 | |

Interior walls were modelled as non-visualized components with a total of 500 m$^2$ wall surface area. They are made of lime silica bricks. The assembly is presented in Table 8. For the detailed component properties as well as climate data see APPENDIX A.

*Table 8: Assembly of interior wall*

| Nr. | Material/Layer (from outside to inside) | Thickness [m] |  |
|---|---|---|---|
| 1 | Interior Plaster (Gypsum Plaster) | 0.015 | |
| 2 | Lime Silica Brick | 0.115 | |
| 3 | Interior Plaster (Gypsum Plaster) | 0.015 | |

WUFI Plus provides multiple options to model different kinds of HVAC systems including several predefined system combinations. The detailed predefined systems, which would be necessary to model TABS are still not fully validated and their usage is not being recommended at this time (Antretter et al., 2017). Therefore an ideal user-defined system was chosen to simulate the influence of the systems as well as the energy demands. Based on the provided project data, the heating and cooling system is assumed to have 20 kW capacity. The volume flow rate of the ventilation system is dependent on the occupancy and is therefore assumed to have a higher volume flow rate during the opening hours. Since humidification and dehumidification of the air take place in the air handling unit, the capacities are proportional to the volume flow rate (see Figure 3).

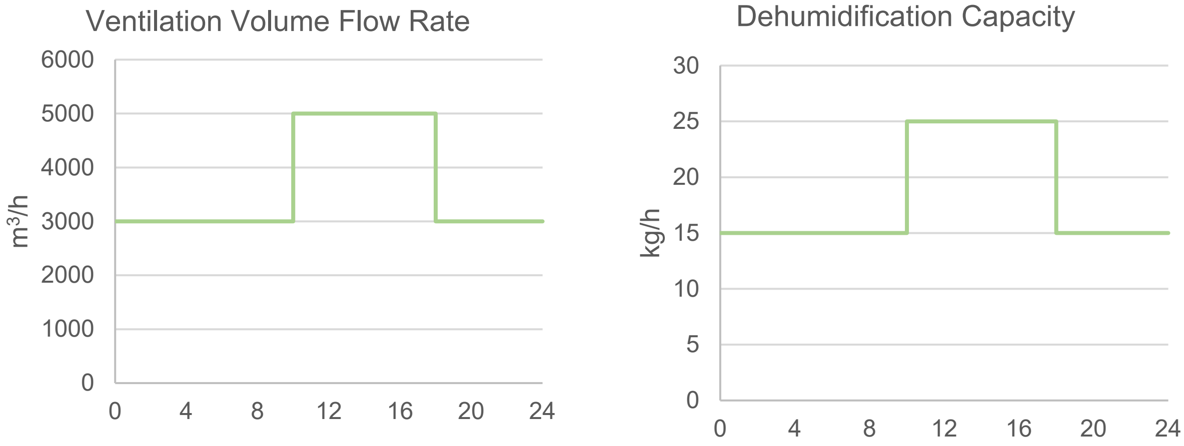


*Figure 3: Ventilation schedule (left) and corresponding dehumidification capacity (right)*

Internal gains are due to people and lighting. The values for the expected number of people and lighting were taken from the reference project. The distribution of internal gains over a day can be seen in Figure 4. The museum will be open seven days a week, so this schedule applies every day. The specific values of heat and moisture gains per person are based on VDI 2078 (Nadler, 2005, Tab. 1), and $CO_2$ emissions by people according to estimations by Heil (2012).

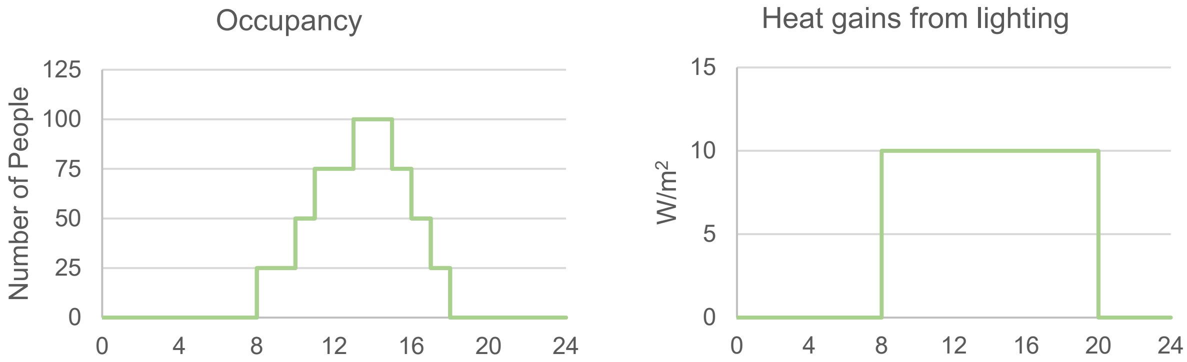


*Figure 4: Schedules for occupancy (left) and lighting (right)*

### 3.1.2 Limitations

To model the effect of hygroscopic properties for surfaces WUFI Plus (Antretter et al., 2017) was used for the simulations. It allows the precise modelling of the building components and their interaction with the interior climate. The modelling of the mechanical systems, however, is not as advanced. There is an output for latent heat due to dehumidification. But this value only includes the absolute difference between the initial condition and the final condition. For the dehumidification process, the air has to be cooled until the dew-point is reached. Therefore, a higher amount of cooling power, as well as heating power to reheat the air afterwards, is needed. The TABS including the system specific thermal inertia is not modelled and would probably lead to different effects for the energy demand and climate conditions. The ventilation system is modelled with a sensible heat recovery efficiency of 80 %. The actual air handling unit would also include heating and cooling coils as well as humidification components. These are modelled separately in the simulations and while the capacities for humidification and dehumidification have been assumed as proportional to the ventilation capacities this might still lead to different results within the zone. Another aspect is the positioning of HVAC components like supply air diffusers. In reality, their positioning is critical to avoid microclimates and drafts, however, this is also not been possible to specify properly within this model.

In addition to the software limitations some additional simplifications have been applied. The reference building has multiple voids that connect different floors to one air volume. This would lead to inter-zonal ventilation and possible stratification effects. Since not all of the floors have windows, a zone without any openings has been modelled.

This single zone might be representative of the exhibition floors of the building but not for the ground floors which include restoration workshops and archives with different climate specifications. To assume the total energy demand of the building, additional calculations would be necessary. Exterior shading due to the façade elements or surrounding buildings have also not been included.

### 3.1.3 Investigated Cases

The external walls with the general construction type of the building are already set. Hence the only components that can still be modified significantly are the interior walls and their surfaces, as well as the interior surfaces of the exterior walls. As described in Section 2.4, thermal inertia and moisture buffering capacities can have a positive effect on room climate and energy demand. To investigate the effect of additional heat storage capacity the interior walls were modelled in four different thicknesses of lime-silica brickwork. Different standard thicknesses of interior walls were used (Cases 1-4) and interior gypsum plaster applied to both surfaces of the walls, as well as the interior surfaces of the exterior walls, also see Table 7 & Table 8. A summary of the investigated cases can be found in Table 9.

The effect of the clay's moisture buffering capacity was investigated by adding different thicknesses of clay plaster on the interior wall surfaces (Cases 5-8). The thicknesses range between 5 and 35 mm and comply with traditional application standards (Naturbo, 2017). One more case (13) with a combination of thermal and moisture buffering capacities was modelled as well. All cases had the climate set points and fluctuations as specified in the provided project data of the museum and in accordance with ASHRAE class AA (Table 4). In this case, a temperature of 20 °C with ± 2K allowed temperature difference and 53 % relative humidity with ± 5 % difference in relative humidity.

Additionally, a building with less building technology was investigated to see the impact of passive measures when higher peaks in humidity and temperature can occur. Four cases with only a heating and ventilation system, but without cooling, humidification or dehumidification were modelled (Cases 9-12).

*Table 9: Overview of investigated cases*

| **Case** | **Wall Thickness** | **Plaster Material and Thickness** | **Systems** |
|---|---|---|---|
| 1 | 11.5 cm | 1.5 cm Gypsum | V,H,C,E,B* |
| 2 | 17.5 cm | 1.5 cm Gypsum | V,H,C,E,B |
| 3 | 24.0 cm | 1.5 cm Gypsum | V,H,C,E,B |
| 4 | 30.0 cm | 1.5 cm Gypsum | V,H,C,E,B |
| 5 | 11.5 cm | 0.5 cm Clay | V,H,C,E,B |
| 6 | 11.5 cm | 1.5 cm Clay | V,H,C,E,B |
| 7 | 11.5 cm | 2.5 cm Clay | V,H,C,E,B |
| 8 | 11.5 cm | 3.5 cm Clay | V,H,C,E,B |
| 9 | 11.5 cm | 1.5 cm Gypsum | V,H |
| 10 | 11.5 cm | 3.5 cm Clay | V,H |
| 11 | 30.0 cm | 3.5 cm Clay | V,H |
| 12 | 30.0 cm | 1.5 cm Gypsum | V,H |
| 13 | 30.0 cm | 3.5 cm Clay | V,H,C,E,B |

**V: ventilation, H: heating, C: cooling, E: dehumidification, B: humidification*

## 3.2 **Result Assessment**

This section presents the specific methods and standards being used for the assessment of energy performance, conservation and comfort requirements as well as life cycle analysis.

### 3.2.1 Energy Performance

The energy performance was assessed by comparing the annual heating and cooling demand. Since humidification and dehumidification have an effect on the energy demand these results were also included. However, as the actual demand of these process is not included in the simulation results, the demand will be displayed in kilograms of water.

### 3.2.2 Performance in Terms of Conservation Requirements

The climate risk assessment was performed by the two methods described in Section 2.2. For the ASHRAE class of control method, the total amount of hours that fulfil the interior climate requirements per class of control will be calculated. The different classes and their respective permitted fluctuation bandwidths are displayed in Table 10. Only when the diurnal and seasonal requirements are met, the data point is considered to be within the class.

*Table 10: ASHRAE control class specifications*

| **ASHRAE - Class of Control** | | | | |
|---|---|---|---|---|
| | AA | $A_s$ | $A_g$ | B |
| Short Time Fluctuations | ± 5 % RH<br>± 2 K | ± 5 % RH<br>± 2 K | ± 10 % RH<br>± 2 K | ± 10 % RH<br>± 5 K |
| Seasonal Fluctuations | No changes in RH<br>+ 5 K / -10 K | +10 % RH/ -10 % RH<br>+ 5 K / -10 K | No changes in RH<br>+ 5 K / -10 K | +10 % RH/ -10 % RH<br>+ 10 K / - no limit |

The specific climate risk assessment suggests a more detailed analysis of specific objects exposed to the indoor environment. Each object is assessed individually on the risk of biological, chemical and mechanical degradation (Martens, 2012).

In this study only the more critical case of a compostable material and possible mould germination and mould growth was assessed. To be able to evaluate the risk for chemical and mechanical degradation the relevant response times (

Table 11) and the climate conditions within these timespans had to be evaluated. For the chemical degradation risk, the Lifetime Multiplier for each object was determined. As long as the lowest value is not below 1, no additional chemical degradation needs to be expected. Mechanical degradation happens whenever the yield point is exceeded, due to expansion and shrinkage of materials. Since all four objects have different material combinations and properties, different response times are relevant to determine the risk for cracks or tears (Martens, 2012, Chapter 5.2).

For each object, empirical data on critical moisture and temperature levels and changes was used and implemented into the assessment. In case of the panel painting, the difference in relative humidity of the surface and of the entire panel are relevant for assessing the probability of mechanically induced damage.

*Table 11: Response times for the evaluated objects (as provided in Martens, 2012)*

| **Object** | **Relevant response(s)** | **Response time** |
|---|---|---|
| Paper | Full response of single sheet | Minutes |
| Panel painting | Surface response just under oil paint<br>Full response of entire panel | 4.3 days<br>26 days |
| Lacquer box (furniture) | Full response of entire lacquer box | 40 days |
| Wooden sculpture | Surface response<br>Sub-surface response causing maximum stress | 10 hours<br>15 days |

Due to the architectural concept (see 3.1) direct solar irradiation can be disregarded in this project and the impact of UV radiation will not be further investigated within this study.

### 3.2.3 Comfort

The thermal comfort of the exhibition space was assessed by the PMV and PPD method described in 2.1.2. Local discomfort due to drafts or operative temperatures will not be investigated in this study. In Table 12, the different categories for thermal comfort are displayed.

*Table 12: Categories of thermal comfort (as specified in SS-EN ISO 7730:2006, Table A.1)*

| **Category** | **Thermal state of the body as a whole** | |
|---|---|---|
| | **PPD [%]** | **PMV [-]** |
| A | < 6 | -0.2 < PMV < + 0.2 |
| B | < 10 | -0.5 < PMV < + 0.5 |
| C | < 15 | -0.7 < PMV < + 0.7 |

### 3.2.4 Life Cycle Assessment

To evaluate the environmental performance of the different passive measures, the Global Warming Potential (GWP) of the construction and the building operation were assessed and compared. Since the energy demand of only one floor was modelled, the same applied to the LCA. Only the materials and energy demand of the investigated floor were assessed. The impact of the building operations was assessed based on the annual energy demands for heating and cooling. However, as described in section 3.1.2, the actual energy demand for the building systems would most probably be higher. This is because the energy demand for the actual components and processes needed for dehumidification ,for example, may not be correctly represented.

All EPD data was obtained from the OEKOBAU.DAT database through the eLCA bauteileditor (https://www.bauteileditor.de/). This tool has been developed by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development. The datasets are already adjusted to the German market, electricity mix and transport.

Since not all datasets include all lifecycle stages, only the data for lifecycle stages that were available for all materials was used. Therefore, only a cradle to gate analysis was performed in terms of the materials (A1-A3). The usage phase was included with the building operations (B) for energy consumption during usage. A detailed report of the data can be found in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

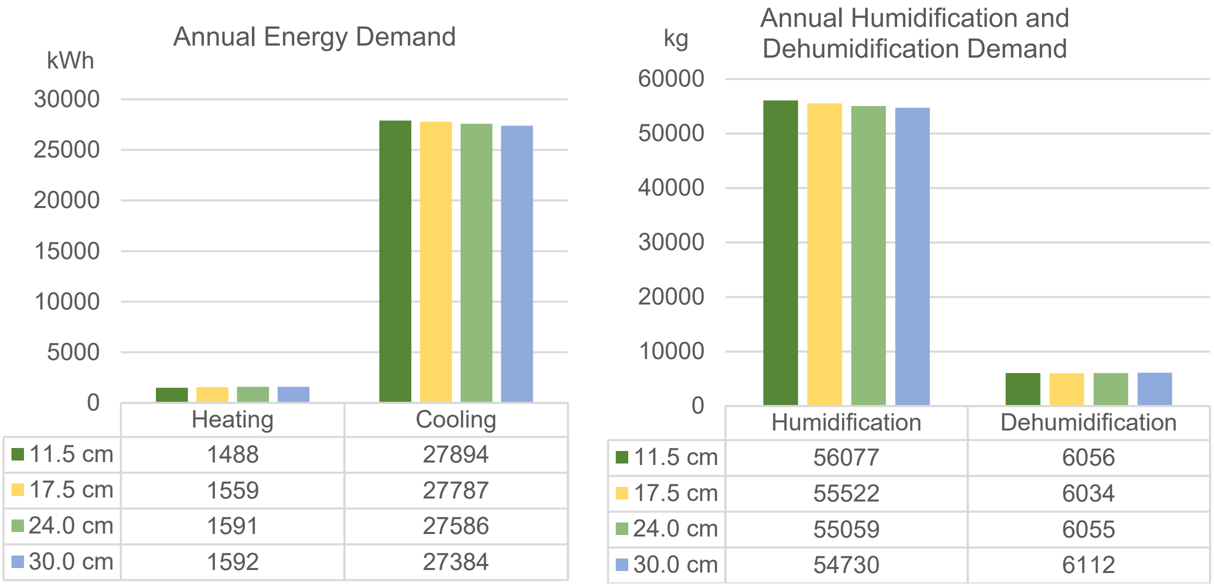
# 4 Results

In this chapter, the results of the thermal simulations and further analysis are displayed and explained. For output from the simulation program are provided in APPENDIX C.

## 4.1 Energy Demand

Figure 5 shows the annual energy demand for heating and cooling as well as the humidification and dehumidification demands in dependence of the interior wall thickness. It can be seen that the heating and dehumidification demands increase with the thickness of the walls while the cooling and humidification demands decrease slightly. The heating demand of around 1 500 kWh for all cases is rather low compared to the cooling demand of close to 28 000 kWh.

When comparing the cooling demand of 11.5 cm thick interior walls and the 30 cm walls an improvement of 1.8 % can be found. While the cooling demand is falling with the increasing thickness of the walls, the heating demand is increasing. When heating and cooling demand are both considered the total energy savings are only 1.4 %.



| | Heating | Cooling |
|---|---|---|
| 🟩 11.5 cm | 1488 | 27894 |
| 🟨 17.5 cm | 1559 | 27787 |
| 🟩 24.0 cm | 1591 | 27586 |
| 🟦 30.0 cm | 1592 | 27384 |

| | Humidification | Dehumidification |
|---|---|---|
| 🟩 11.5 cm | 56077 | 6056 |
| 🟨 17.5 cm | 55522 | 6034 |
| 🟩 24.0 cm | 55059 | 6055 |
| 🟦 30.0 cm | 54730 | 6112 |

*Figure 5: Demands of Heating and Cooling (left), Demands of Humidification and Dehumidification (right) by Interior Wall Thickness (Cases 1 - 4)*

The results of the investigations on the moisture buffering effect of clay plaster can be seen in Figure 6. The dehumidification demand could be reduced by adding clay plaster to the interior wall surfaces. Between using 1.5 cm gypsum plaster (Case 1) and 3.5 cm clay plaster (Case 8), a reduction of about 2 % was possible.

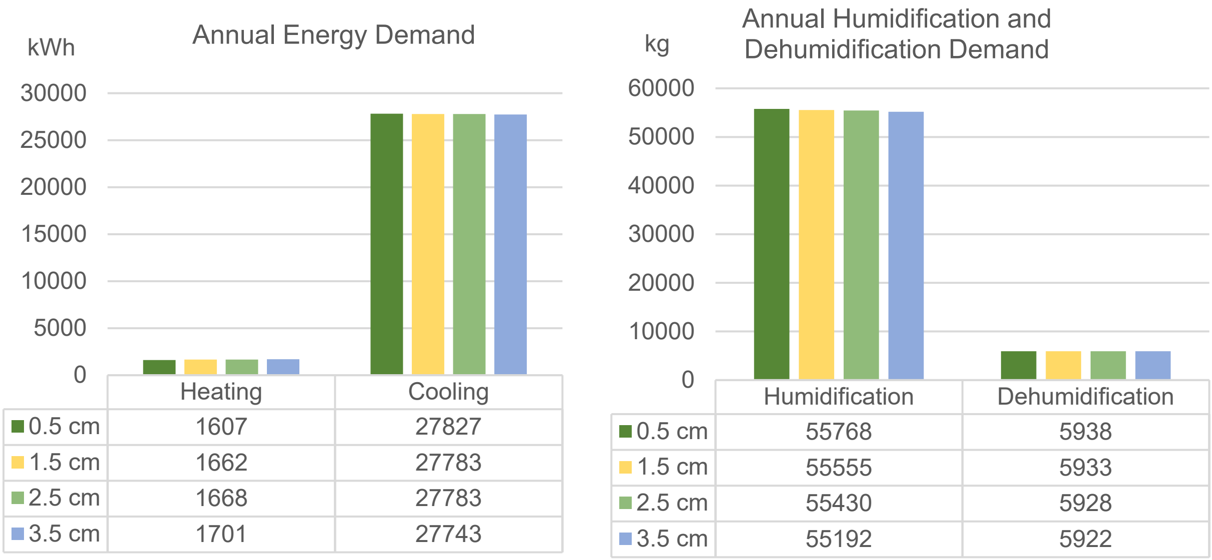


*Figure 6: Demands of Heating and Cooling (left) and Demands of Humidification and Dehumidification (right) by Clay Plaster Thickness (Cases 5 - 8)*

In Case 13, the combination of thermal mass and moisture buffering capacity was investigated. The results presented in Table 13 show that while the heating demand is slightly higher compared to Case 1 the cooling demand is the lowest of all cases. The humidification demand is also the lowest while the dehumidification demand is around the average of all results. When heating and cooling demand are both considered the resulting total energy demand is 1.8 % lower than in the base case.

*Table 13: Annual Demands for Heating, Cooling, Humidification and Dehumidification for Case 13*

| **30.0 cm walls with 3.5 cm clay plaster** | | | |
|---|---|---|---|
| Heating | Cooling | Humidification | Dehumidification |
| 1 686 kWh | 27 171 kWh | 54 028 kg | 6 018 kg |

## 4.2 Risk Assessment

For the Classes of Control method (ASHRAE, 2015), the total amount of hours that fulfil the interior climate requirements per class are shown in Table 14. Since all of the cases have the same system capacities and set points the results of case 1 are representative of cases 1 to 8 and 13. The table shows that even the most critical climate class (AA) is met over 99 % of the time.

*Table 14: ASHRAE Class of Control Results*

| **Amount of Hours within ASHRAE - Classes of Control** | | | |
|---|---|---|---|
| AA | $A_s$ | $A_g$ | B |
| 99.61 % | 99.97 % | 99.65 % | 100 % |

Table 15 shows that there is no risk for biological, chemical or mechanical degradation. The high Lifetime Multiplier value suggests, that the climate conditions are rather favourable for conservation purposes.

*Table 15: Specific Climate Risk Assessment Results (Case 1)*

| **Specific Climate Risk Assessment Method** | | | |
|---|---|---|---|
| Risk | Biological Degradation | Chemical Degradation | Mechanical Degradation |
| Method | Mould Growth [%] | Lifetime Multiplier [-] | Damage Possible or Likely [%] |
| Paper | 0 | 1.28 | - |
| Panel Painting | 0 | 1.20 | 0 |
| Furniture | 0 | 1.30 | 0 |
| Wooden Sculpture | 0 | 1.16 | 0 |

## 4.3 **Thermal Comfort**

The thermal comfort conditions in cases 1-8 and 13 are similar due to the specific set points and small allowed fluctuations. In Figure 7 the percentage of occupied hours which are within the different comfort categories are displayed. It can be seen, that 11 % of the hours are within the highest comfort category A, while half of the time is still within category B and 6 % of the time is in comfort category C. The PMV shows, that the reason for the high amount of dissatisfied (>15 % during 30 % of occupied hours) is due to people perceiving the space as too cold. This is due to the low setpoints, which allow 18 °C in the exhibition space.

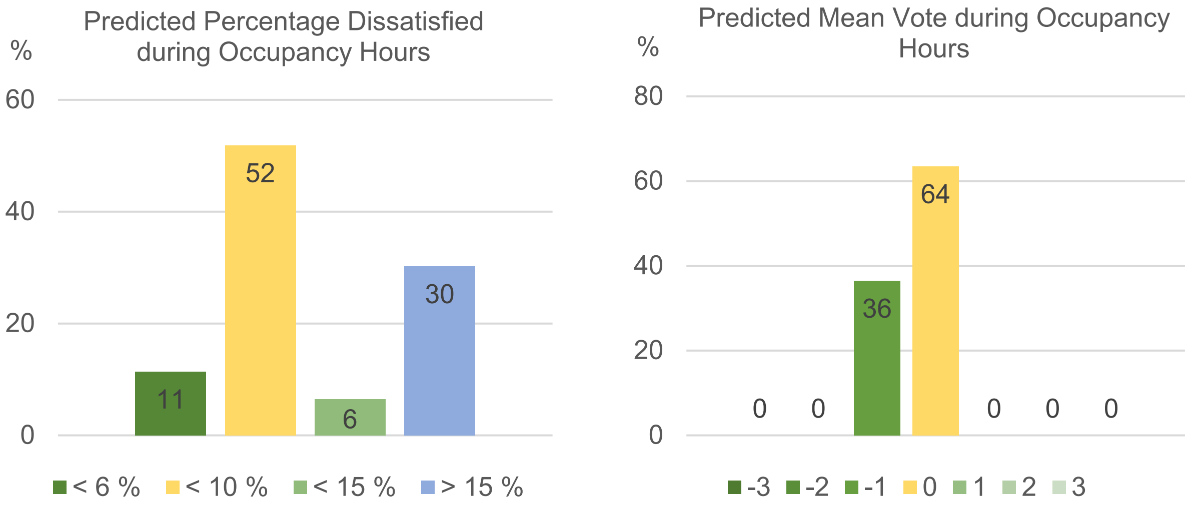


*Figure 7: PPD (left) & PMV (right) for Case 1*

## 4.4 LCA

In Figure 8, the difference in Global Warming Potential due to difference in construction between case 1 and case 13 are visualized. Changing the wall thickness to 30 cm and adding clay plaster on all interior wall surfaces increased the GWP of the production by nearly 600 kg $CO_2$ equivalent. By implementing these measures the impact of the building operations could however be reduced by 400 kg $CO_2$ equivalent per year. Therefore these measures prove to be environmentally profitable in less than two years. However, the overall impact compared to the total energy demand is still small with less than 2 % savings.

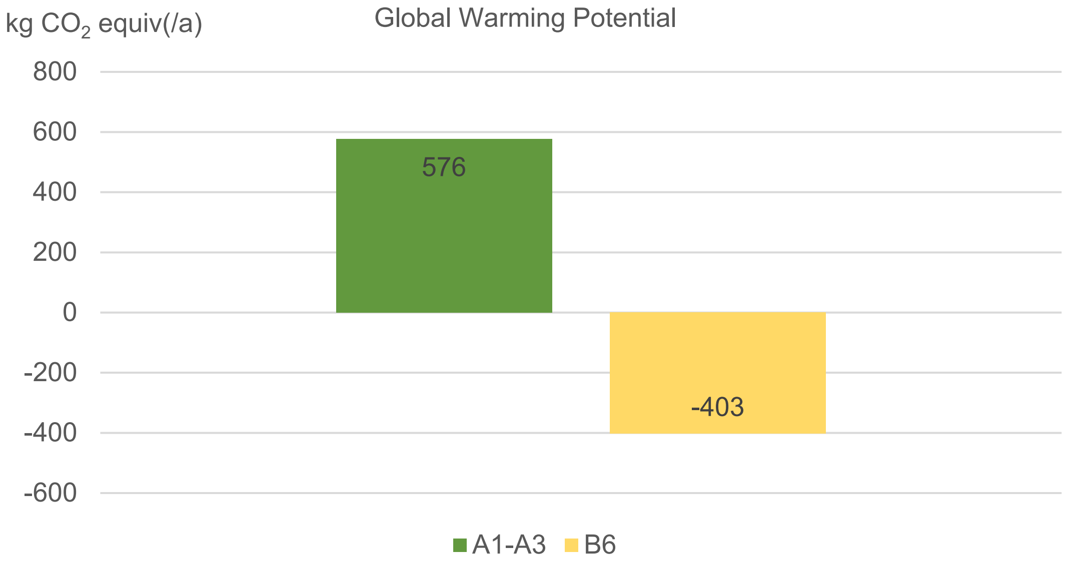


*Figure 8: Change in GWP between Case 1 and Case 13*

# 5 Critical Review

In this chapter, the results of the critical review, including the analysis based on the specific climate risk assessment method are presented and explained.

## 5.1 Minimal Level of Control

In cases 9 - 12 the effect of the passive measures in a lower level of control were investigated. For these case only a heating system was modelled, which would be the case for smaller museums, especially when they're housed in heritage buildings as well. The effect of a higher heating demand with increasing wall thickness and clay plaster instead of gypsum plaster also occurred in this study (Figure 9).

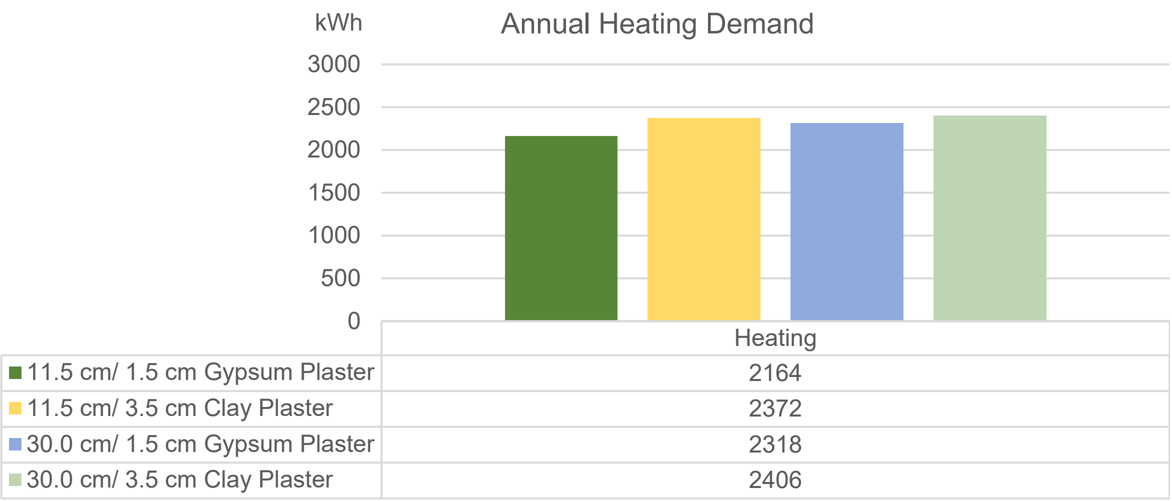


*Figure 9: Heating Demand without Cooling, Humidification or Dehumidification (Cases 9 - 12)*

The results of Cases 9 - 12 confirmed that the impact of passive measures is greater in a less air-conditioned space. As displayed in Table 16, lower thermal mass and moisture buffering capacity (Case 9) resulted in 188 hours above 35 °C. By adding clay plaster (Case 10) the hours above 35 °C were already halved. The combination of 30.0 cm thick walls and clay plaster (Case 12) showed no more hours above 35 °C. The difference in relative humidity levels are less evident. However, thicker walls and clay plaster seem to buffer the peaks in low relative humidity. While in Case 9, the base case, 4544 hours are below 30 % RH. The thicker walls and clay plaster (Case 12) lead to a reduction of over 600 hours which are falling below that value.

*Table 16: Interior Climate Conditions (Cases 9 - 12)*

| **Case** | **Wall Thickness/ Plaster Material and Thickness** | **Temperature** | | | **Relative Humidity** | | | |
|---|---|---|---|---|---|---|---|---|
| | | **> 25 °C** | **> 30 °C** | **> 35 °C** | **< 20 %** | **< 30 %** | **< 40 %** | **> 60 %** |
| 9 | 11.5 cm/ 1.5 cm Gypsum | 4707 | 2880 | 188 | 228 | 4544 | 8254 | 4 |
| 10 | 11.5 cm/ 3.5 cm Clay | 4696 | 2816 | 94 | 215 | 4344 | 8201 | 7 |
| 11 | 30.0 cm/ 1.5 cm Gypsum | 4665 | 2695 | 13 | 222 | 4092 | 8068 | 4 |
| 12 | 30.0 cm/ 3.5 cm Clay | 4649 | 2589 | 0 | 199 | 3897 | 8036 | 6 |

However, without cooling, humidification or dehumidification, it was not possible to meet the conservation requirements. The ASHRAE classes of control were not fulfilled and also the specific climate risk assessment showed an increased probability for damage. As displayed in Table 17, in all four cases, the risk of mechanical degradation for the furniture (lacquer box) and the wooden sculpture was suspected.

*Table 17: Specific Climate Risk Assessment (Cases 9 - 12)*

| **Case** | **Risk** | **Biological Degradation** | **Chemical Degradation** | **Mechanical Degradation** |
|---|---|---|---|---|
| | **Method** | **Mycelium Growth Rate [mm/day]** | **Lifetime Multiplier [-]** | **Damage Possible [%]** |
| 9 | Paper | 0 | 1.27 | - |
| | Panel Painting | 0 | 1.31 | 0 |
| | Furniture | 0 | 1.30 | 5.8 |
| | Wooden Sculpture | 0 | 1.28 | 0.5 |
| 10 | Paper | 0 | 1.21 | - |
| | Panel Painting | 0 | 1.30 | 0 |
| | Furniture | 0 | 1.31 | 6.0 |
| | Wooden Sculpture | 0 | 1.26 | 0.7 |
| 11 | Paper | 0 | 1.27 | - |
| | Panel Painting | 0 | 1.30 | 0 |
| | Furniture | 0 | 1.30 | 5.8 |
| | Wooden Sculpture | 0 | 1.28 | 0.5 |
| 12 | Paper | 0 | 1.21 | - |
| | Panel Painting | 0 | 1.30 | 0 |
| | Furniture | 0 | 1.31 | 6.0 |
| | Wooden Sculpture | 0 | 1.26 | 0.7 |

## 5.2 Level of Control based on specific climate risk assessment

While a positive impact of passive measures could be proved by the simulation results, the total energy demand of the museum building remained very high. The strict climate requirements force an energy-intensive constant air conditioning.

The room climate guidelines have been developed parallel to the technological advancement in mechanical systems, hence the indoor climate requirements became ever stricter over the course of the twentieth century (Kramer et al., 2015). With the specific climate risk assessment tool (Martens, 2012), the effect of different indoor climate conditions can be evaluated and adjusted while still ensuring the safety of the exhibits.

Therefore, another study was performed to assess the impact of different climate set points. While the construction remained the same (see Case 1), the temperature and humidity setpoints were changed. Instead of complying with the strict requirements requested by the costumer, and ASHRAE Class AA (20 °C ± 2K and 53 %RH ± 5 %) the allowable changes were based on the specific climate risk assessment. A summary of the investigated cases can be found in Table 18.

*Table 18: Investigated cases in set-point analysis*

| Case | Temperature Set-points | Humidity Set-points |
|---|---|---|
| A | 18 °C – 22 °C | 48 % – 58 % |
| B | 19 °C – 23 °C | 48 % – 58 % |
| C | 18 °C – 23 °C | 48 % – 58 % |
| D | 18 °C – 25 °C | 48 % – 58 % |
| E | 18 °C – 22 °C | 43 % – 58 % |
| F | 18 °C – 22 °C | 48 % – 63 % |
| G | 18 °C – 22 °C | 43 % – 63 % |
| H | 18 °C – 25 °C | 43 % – 63 % |
| I | 19 °C – 25 °C | 43 % – 63 % |

The detailed simulation outputs of all cases can be found in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The impact of a change in setpoints will be explained based on the example of Case A and I. Case I was chosen since it allowed the most comfortable room climate (not allowing temperatures below 19 °C), while still complying with the conservation criteria. While Case A is identical to Case 1. For Case I the allowed temperature and humidity range was extended. In Figure 10, the energy, humidification and dehumidification demands are displayed. The higher heating setpoint temperature of 19 °C results in an increase in heating demand, but the cooling demand was reduced by 33 % due to the upper limit of 25 °C. The absolute savings in annual energy demands are nearly 8000 kWh.

In dehumidification demand, the difference was even more drastic, a reduction of over 99 % was possible. Due to the energy-intensive process of dehumidification, this would have an even bigger impact on the total energy demand.

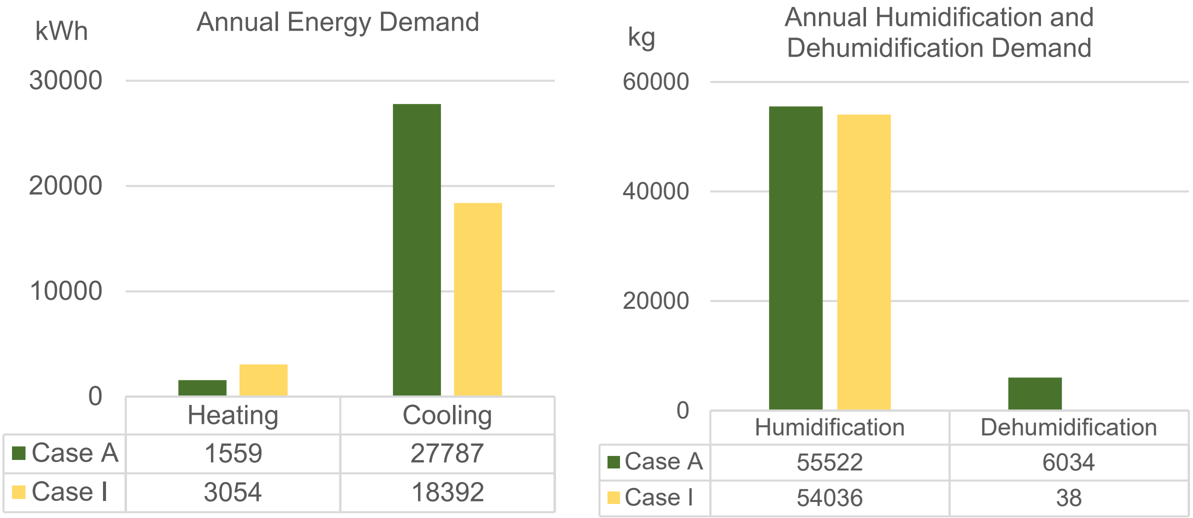


*Figure 10: Annual Demands of Heating and Cooling (left) and annual Demands of Humidification and Dehumidification (right) for Cases A & I*

The climate risk assessment did not reveal any risk for biological, chemical or mechanical deterioration while the energy demand could be reduced considerably. Figure 11 shows that even the room comfort could be improved. The predicted amount of people perceiving the climate as ‘neutral’ on the thermal sensation scale rose from 64 % to 69 %.

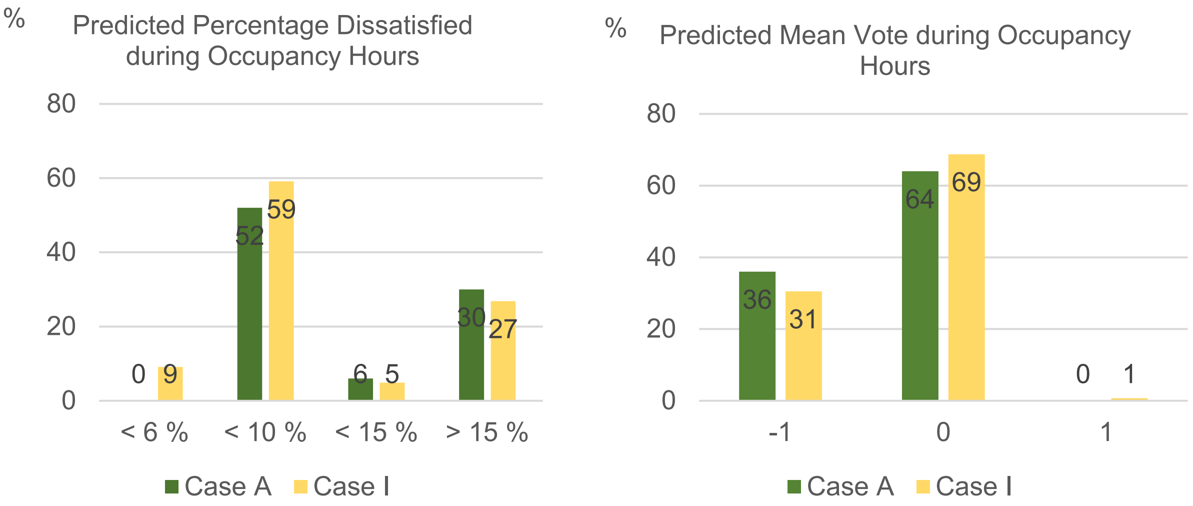


*Figure 11:PPD (left) and PMV (right) for Cases A & I*

The specific climate risk assessment shows that Case I does not result in any additional risk of biological, chemical or mechanical degradation (Table 20). But if the ASHRAE classes would be considered, just Class B would be achieved. Less than 4 % of the hourly data complies with class AA. When higher seasonal changes are allowed ($A_s$) nearly 80 % are within class A. Only allowing short time gradients ($A_g$) results in 15 % compliance with class A.

*Table 19: ASHRAE Class of Control Results for Case I*

| **Amount of Hours within ASHRAE - Classes of Control** | | | |
|---|---|---|---|
| AA | $A_s$ | $A_g$ | B |
| 3.1 % | 78.4 % | 15.2 % | 100 % |

*Table 20: Specific Climate Risk Assessment Results for Case I*

| **Specific Climate Risk Assessment Method** | | | |
|---|---|---|---|
| Risk | Biological Degradation | Chemical Degradation | Mechanical Degradation |
| Method | Mould Growth [%] | Lifetime Multiplier [-] | Damage Possible or Likely [%] |
| Paper | 0 | 1.14 | - |
| Panel Painting | 0 | 1.25 | 0 |
| Furniture | 0 | 1.30 | 0 |
| Wooden Sculpture | 0 | 1.09 | 0 |

# 6 Discussion & Conclusion

The results of the energy assessment show that the passive measures do indeed have an effect on heating, cooling and dehumidification demand. The changes in heating and cooling demand are in line with the findings by Reilly and Kinnane (2017), who found that in cooling dominated climates raising the thermal mass could have a positive effect on cooling demand, whereas in heating dominated climates it tends to increase the heating demand. Since Germany is located in a temperate climate zone, both effects were found. The cooling demand decreased with thicker interior walls, while the heating demand increased. The reduction of humidification and dehumidification demand by using clay plaster was also apparent. Similar findings were also reported by Liuzzi (2017) in which the cooling demand could be lowered by 9 % due to clay-based plaster. Although in this case, the impact of the clay plaster in cooling and dehumidification was less significant. A possible explanation for this low impact could be the high level of control of the interior climate. The clay plaster buffers peaks in humidity, however, the controlled environment of a museum does not allow these peaks to even appear at all.

The life cycle assessment of increased interior wall thickness and clay plaster showed that due to their rather small impact on the construction emissions an amortisation in less than two years would be possible. The impact of thermal mass could probably be increased if the whole envelope, including exterior walls and ceilings would have been open to changes. It could result in more significant effects, as observed in a study by Kuczyński and Staszczuk (2020). But due to the architectural specifications, it was not possible to change the general type of construction. The initial design, however, does already include important preventive conservation aspects like the lack of UV radiation and highly insulated solid walls for stable climate conditions. Especially considering future climate conditions a space with less interaction to the outside could prove valuable for the preservation of cultural goods.

The integration of room comfort assessment showed the difficulty in fulfilling comfort and conservation criteria at the same time. The predicted mean vote in the base case showed, that people were already feeling cold during more than a third of the occupied hours, because temperatures as low as 18 °C were allowed. But in order to prevent chemical degradation temperature and humidity should be as low as possible. Therefore, a balance and the prioritising between comfort and conservation criteria needs to be assessed individually in each case.

By using the specific climate risk assessment method, it was possible to confirm that broader climate set points could be allowed, without compromising on the safety of collections. With less restrictive room climate requirements, the mechanical systems would not have to be as large and a lot of energy could be saved. However, this is with the addition, that his method (Martens, 2012) requires profound knowledge about the collection and the type of objects it includes. While most objects in mixed collections belong to a low sensitivity group (see Section 2.1.1) there might still be exceptions. A solution for those could be the usage of separately conditioned display cases or as in a study by Verticchio et al. (2019), the implementation of passive microclimate frames. That way the objects with high sensitivity remain in a safe environment while most of the space can be air-conditioned with less strict climate control.

A promising approach for future studies could be the investigation of the impact of passive measures in combination with an elaborate conservation risk assessment. Since the specific climate risk assessment allows to extend the temperature and humidity limits, the energy demand for air-conditioning could already be reduced. The passive measures have a bigger impact in less controlled environments, by combining those with bigger fluctuations in temperature and humidity, the effect could be enhanced even further. But generally, the extension of temperature and humidity range could prove difficult due to the current situation with insurance policies, often demanding the highest classes of control. Therefore a change in the approach and the current policies would have to take place to allow to not only sustain the heritage and cultural goods in museums and galleries, but do so in a sustainable way.

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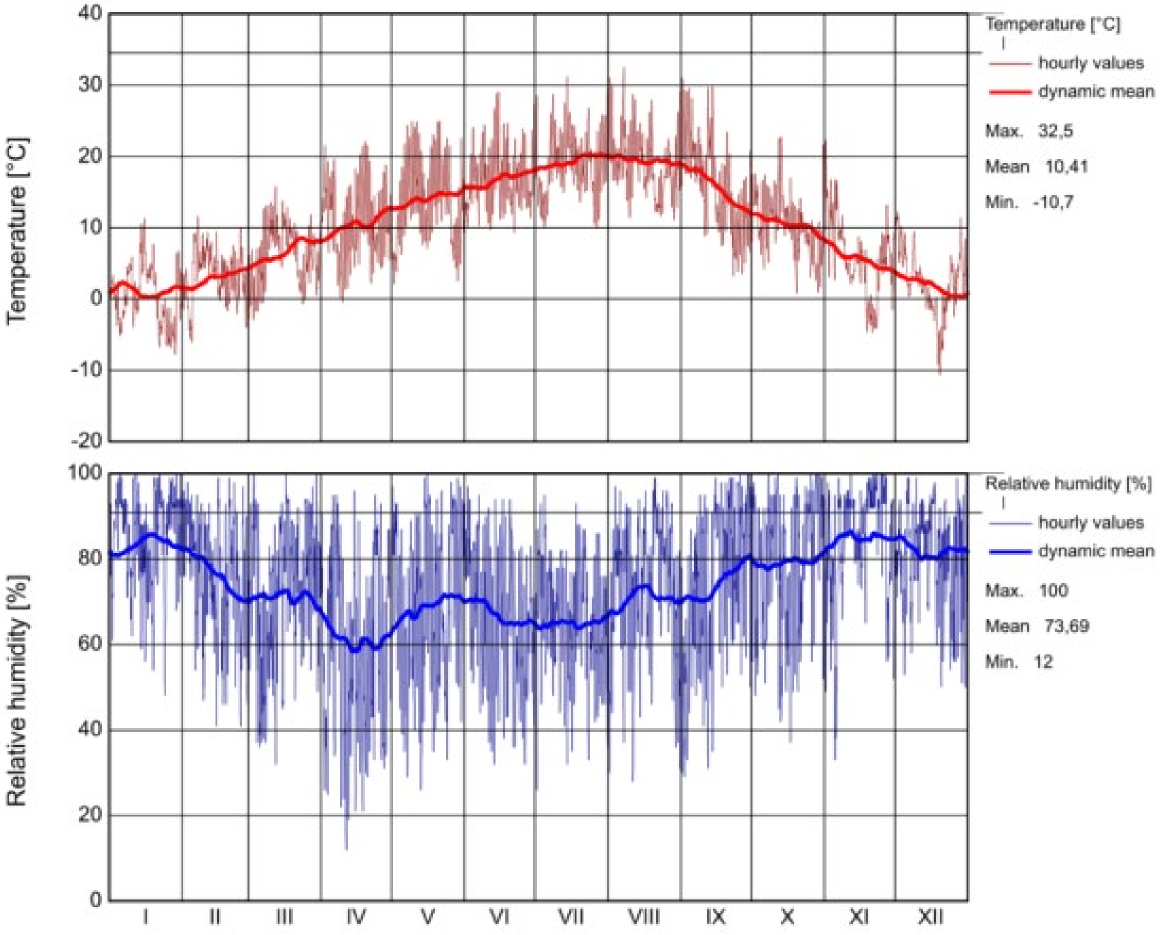
# APPENDIX A

## WUFI Plus Simulation Input Data

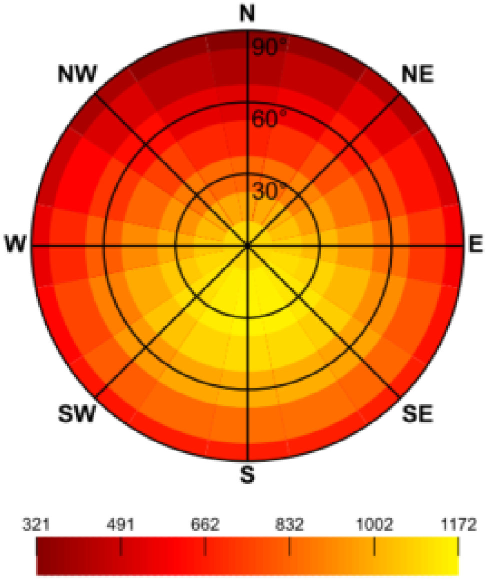
### Climate

**Case 13: Main climate**

| Freiburg (Moisture Reference Year) | | |
|---|---|---|
| Latitude | [°] | 48 |
| Longitude | [°] | 7,9 |
| Height NN | [m] | 269 |
| Time zone | [Hours from UTC] | 1 |
| Additional data | | |
| Albedo | | User defined |
| Ground reflectance short | | 0,2 |
| Ground reflectance long | | 0,1 |
| Ground emission | | 0,9 |
| Cloud index (only WET-file) | | 0,7 |
| CO2-concentration | [mg/m³] | 350 |



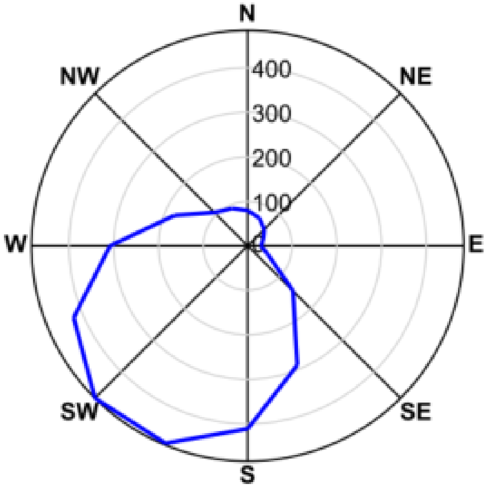
Sun radiation sum [kWh/m²a]



Counterradiation sum [kWh/m²a]: 2431,3

Mean cloud index [-]: 0,65

Driving rain sum [mm/a]



Normal rain sum [mm/a]: 939,8

Mean wind speed [m/s]: 2,35

## Conditioned zones

**Case 13/Zone 1: General data**

| | | |
|---|---|---|
| Name | | Simulated zone |
| Geometry | | |
| Gross volume (From visualized volume and components) | [m³] | 7350 |
| Net volume (User defined) | [m³] | 5750 |
| Floor area (User defined) | [m²] | 1150 |
| Other parameters | | |
| Initial temperature | [°C] | 20 |
| Initial rel. humidity | [%] | 55 |
| Initial CO2-concentration | [ppmv] | 400 |
| Distribution of solar gains on inner surfaces | | Proportional to area |
| Solar radiation direct to inner air | [-] | 0,1 |

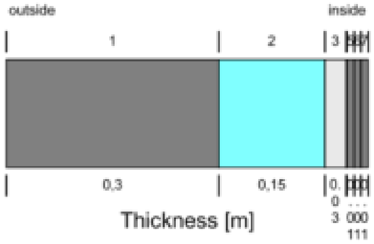
## Assemblies/window types/solar protection

### Assembly (Id.4): Intermediate Floor

Homogenous layers

Thermal resistance: 0,46 m²K/W (without Rsi, Rse)

Heat transfer coefficient (U-value): 1,493 W/m²K



Thickness: 0,511 m

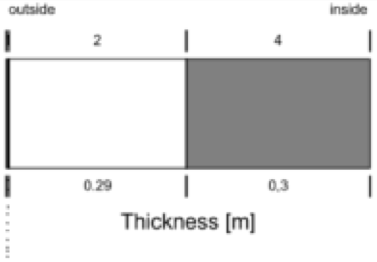
| Nr. | Material/Layer (from outside to inside) | ρ [kg/m³] | c [J/kgK] | λ [W/mK] | Thickness [m] | Color |
|---|---|---|---|---|---|---|
| 1 | Concrete, C35/45 | 2220 | 850 | 1,6 | 0,3 | ▩ |
| 2 | Air Layer 150 mm | 1,3 | 1000 | 0,94 | 0,15 | 🟦 |
| 3 | Gypsum-Fibreboard | 1153 | 1200 | 0,32 | 0,03 | □ |
| 4 | vapour retarder (sd=1m) | 130 | 2300 | 2,3 | 10E-4 | 🟦 |
| 5 | Concrete Screed, bottom layer | 1990 | 850 | 1,6 | 0,01 | ▩ |
| 6 | Concrete Screed, mid layer | 1970 | 850 | 1,6 | 0,01 | ▩ |
| 7 | Concrete Screed, top layer | 1890 | 850 | 1,6 | 0,01 | ▩ |

### Assembly (Id.2): Roof

Homogenous layers

Thermal resistance: 7,439 m²K/W (without Rsi, Rse)

Heat transfer coefficient (U-value): 0,132 W/m²K



Thickness: 0,596 m

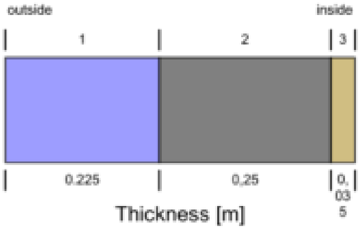
| Nr. | Material/Layer (from outside to inside) | ρ [kg/m³] | c [J/kgK] | λ [W/mK] | Thickness [m] | Color |
|---|---|---|---|---|---|---|
| 1 | Bituminous Paper (#15 Felt) | 715 | 1500 | 4 | 50E-4 | ⬛ |
| 2 | Polystyrene, expanded | 20 | 1500 | 0,04 | 0,29 | ⬜ |
| 3 | vapour retarder (sd=1m) | 130 | 2300 | 2,3 | 10E-4 | 🟦 |
| 4 | Concrete, C35/45 | 2220 | 850 | 1,6 | 0,3 | ▩ |

### Assembly (Id.14): Exterior Wall Clay 3.5

Homogenous layers

Thermal resistance: 6,445 m²K/W (without Rsi, Rse)

Heat transfer coefficient (U-value): 0,151 W/m²K



Thickness: 0,51 m

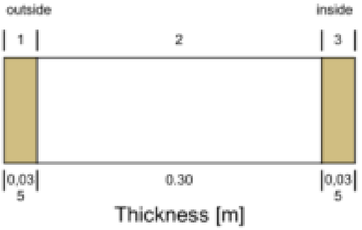
| Nr. | Material/Layer (from outside to inside) | ρ [kg/m³] | c [J/kgK] | λ [W/mK] | Thickness [m] | Color |
|---|---|---|---|---|---|---|
| 1 | Expanded Polystyrene Insulation | 14,8 | 1470 | 0,036 | 0,225 | 🟦 |
| 2 | Concrete, C35/45 | 2220 | 850 | 1,6 | 0,25 | ⬛ |
| 3 | dena Mud Plaster | 1514 | 1000 | 0,9 | 0,035 | 🟫 |

### Assembly (Id.16): Interior Wall 30 Clay 3.5

Homogenous layers

Thermal resistance: 0,378 m²K/W (without Rsi, Rse)

Heat transfer coefficient (U-value): 1,568 W/m²K



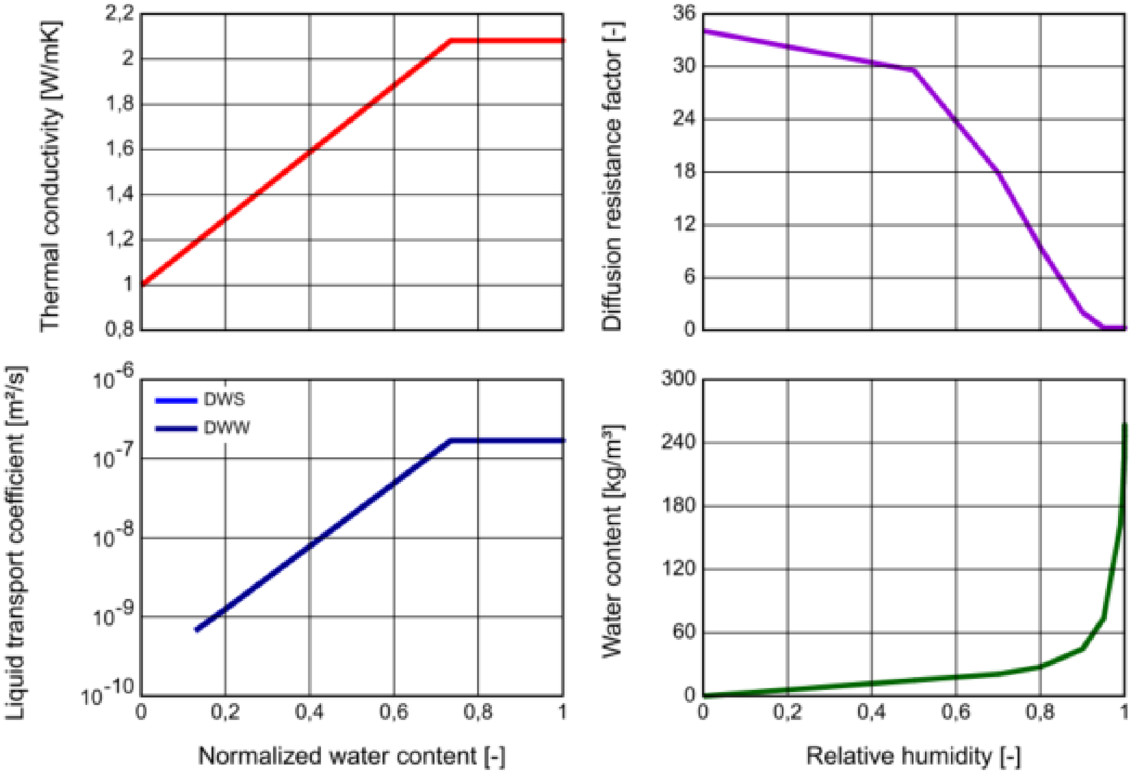
Thickness: 0,37 m

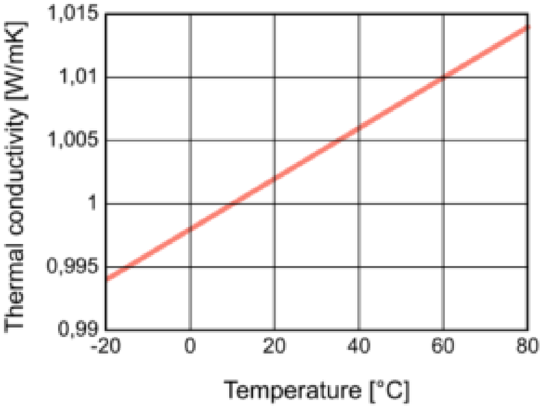
| Nr. | Material/Layer (from outside to inside) | ρ [kg/m³] | c [J/kgK] | λ [W/mK] | Thickness [m] | Color |
|---|---|---|---|---|---|---|
| 1 | dena Mud Plaster | 1514 | 1000 | 0,9 | 0,035 | 🟫 |
| 2 | Lime Silica Brick (density: 1830 kg/m³) | 1830 | 850 | 1 | 0,3 | ⬜ |
| 3 | dena Mud Plaster | 1514 | 1000 | 0,9 | 0,035 | 🟫 |

**Material: Lime Silica Brick (density: 1830 kg/m³)**

| | | |
|---|---|---|
| Bulk density | [kg/m³] | 1830 |
| Porosity | | 0,35 |
| Specific heat capacity | [J/kgK] | 850 |
| Thermal conductivity, dry, 10 C/50 F | [W/mK] | 1 |
| Water vapor diffusion resistance factor | | 34,1 |

| | | |
|---|---|---|
| Typical built-in moisture | [kg/m³] | 27,474 |
| Temp-dep. thermal cond. supplement | [W/mK²] | 2E-4 |
| Color | | |

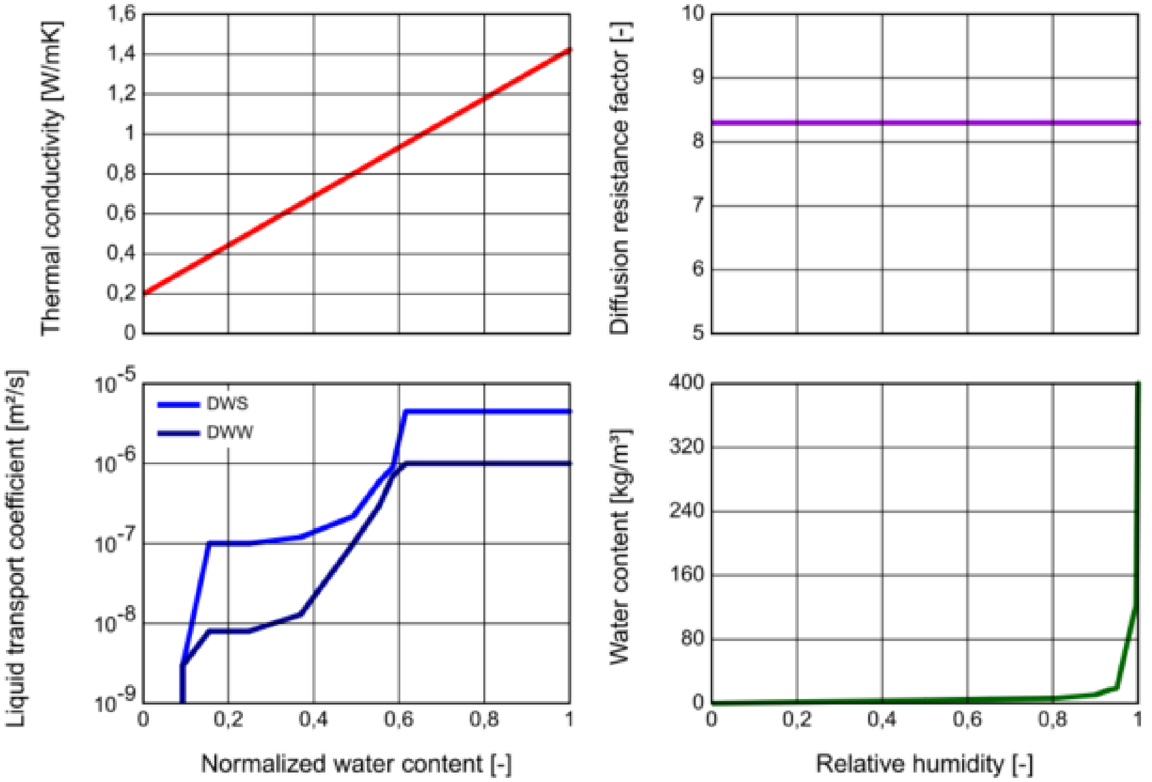


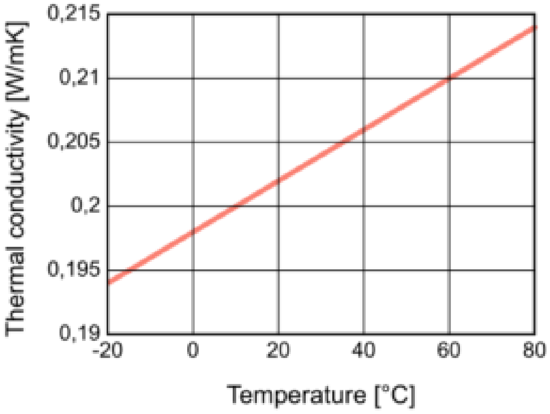


**Material: Interior Plaster (Gypsum Plaster)**

| | | |
|---|---|---|
| Bulk density | [kg/m³] | 850 |
| Porosity | | 0,65 |
| Specific heat capacity | [J/kgK] | 850 |
| Thermal conductivity, dry, 10 C/50 F | [W/mK] | 0,2 |
| Water vapor diffusion resistance factor | | 8,3 |

| | | |
|---|---|---|
| Typical built-in moisture | [kg/m³] | 400 |
| Thermal conductivity supplement | [%/M.-%] | 8 |
| Temp-dep. thermal cond. supplement | [W/mK²] | 2E-4 |
| Color | | |

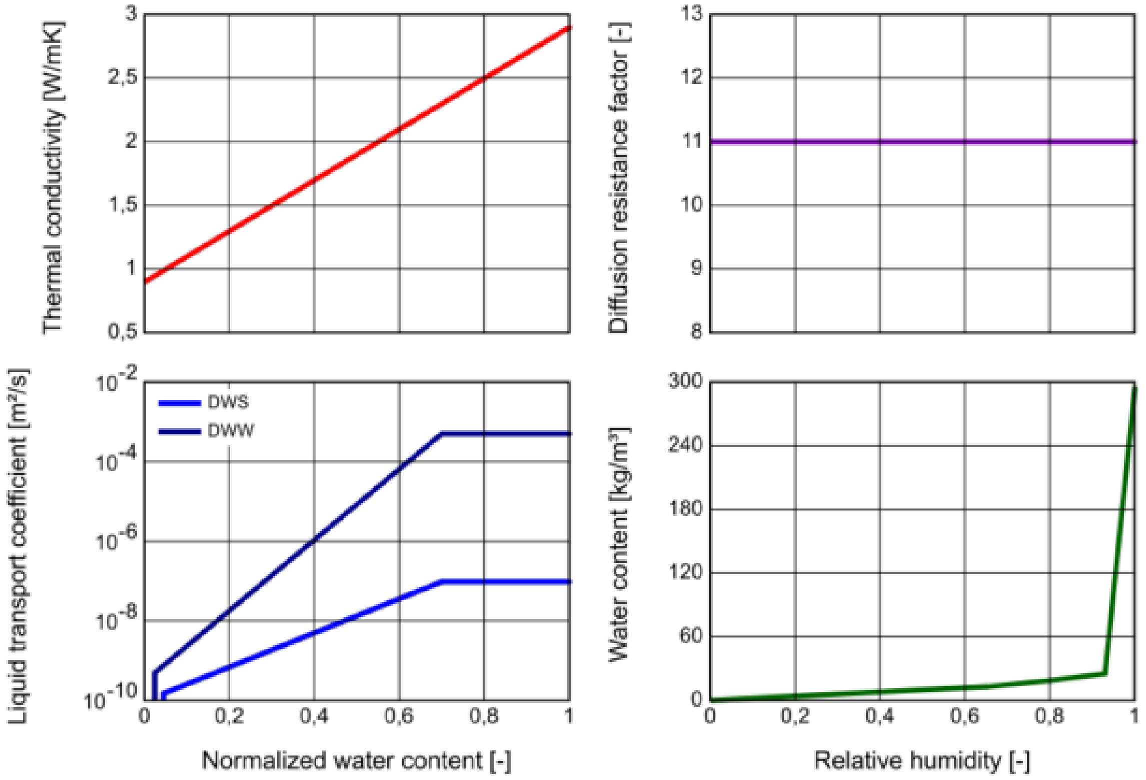


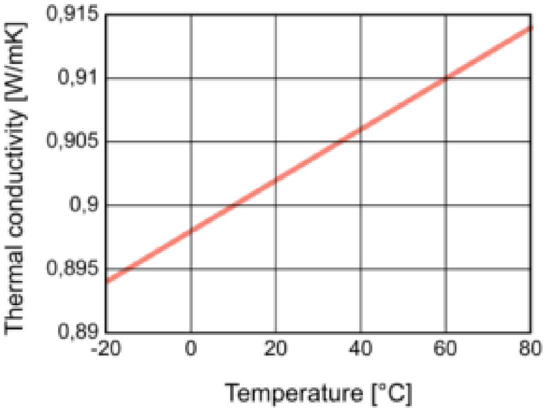


**Material: dena Mud Plaster**

| | | |
|---|---|---|
| Bulk density | [kg/m³] | 1514 |
| Porosity | | 0,42 |
| Specific heat capacity | [J/kgK] | 1000 |
| Thermal conductivity, dry, 10 C/50 F | [W/mK] | 0,9 |
| Water vapor diffusion resistance factor | | 11 |

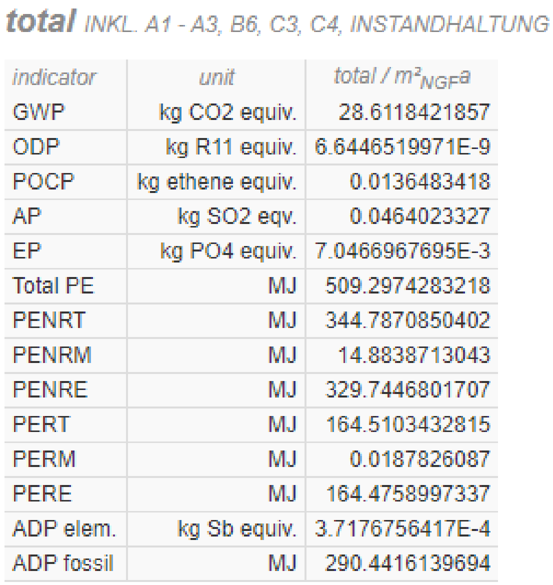
| | | |
|---|---|---|
| Typical built-in moisture | [kg/m³] | 294 |
| Reference water content | [kg/m³] | 19 |
| Free water saturation | [kg/m³] | 294 |
| Water absorption coefficient | [kg/m²s^0.5] | 0,0467 |
| Thermal conductivity supplement | [%/M.-%] | 8 |
| Temp-dep. thermal cond. supplement | [W/mK²] | 2E-4 |
| Color | | 🟫 |





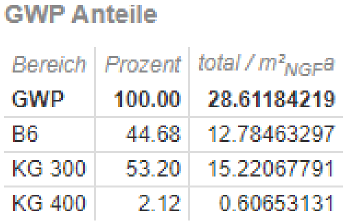
# Appendix B

## LCA Results and Construction Assembly Case 1



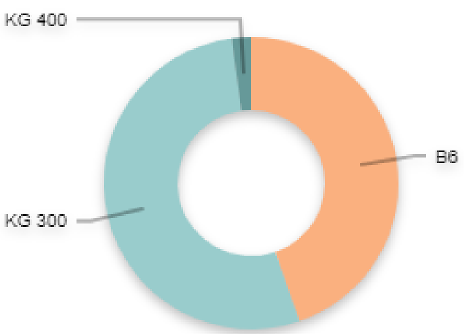
**total** *INKL. A1 - A3, B6, C3, C4, INSTANDHALTUNG*

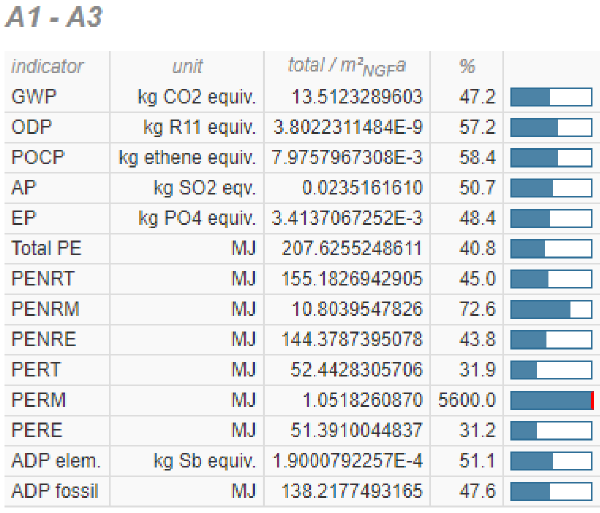
| *indicator* | *unit* | *total / m$^2_{NGF}$a* |
|---|---|---|
| GWP | kg CO2 equiv. | 28.6118421857 |
| ODP | kg R11 equiv. | 6.6446519971E-9 |
| POCP | kg ethene equiv. | 0.0136483418 |
| AP | kg SO2 eqv. | 0.0464023327 |
| EP | kg PO4 equiv. | 7.0466967695E-3 |
| Total PE | MJ | 509.2974283218 |
| PENRT | MJ | 344.7870850402 |
| PENRM | MJ | 14.8838713043 |
| PENRE | MJ | 329.7446801707 |
| PERT | MJ | 164.5103432815 |
| PERM | MJ | 0.0187826087 |
| PERE | MJ | 164.4758997337 |
| ADP elem. | kg Sb equiv. | 3.7176756417E-4 |
| ADP fossil | MJ | 290.4416139694 |



**GWP Anteile**

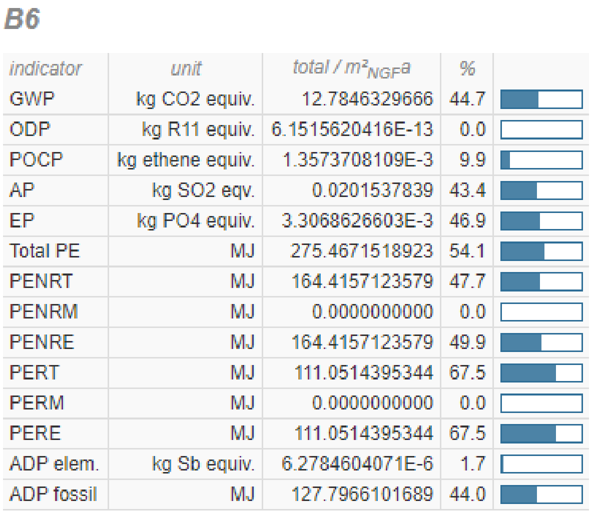
| *Bereich* | *Prozent* | *total / m$^2_{NGF}$a* |
|---|---|---|
| **GWP** | **100.00** | **28.61184219** |
| B6 | 44.68 | 12.78463297 |
| KG 300 | 53.20 | 15.22067791 |
| KG 400 | 2.12 | 0.60653131 |





*A1 - A3*

| *indicator* | *unit* | *total / m$^2_{NGF}$a* | *%* |
|---|---|---|---|
| GWP | kg CO2 equiv. | 13.5123289603 | 47.2 |
| ODP | kg R11 equiv. | 3.8022311484E-9 | 57.2 |
| POCP | kg ethene equiv. | 7.9757967308E-3 | 58.4 |
| AP | kg SO2 eqv. | 0.0235161610 | 50.7 |
| EP | kg PO4 equiv. | 3.4137067252E-3 | 48.4 |
| Total PE | MJ | 207.6255248611 | 40.8 |
| PENRT | MJ | 155.1826942905 | 45.0 |
| PENRM | MJ | 10.8039547826 | 72.6 |
| PENRE | MJ | 144.3787395078 | 43.8 |
| PERT | MJ | 52.4428305706 | 31.9 |
| PERM | MJ | 1.0518260870 | 5600.0 |
| PERE | MJ | 51.3910044837 | 31.2 |
| ADP elem. | kg Sb equiv. | 1.9000792257E-4 | 51.1 |
| ADP fossil | MJ | 138.2177493165 | 47.6 |



*B6*

| *indicator* | *unit* | *total / m$^2_{NGF}$a* | *%* |
|---|---|---|---|
| GWP | kg CO2 equiv. | 12.7846329666 | 44.7 |
| ODP | kg R11 equiv. | 6.1515620416E-13 | 0.0 |
| POCP | kg ethene equiv. | 1.3573708109E-3 | 9.9 |
| AP | kg SO2 eqv. | 0.0201537839 | 43.4 |
| EP | kg PO4 equiv. | 3.3068626603E-3 | 46.9 |
| Total PE | MJ | 275.4671518923 | 54.1 |
| PENRT | MJ | 164.4157123579 | 47.7 |
| PENRM | MJ | 0.0000000000 | 0.0 |
| PENRE | MJ | 164.4157123579 | 49.9 |
| PERT | MJ | 111.0514395344 | 67.5 |
| PERM | MJ | 0.0000000000 | 0.0 |
| PERE | MJ | 111.0514395344 | 67.5 |
| ADP elem. | kg Sb equiv. | 6.2784604071E-6 | 1.7 |
| ADP fossil | MJ | 127.7966101689 | 44.0 |

## *331 exterior load-bearing walls* *EXTERIOR WALLS*

### Exterior Wall

| | |
|---|---|
| amount in the building: | 800.00 m² |
| dimensions: | 557220.00 kg |
| DIN 276: | 331 exterior load-bearing walls |

*Geometric components*

1. Bewehrungsstahl *new structure* *amount* 144440 kg *Flächenanteil* 10.0% *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C1 demolition | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C2 transport | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |

1. Beton der Druckfestigkeitsklasse C 35/45 *new structure* *amount* 165.6 m³ *Flächenanteil* 90.0% *Replace after 50 years*

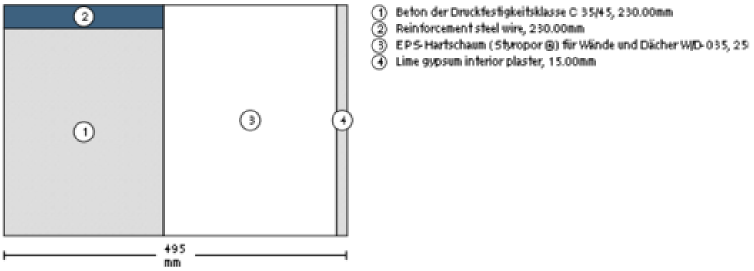
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| B1 Use | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C1 demolition | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C2 transport | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C3 waste processing | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| D Reuse potential | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m³ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |

2. EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 *new structure* *amount* 200 m³ *Replace after 40 years (1 times)*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m³ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |
| C4 Landfilling | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m³ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |
| D Reuse potential | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m³ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |

3. Kalk-Gips-Innenputz *new structure* *amount* 10800 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Kalk-Gips-Innenputz | 1.00 m³ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C2 transport | 100% | Kalk-Gips-Innenputz | 1.00 m³ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C3 waste processing | 100% | Bauschuttaufbereitung | 1.00 kg | 4a937f66-c9c2-402b-9a00-83767031bfa7 |
| C4 Landfilling | 100% | Kalk-Gips-Innenputz | 1.00 m³ | 70f6e305-e46f-4719-a94f-70267b936029 |



## 341 load-bearing interior walls *INTERIOR WALLS*

### Interior Walls

| | |
|---|---|
| amount in the building: | 500.00 $m^2$ |
| dimensions: | 128500.00 kg |
| DIN 276: | 341 load-bearing interior walls |

*Geometric components*

1. Kalk-Gips-Innenputz *new structure* *amount*6750 kg *Replace after 50 years*

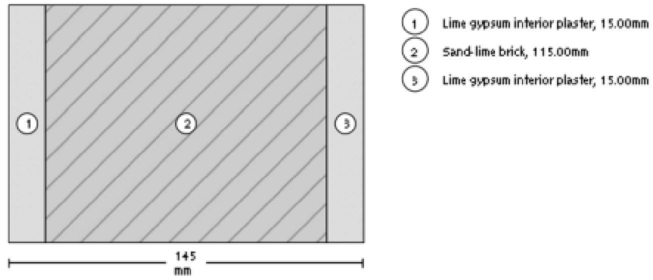
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C2 transport | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C3 waste processing | 100% | Bauschuttaufbereitung | 1.00 kg | 4a937f66-c9c2-402b-9a00-83767031bfa7 |
| C4 Landfilling | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |

4. Kalksandstein Mix *new structure* *amount*57.5 $m^3$ *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Kalksandstein Mix | 1.00 $m^3$ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C1 demolition | 100% | Kalksandstein Mix | 1.00 $m^3$ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C2 transport | 100% | Kalksandstein Mix | 1.00 $m^3$ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C3 waste processing | 100% | Kalksandstein Mix | 1.00 $m^3$ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| D Reuse potential | 100% | Kalksandstein Mix | 1.00 $m^3$ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |

7. Kalk-Gips-Innenputz *new structure* *amount*6750 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C2 transport | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |
| C3 waste processing | 100% | Bauschuttaufbereitung | 1.00 kg | 4a937f66-c9c2-402b-9a00-83767031bfa7 |
| C4 Landfilling | 100% | Kalk-Gips-Innenputz | 1.00 $m^3$ | 70f6e305-e46f-4719-a94f-70267b936029 |



## ***351 ceiling structures*** *CEILINGS*

### Intermediate Floors

| | |
|---|---|
| amount in the building: | 1200.00 $m^2$ |
| dimensions: | 1150200.00 kg |
| DIN 276: | 351 ceiling structures |

### *Geometric components*

1. Beton der Druckfestigkeitsklasse C 35/45 *new structure* *amount*324 $m^3$ *Flächenanteil* 90.0% *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| B1 Use | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C1 demolition | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C2 transport | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C3 waste processing | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| D Reuse potential | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |

1. Bewehrungsstahl *new structure* *amount*282600 kg *Flächenanteil* 10.0% *Replace after 50 years*

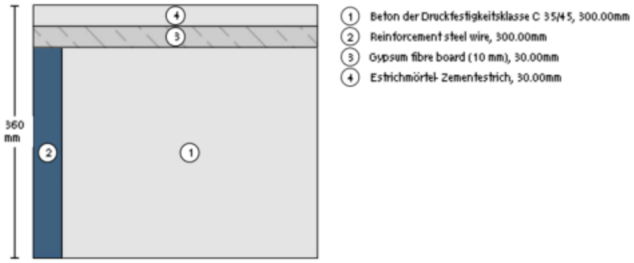
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C1 demolition | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C2 transport | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |

2. Gipsfaserplatte *new structure* *amount*36000 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Gipsfaserplatte (Dicke 0,01 m) | 1.00 $m^2$ | 6d535792-4351-4d7d-97c6-6d2c3624f3e0 |
| C2 transport | 100% | Gipsfaserplatte (Dicke 0,01 m) | 1.00 $m^2$ | 6d535792-4351-4d7d-97c6-6d2c3624f3e0 |
| C3 waste processing | 100% | Gipsfaserplatte (Dicke 0,01 m) | 1.00 $m^2$ | 6d535792-4351-4d7d-97c6-6d2c3624f3e0 |
| C4 Landfilling | 100% | Gipsfaserplatte (Dicke 0,01 m) | 1.00 $m^2$ | 6d535792-4351-4d7d-97c6-6d2c3624f3e0 |

3. Estrichmörtel-Zementestrich *new structure* *amount*54000 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Estrichmörtel-Zementestrich | 1.00 kg | f2053ffa-dd55-47c6-92ed-e98d726db546 |
| B1 Use | 100% | Estrichmörtel-Zementestrich | 1.00 kg | f2053ffa-dd55-47c6-92ed-e98d726db546 |
| C4 Landfilling | 100% | Estrichmörtel-Zementestrich | 1.00 kg | f2053ffa-dd55-47c6-92ed-e98d726db546 |
| D Reuse potential | 100% | Estrichmörtel-Zementestrich | 1.00 kg | f2053ffa-dd55-47c6-92ed-e98d726db546 |



## **361 roof constructions** *ROOFS*

### Roof

| | |
|---|---|
| amount in the building: | 1200.00 $m^2$ |
| dimensions: | 1072704.00 kg |
| DIN 276: | 361 roof constructions |

### *Geometric components*

1. Beton der Druckfestigkeitsklasse C 35/45 *new structure* *amount*324 $m^3$ *Flächenanteil* 90.0% *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| B1 Use | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C1 demolition | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C2 transport | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C3 waste processing | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| D Reuse potential | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 $m^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |

1. Bewehrungsstahl *new structure* *amount*282600 kg *Flächenanteil* 10.0% *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C1 demolition | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C2 transport | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |

2. Dampfbremse PE *new structure* *amount*240 kg *Replace after 40 years (1 times)*

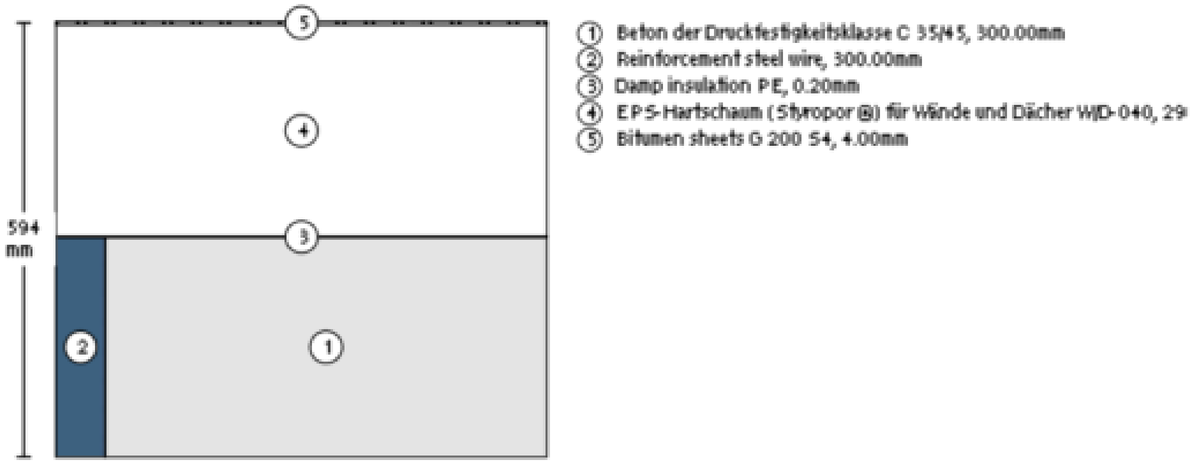
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Dampfbremse PE (Dicke 0,0002 m) | 1.00 $m^2$ | 99792cbc-c5f4-4d2d-bc9e-3790509891a0 |
| C1 demolition | 100% | Dampfbremse PE (Dicke 0,0002 m) | 1.00 $m^2$ | 99792cbc-c5f4-4d2d-bc9e-3790509891a0 |
| C2 transport | 100% | Dampfbremse PE (Dicke 0,0002 m) | 1.00 $m^2$ | 99792cbc-c5f4-4d2d-bc9e-3790509891a0 |
| C3 waste processing | 100% | Dampfbremse PE (Dicke 0,0002 m) | 1.00 $m^2$ | 99792cbc-c5f4-4d2d-bc9e-3790509891a0 |
| D Reuse potential | 100% | Dampfbremse PE (Dicke 0,0002 m) | 1.00 $m^2$ | 99792cbc-c5f4-4d2d-bc9e-3790509891a0 |

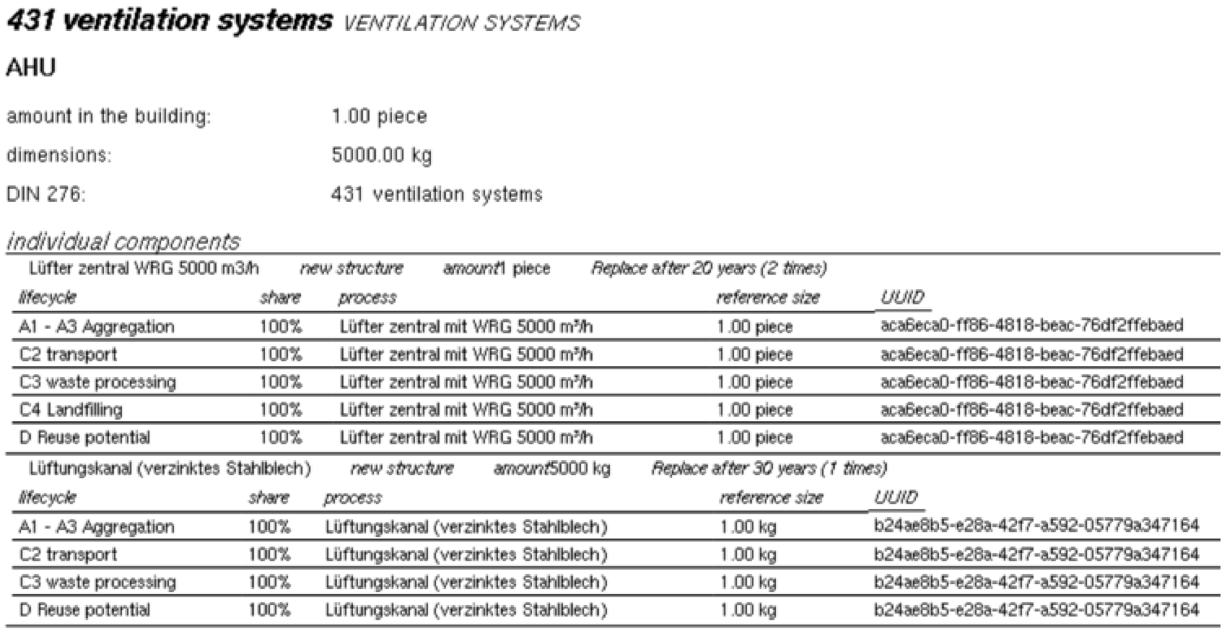
3. EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-040 *new structure* *amount*348 $m^3$ *Replace after 40 years (1 times)*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-040 | 1.00 $m^3$ | 64564161-a587-47de-b195-b6b13b3bfb07 |
| C4 Landfilling | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-040 | 1.00 $m^3$ | 64564161-a587-47de-b195-b6b13b3bfb07 |
| D Reuse potential | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-040 | 1.00 $m^3$ | 64564161-a587-47de-b195-b6b13b3bfb07 |

4. Bitumenbahnen G 200 S4 *new structure* *amount*6000 kg *Replace after 30 years (1 times)*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Bitumenbahnen G 200 S4 (Dicke 0,004 m) | 1.00 $m^2$ | 64da45fc-f415-4875-8a4e-7c23fe7a7aa9 |
| C2 transport | 100% | Bitumenbahnen G 200 S4 (Dicke 0,004 m) | 1.00 $m^2$ | 64da45fc-f415-4875-8a4e-7c23fe7a7aa9 |
| C3 waste processing | 100% | Bitumenbahnen G 200 S4 (Dicke 0,004 m) | 1.00 $m^2$ | 64da45fc-f415-4875-8a4e-7c23fe7a7aa9 |
| C4 Landfilling | 100% | Bitumenbahnen G 200 S4 (Dicke 0,004 m) | 1.00 $m^2$ | 64da45fc-f415-4875-8a4e-7c23fe7a7aa9 |
| D Reuse potential | 100% | Verbrennung Hausmüll | 1.00 kg | 34694710-3153-4055-806d-9e841f266fd2 |





## ***431 ventilation systems*** *VENTILATION SYSTEMS*

### AHU

| | |
|---|---|
| amount in the building: | 1.00 piece |
| dimensions: | 5000.00 kg |
| DIN 276: | 431 ventilation systems |

*individual components*

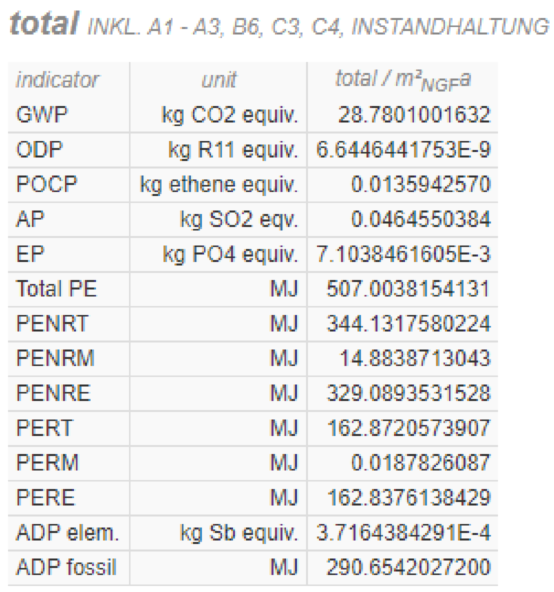
Lüfter zentral WRG 5000 m3/h *new structure* *amount*1 piece *Replace after 20 years (2 times)*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Lüfter zentral mit WRG 5000 m³/h | 1.00 piece | aca6eca0-ff86-4818-beac-76df2ffebaed |
| C2 transport | 100% | Lüfter zentral mit WRG 5000 m³/h | 1.00 piece | aca6eca0-ff86-4818-beac-76df2ffebaed |
| C3 waste processing | 100% | Lüfter zentral mit WRG 5000 m³/h | 1.00 piece | aca6eca0-ff86-4818-beac-76df2ffebaed |
| C4 Landfilling | 100% | Lüfter zentral mit WRG 5000 m³/h | 1.00 piece | aca6eca0-ff86-4818-beac-76df2ffebaed |
| D Reuse potential | 100% | Lüfter zentral mit WRG 5000 m³/h | 1.00 piece | aca6eca0-ff86-4818-beac-76df2ffebaed |

Lüftungskanal (verzinktes Stahlblech) *new structure* *amount*5000 kg *Replace after 30 years (1 times)*

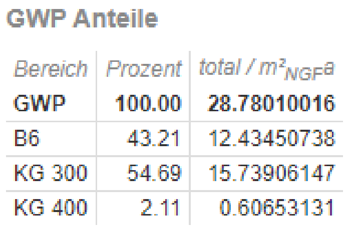
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Lüftungskanal (verzinktes Stahlblech) | 1.00 kg | b24ae8b5-e28a-42f7-a592-05779a347164 |
| C2 transport | 100% | Lüftungskanal (verzinktes Stahlblech) | 1.00 kg | b24ae8b5-e28a-42f7-a592-05779a347164 |
| C3 waste processing | 100% | Lüftungskanal (verzinktes Stahlblech) | 1.00 kg | b24ae8b5-e28a-42f7-a592-05779a347164 |
| D Reuse potential | 100% | Lüftungskanal (verzinktes Stahlblech) | 1.00 kg | b24ae8b5-e28a-42f7-a592-05779a347164 |

## LCA Results and Changed Components for Case 13



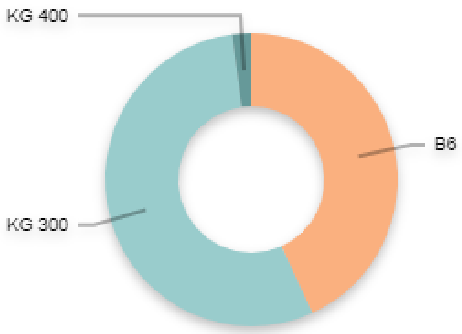
***total*** *INKL. A1 - A3, B6, C3, C4, INSTANDHALTUNG*

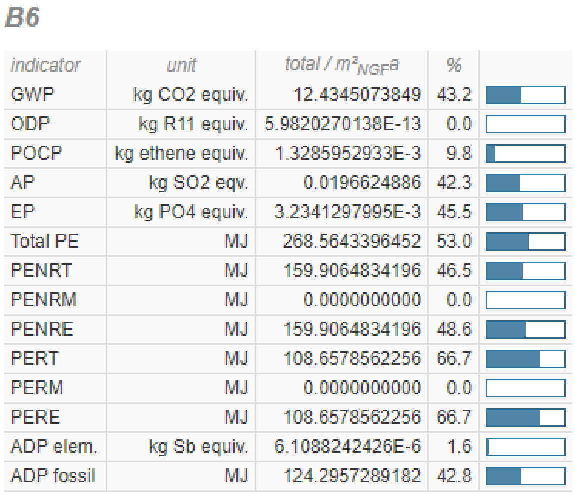
| *indicator* | *unit* | *total / $m^2_{NGF}a$* |
|---|---|---|
| GWP | kg CO2 equiv. | 28.7801001632 |
| ODP | kg R11 equiv. | 6.6446441753E-9 |
| POCP | kg ethene equiv. | 0.0135942570 |
| AP | kg SO2 eqv. | 0.0464550384 |
| EP | kg PO4 equiv. | 7.1038461605E-3 |
| Total PE | MJ | 507.0038154131 |
| PENRT | MJ | 344.1317580224 |
| PENRM | MJ | 14.8838713043 |
| PENRE | MJ | 329.0893531528 |
| PERT | MJ | 162.8720573907 |
| PERM | MJ | 0.0187826087 |
| PERE | MJ | 162.8376138429 |
| ADP elem. | kg Sb equiv. | 3.7164384291E-4 |
| ADP fossil | MJ | 290.6542027200 |



**GWP Anteile**

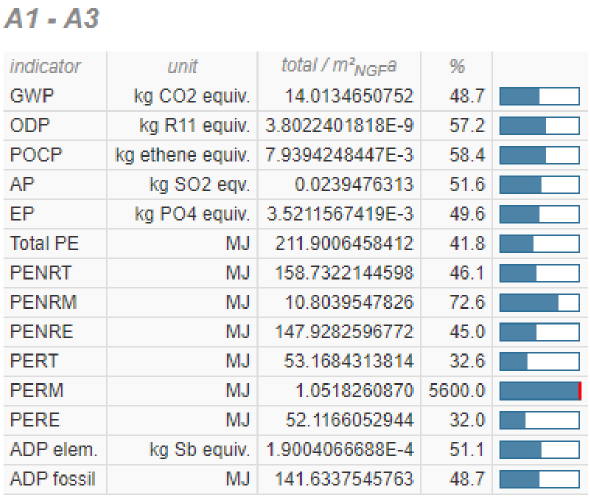
| *Bereich* | *Prozent* | *total / $m^2_{NGF}a$* |
|---|---|---|
| **GWP** | **100.00** | **28.78010016** |
| B6 | 43.21 | 12.43450738 |
| KG 300 | 54.69 | 15.73906147 |
| KG 400 | 2.11 | 0.60653131 |





***B6***

| *indicator* | *unit* | *total / $m^2_{NGF}a$* | *%* |
|---|---|---|---|
| GWP | kg CO2 equiv. | 12.4345073849 | 43.2 |
| ODP | kg R11 equiv. | 5.9820270138E-13 | 0.0 |
| POCP | kg ethene equiv. | 1.3285952933E-3 | 9.8 |
| AP | kg SO2 eqv. | 0.0196624886 | 42.3 |
| EP | kg PO4 equiv. | 3.2341297995E-3 | 45.5 |
| Total PE | MJ | 268.5643396452 | 53.0 |
| PENRT | MJ | 159.9064834196 | 46.5 |
| PENRM | MJ | 0.0000000000 | 0.0 |
| PENRE | MJ | 159.9064834196 | 48.6 |
| PERT | MJ | 108.6578562256 | 66.7 |
| PERM | MJ | 0.0000000000 | 0.0 |
| PERE | MJ | 108.6578562256 | 66.7 |
| ADP elem. | kg Sb equiv. | 6.1088242426E-6 | 1.6 |
| ADP fossil | MJ | 124.2957289182 | 42.8 |



***A1 - A3***

| *indicator* | *unit* | *total / $m^2_{NGF}a$* | *%* |
|---|---|---|---|
| GWP | kg CO2 equiv. | 14.0134650752 | 48.7 |
| ODP | kg R11 equiv. | 3.8022401818E-9 | 57.2 |
| POCP | kg ethene equiv. | 7.9394248447E-3 | 58.4 |
| AP | kg SO2 eqv. | 0.0239476313 | 51.6 |
| EP | kg PO4 equiv. | 3.5211567419E-3 | 49.6 |
| Total PE | MJ | 211.9006458412 | 41.8 |
| PENRT | MJ | 158.7322144598 | 46.1 |
| PENRM | MJ | 10.8039547826 | 72.6 |
| PENRE | MJ | 147.9282596772 | 45.0 |
| PERT | MJ | 53.1684313814 | 32.6 |
| PERM | MJ | 1.0518260870 | 5600.0 |
| PERE | MJ | 52.1166052944 | 32.0 |
| ADP elem. | kg Sb equiv. | 1.9004066688E-4 | 51.1 |
| ADP fossil | MJ | 141.6337545763 | 48.7 |

## **331 exterior load-bearing walls** *EXTERIOR WALLS*

### Exterior Wall

| | |
|---|---|
| amount in the building: | 800.00 m$^2$ |
| dimensions: | 571620.00 kg |
| DIN 276: | 331 exterior load-bearing walls |

*Geometric components*

1. Bewehrungsstahl *new structure* *amount*144440 kg *Flächenanteil* 10.0% *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C1 demolition | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |
| C2 transport | 100% | Bewehrungsstahl | 1.00 kg | e9ae96ee-ba8d-420d-9725-7c8abd06e082 |

1. Beton der Druckfestigkeitsklasse C 35/45 *new structure* *amount*165.6 m$^3$ *Flächenanteil* 90.0% *Replace after 50 years*

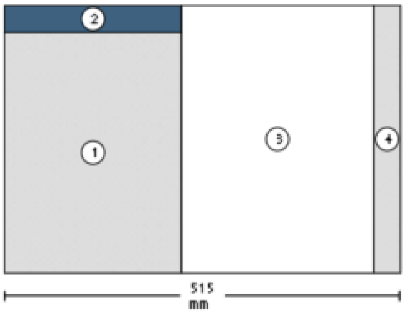
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| B1 Use | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C1 demolition | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C2 transport | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| C3 waste processing | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |
| D Reuse potential | 100% | Beton der Druckfestigkeitsklasse C 35/45 | 1.00 m$^3$ | cbc63bd5-2bfe-4381-b644-78df1bce86f3 |

2. EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 *new structure* *amount*200 m$^3$ *Replace after 40 years (1 times)*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m$^3$ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |
| C4 Landfilling | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m$^3$ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |
| D Reuse potential | 100% | EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035 | 1.00 m$^3$ | c5edec42-1921-46c6-a3aa-5cbd27685a74 |

3. Lehmputz *new structure* *amount*25200 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Lehmputz | 1.00 m$^3$ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C2 transport | 100% | Lehmputz | 1.00 m$^3$ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C3 waste processing | 100% | Lehmputz | 1.00 m$^3$ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| D Reuse potential | 100% | Lehmputz | 1.00 m$^3$ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |



① Beton der Druckfestigkeitsklasse C 35/45, 230.00mm
② Reinforcement steel wire, 230.00mm
③ EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035, 25
④ Clay plaster, 35.00mm

## 341 load-bearing interior walls *INTERIOR WALLS*

### Interior Walls

| | |
|---|---|
| amount in the building: | 500.00 m² |
| dimensions: | 331500.00 kg |
| DIN 276: | 341 load-bearing interior walls |

*Geometric components*

1. Lehmputz *new structure* *amount*15750 kg *Replace after 50 years*

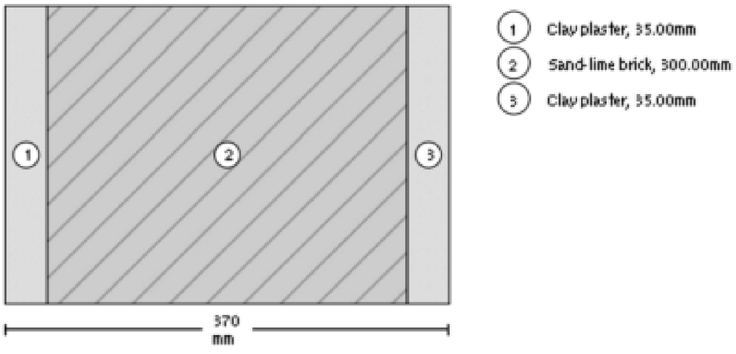
| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C2 transport | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C3 waste processing | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| D Reuse potential | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |

4. Kalksandstein Mix *new structure* *amount*150 m³ *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Kalksandstein Mix | 1.00 m³ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C1 demolition | 100% | Kalksandstein Mix | 1.00 m³ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C2 transport | 100% | Kalksandstein Mix | 1.00 m³ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| C3 waste processing | 100% | Kalksandstein Mix | 1.00 m³ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |
| D Reuse potential | 100% | Kalksandstein Mix | 1.00 m³ | 29e6c6cf-0552-4e4b-85c7-26a68a625252 |

7. Lehmputz *new structure* *amount*15750 kg *Replace after 50 years*

| *lifecycle* | *share* | *process* | *reference size* | *UUID* |
|---|---|---|---|---|
| A1 - A3 Aggregation | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C2 transport | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| C3 waste processing | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |
| D Reuse potential | 100% | Lehmputz | 1.00 m³ | 8be785fa-5548-4ea5-a2d7-b962675b9eff |



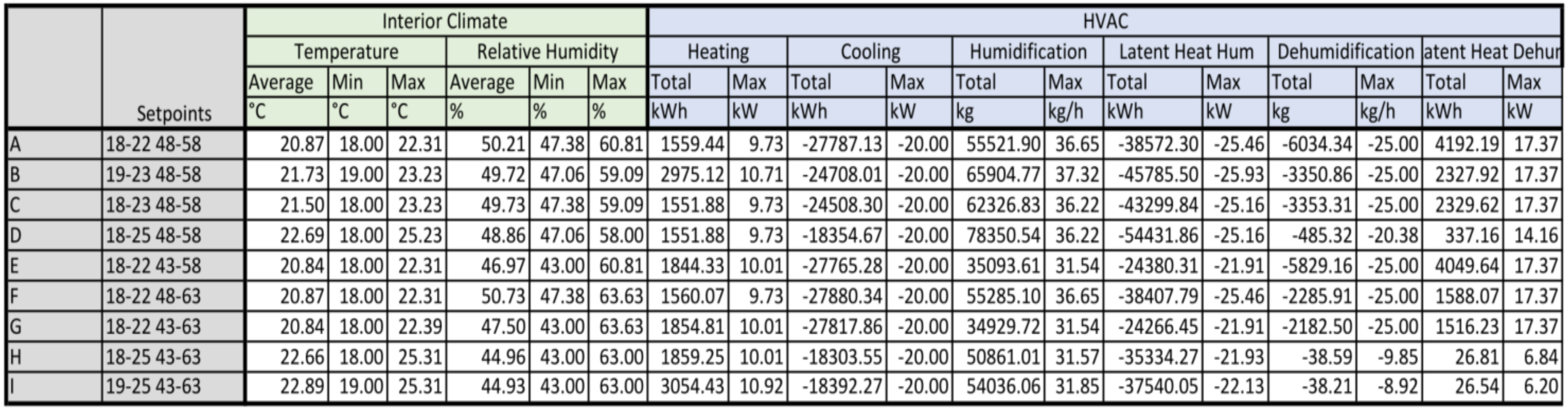
# APPENDIX C

**Simulation Results for Cases 1-13**

| | Interior Wall | Interior Climate | | | | | | HVAC | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Temperature | | | Relative Humidity | | | Heating | | Cooling | | Humidification | | Latent Heat Hum | | Dehumidification | | tent Heat Dehu | |
| | | Average | Min | Max | Average | Min | Max | Total | Max | Total | Max | Total | Max | Total | Max | Total | Max | Total | Max |
| | | °C | °C | °C | % | % | % | kWh | kW | kWh | kW | kg | kg/h | kWh | kW | kg | kg/h | kWh | kW |
| 1 | 11.5 Gypsum | 20.88 | 18.00 | 22.31 | 50.21 | 47.38 | 60.81 | 1487.56 | 9.69 | -27893.61 | -20.00 | 56077.04 | 36.70 | -38957.97 | -25.50 | -6056.23 | -25.00 | 4207.40 | 17.37 |
| 2 | 17.5 Gypsum | 20.87 | 18.00 | 22.31 | 50.21 | 47.38 | 60.81 | 1559.44 | 9.73 | -27787.13 | -20.00 | 55521.90 | 36.65 | -38572.30 | -25.46 | -6034.34 | -25.00 | 4192.19 | 17.37 |
| 3 | 24 Gypsum | 20.86 | 18.00 | 22.27 | 50.22 | 47.38 | 60.81 | 1591.08 | 9.68 | -27585.72 | -20.00 | 55059.21 | 36.34 | -38250.86 | -25.25 | -6055.21 | -25.00 | 4206.69 | 17.37 |
| 4 | 30 Gypsum | 20.86 | 18.00 | 22.27 | 50.23 | 47.38 | 60.97 | 1592.19 | 9.64 | -27384.45 | -20.00 | 54729.61 | 35.44 | -38021.87 | -24.62 | -6111.82 | -25.00 | 4246.02 | 17.37 |
| 5 | 11.5 Clay 0.5 | 20.88 | 18.00 | 22.23 | 50.20 | 47.38 | 60.81 | 1606.57 | 9.80 | -27826.58 | -20.00 | 55767.72 | 36.65 | -38743.07 | -25.46 | -5938.00 | -25.00 | 4125.26 | 17.37 |
| 6 | 11.5 Clay 1.5 | 20.88 | 18.00 | 22.23 | 50.20 | 47.38 | 60.81 | 1662.15 | 9.80 | -27782.65 | -20.00 | 55554.58 | 36.69 | -38595.00 | -25.49 | -5932.90 | -25.00 | 4121.72 | 17.37 |
| 7 | 11.5 Clay 2.5 | 20.88 | 18.00 | 22.23 | 50.20 | 47.38 | 60.81 | 1667.67 | 9.83 | -27782.73 | -20.00 | 55430.44 | 36.69 | -38508.76 | -25.49 | -5927.66 | -25.00 | 4118.07 | 17.37 |
| 8 | 11.5 Clay 3.5 | 20.87 | 18.00 | 22.23 | 50.20 | 47.38 | 60.81 | 1701.04 | 9.98 | -27743.02 | -20.00 | 55191.66 | 36.69 | -38342.87 | -25.49 | -5921.61 | -25.00 | 4113.87 | 17.37 |
| 9 | 11.5 Gypsum No AirCon | 26.15 | 18.00 | 35.59 | 29.99 | 14.09 | 48.16 | 2163.71 | 11.74 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | 11.5 Clay 3.5 No AirCon | 26.04 | 18.00 | 35.32 | 30.30 | 14.41 | 47.69 | 2372.47 | 11.84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 11 | 30 Clay 3.5 No AirCon | 25.80 | 18.00 | 34.85 | 30.99 | 14.25 | 49.41 | 2405.81 | 11.82 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 12 | 30 Gypsum No AirCon | 25.89 | 18.00 | 35.13 | 30.72 | 13.94 | 49.56 | 2317.94 | 11.78 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 13 | 30 Clay 3.5 cm | 20.85 | 18.00 | 22.23 | 50.23 | 47.53 | 60.81 | 1686.03 | 9.88 | -27171.33 | -20.00 | 54028.06 | 35.13 | -37534.49 | -24.41 | -6018.02 | -25.00 | 4180.85 | 17.37 |

# Appendix D

## Simulation Results for Cases A-I



| | | Interior Climate | | | | | | HVAC | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Temperature | | | Relative Humidity | | | Heating | | Cooling | | Humidification | | Latent Heat Hum | | Dehumidification | | atent Heat Dehur | |
| | | Average | Min | Max | Average | Min | Max | Total | Max | Total | Max | Total | Max | Total | Max | Total | Max | Total | Max |
| | Setpoints | °C | °C | °C | % | % | % | kWh | kW | kWh | kW | kg | kg/h | kWh | kW | kg | kg/h | kWh | kW |
| A | 18-22 48-58 | 20.87 | 18.00 | 22.31 | 50.21 | 47.38 | 60.81 | 1559.44 | 9.73 | -27787.13 | -20.00 | 55521.90 | 36.65 | -38572.30 | -25.46 | -6034.34 | -25.00 | 4192.19 | 17.37 |
| B | 19-23 48-58 | 21.73 | 19.00 | 23.23 | 49.72 | 47.06 | 59.09 | 2975.12 | 10.71 | -24708.01 | -20.00 | 65904.77 | 37.32 | -45785.50 | -25.93 | -3350.86 | -25.00 | 2327.92 | 17.37 |
| C | 18-23 48-58 | 21.50 | 18.00 | 23.23 | 49.73 | 47.38 | 59.09 | 1551.88 | 9.73 | -24508.30 | -20.00 | 62326.83 | 36.22 | -43299.84 | -25.16 | -3353.31 | -25.00 | 2329.62 | 17.37 |
| D | 18-25 48-58 | 22.69 | 18.00 | 25.23 | 48.86 | 47.06 | 58.00 | 1551.88 | 9.73 | -18354.67 | -20.00 | 78350.54 | 36.22 | -54431.86 | -25.16 | -485.32 | -20.38 | 337.16 | 14.16 |
| E | 18-22 43-58 | 20.84 | 18.00 | 22.31 | 46.97 | 43.00 | 60.81 | 1844.33 | 10.01 | -27765.28 | -20.00 | 35093.61 | 31.54 | -24380.31 | -21.91 | -5829.16 | -25.00 | 4049.64 | 17.37 |
| F | 18-22 48-63 | 20.87 | 18.00 | 22.31 | 50.73 | 47.38 | 63.63 | 1560.07 | 9.73 | -27880.34 | -20.00 | 55285.10 | 36.65 | -38407.79 | -25.46 | -2285.91 | -25.00 | 1588.07 | 17.37 |
| G | 18-22 43-63 | 20.84 | 18.00 | 22.39 | 47.50 | 43.00 | 63.63 | 1854.81 | 10.01 | -27817.86 | -20.00 | 34929.72 | 31.54 | -24266.45 | -21.91 | -2182.50 | -25.00 | 1516.23 | 17.37 |
| H | 18-25 43-63 | 22.66 | 18.00 | 25.31 | 44.96 | 43.00 | 63.00 | 1859.25 | 10.01 | -18303.55 | -20.00 | 50861.01 | 31.57 | -35334.27 | -21.93 | -38.59 | -9.85 | 26.81 | 6.84 |
| I | 19-25 43-63 | 22.89 | 19.00 | 25.31 | 44.93 | 43.00 | 63.00 | 3054.43 | 10.92 | -18392.27 | -20.00 | 54036.06 | 31.85 | -37540.05 | -22.13 | -38.21 | -8.92 | 26.54 | 6.20 |

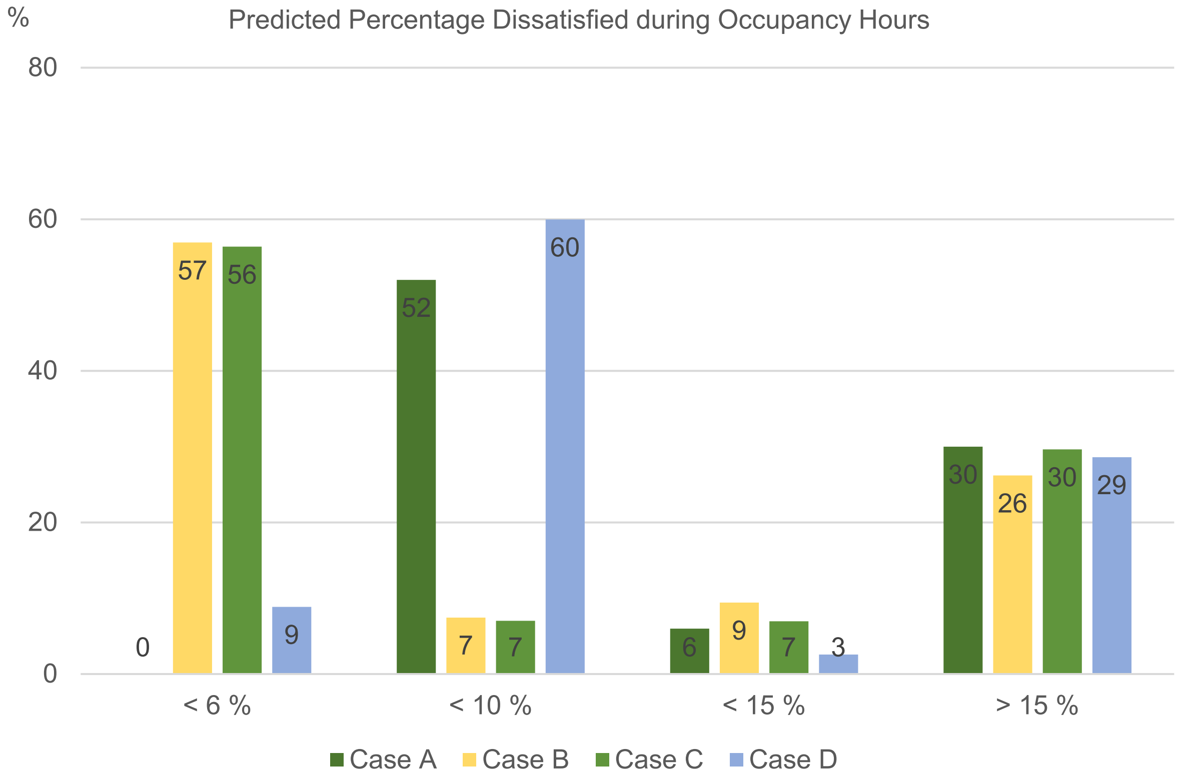
## Results of Specific Climate Risk Assessment in Cases A-I

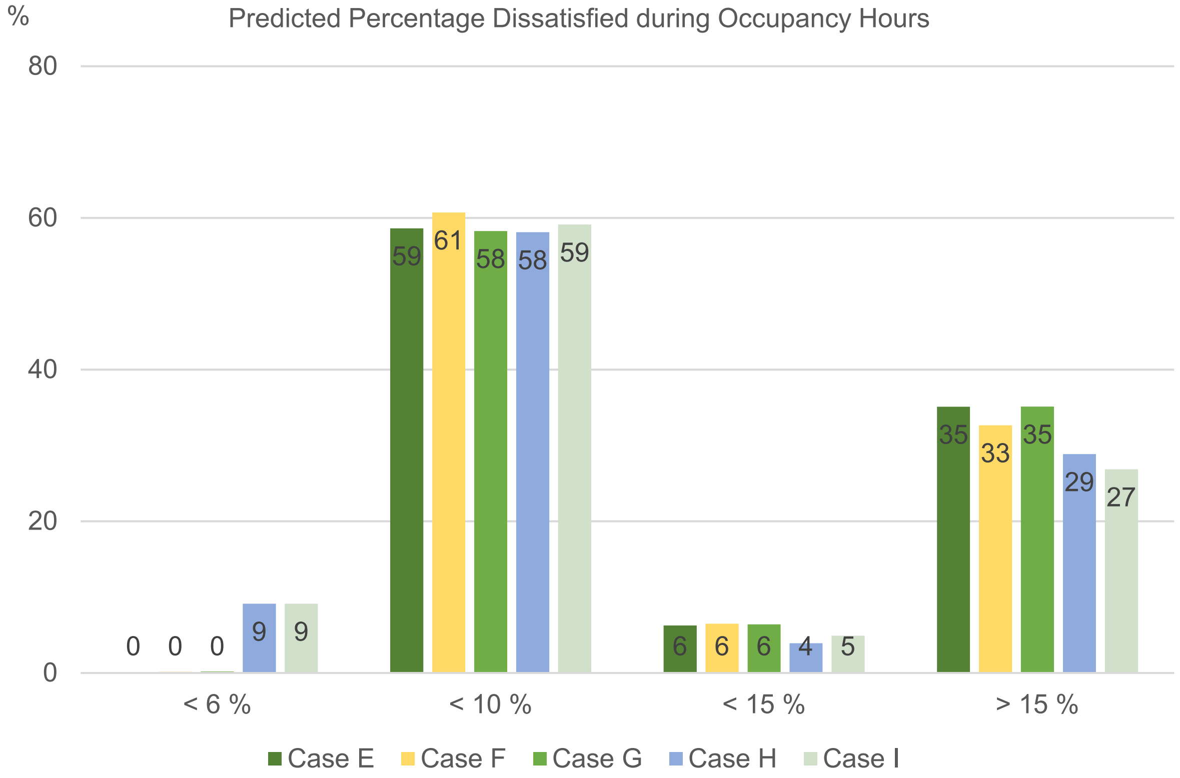
| Case A<br>18-22<br>48-58 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.28 | Panel Painting | 100 | 0 | 0 | AA | 99.6 |
| | 4 mm/day | 0 | Panel Painting | 1.20 | Lacquer Box | 100 | 0 | 0 | As | 100.0 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 99.6 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.16 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |
| Case B<br>19-23<br>48-58 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.30 | Panel Painting | 100 | 0 | 0 | AA | 99.7 |
| | 4 mm/day | 0 | Panel Painting | 1.20 | Lacquer Box | 100 | 0 | 0 | As | 100.0 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 99.7 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.15 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |
| Case C<br>18-23<br>48-58 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.30 | Panel Painting | 100 | 0 | 0 | AA | 99.7 |
| | 4 mm/day | 0 | Panel Painting | 1.20 | Lacquer Box | 100 | 0 | 0 | As | 100.0 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 99.8 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.15 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |

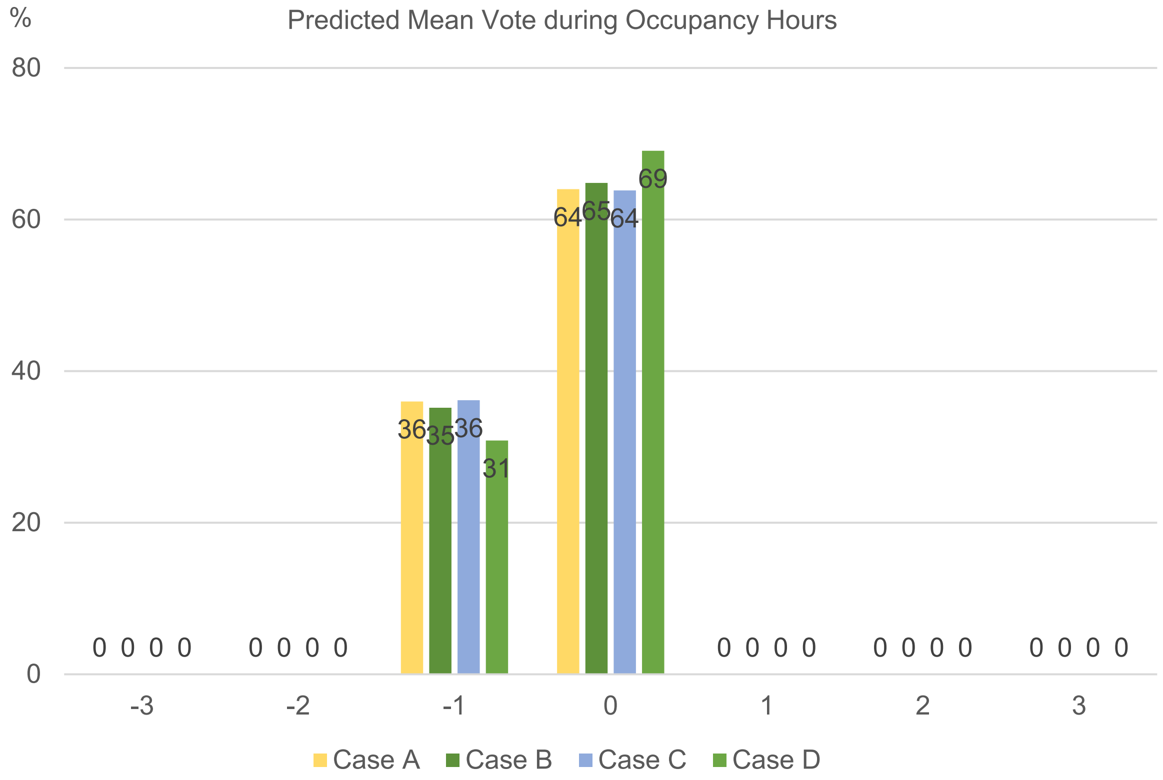
| Case D<br>18-25<br>48-58 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.28 | Panel Painting | 100 | 0 | 0 | AA | 99.4 |
| | 4 mm/day | 0 | Panel Painting | 1.24 | Lacquer Box | 100 | 0 | 0 | As | 99.7 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 99.5 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.14 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |
| Case E<br>18-22<br>43-58 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.28 | Panel Painting | 100 | 0 | 0 | AA | 13.7 |
| | 4 mm/day | 0 | Panel Painting | 1.21 | Lacquer Box | 100 | 0 | 0 | As | 69.0 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 31.3 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.16 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |
| Case F<br>18-22<br>48-63 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.21 | Panel Painting | 100 | 0 | 0 | AA | 69.7 |
| | 4 mm/day | 0 | Panel Painting | 1.12 | Lacquer Box | 100 | 0 | 0 | As | 75.5 |
| | 3 mm/day | 0 | Lacquer Box | 1.28 | Wooden Sculpture | 100 | 0 | 0 | Ag | 87.3 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.06 | | | | | B | 99.9 |
| | 1mm/ day | 0 | | | | | | | | |
| Case G<br>18-22<br>43-63 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.21 | Panel Painting | 100 | 0 | 0 | AA | 4.3 |
| | 4 mm/day | 0 | Panel Painting | 1.12 | Lacquer Box | 100 | 0 | 0 | As | 64.9 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 19.8 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.06 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |

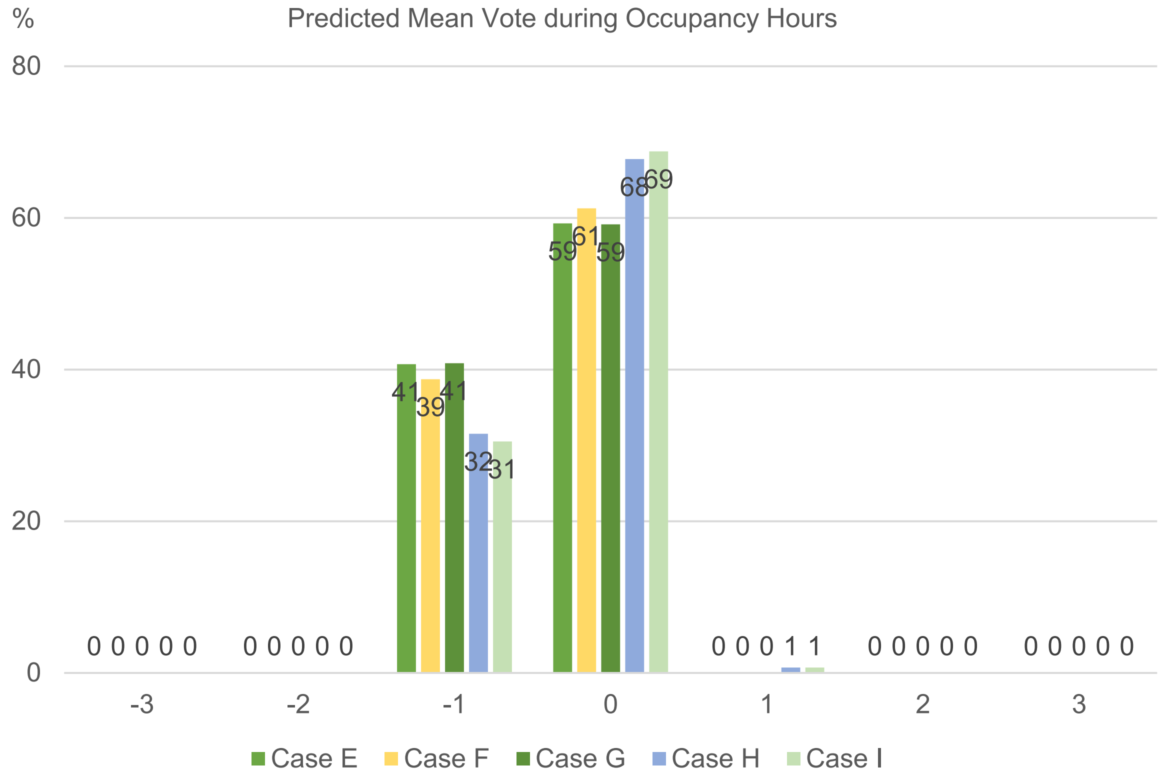
| Case H<br>18-25<br>43-63 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.14 | Panel Painting | 100 | 0 | 0 | AA | 3.2 |
| | 4 mm/day | 0 | Panel Painting | 1.25 | Lacquer Box | 100 | 0 | 0 | As | 78.4 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 15.3 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.09 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |
| Case I<br>18-25<br>43-63 | **Biological** | | **Chemical** | | **Mechanical** | | | | **ASHRAE** | |
| | Mycelium Growth Rate | | Lifetime Multiplier | | | Safe | Damage Possible | Damage Likely | Class of Control | |
| | 5 mm/day | 0 | Paper | 1.14 | Panel Painting | 100 | 0 | 0 | AA | 3.1 |
| | 4 mm/day | 0 | Panel Painting | 1.25 | Lacquer Box | 100 | 0 | 0 | As | 78.4 |
| | 3 mm/day | 0 | Lacquer Box | 1.30 | Wooden Sculpture | 100 | 0 | 0 | Ag | 15.2 |
| | 2 mm/day | 0 | Wooden Sculpture | 1.09 | | | | | B | 100.0 |
| | 1mm/ day | 0 | | | | | | | | |

## Results of Room Comfort in Cases A-I






%
Predicted Mean Vote during Occupancy Hours
80
60
40
20
0
0 0 0 0
0 0 0 0
36 35 36 31
64 65 64 69
0 0 0 0
0 0 0 0
0 0 0 0
-3
-2
-1
0
1
2
3
Case A
Case B
Case C
Case D


%
Predicted Mean Vote during Occupancy Hours
80
60
40
20
0
0 0 0 0 0
0 0 0 0 0
41 39 41 32 31
59 61 59 68 69
0 0 0 1 1
0 0 0 0 0
0 0 0 0 0
-3
-2
-1
0
1
2
3
Case E
Case F
Case G
Case H
Case I

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