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Evaluation of wood constructions' performance for rooftop extensions

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs / Diplom-Ingenieurin unter der Leitung

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KURZFASSUNG

Aufgrund der steigenden Nachfrage nach Wohnraum in der Stadt Wien, aber auch generell im zentraleuropäischen Bereich, sowie den Einschränkungen, die das Bauen im dichten, innerstädtischen Bereich bestimmen, spielt die Sanierung und Erweiterung des Bestandes – beispielsweise durch Dachausbauten - eine wichtige Rolle in der Entwicklung der gebauten Umwelt im 21. Jahrhundert. In diesem Zusammenhang wird oftmals auf das große Potential von Holzbaukonstruktion hingewiesen. Prinzipiell sagt man Holzbaukonstruktionen ein Potential für Schnellmontagelösungen zu, darüber hinaus gilt der Holzbau infolge der guten Ökobilanz von Holz als umweltfreundlich, sowie durch die günstigen bauphysikalischen Kennwerte von Holz und Holzwerkstoffen als Material, dass hoch-energieeffiziente Bauelemente und Bauwerke ermöglicht. In dieser Masterthese soll dies für Dachgeschossausbauten geprüft und auch konstruktiv weitergedacht bzw. weiterentwickelt werden.

Im Detail befasst sich diese Masterarbeit mit der integralen Bewertung verschiedener Dachgeschosslösungen für ein (repräsentatives) Referenzgebäude in Wien. Die dabei durchgeführte Forschung zielt darauf ab, die Leistung von sechs Alternativkonstruktionen (Varianten von Holzbauten, Stahl und Beton) in Bezug auf thermisches Verhalten, ökologische Auswirkungen und Kosten-Zeit-Aufwand zu bewerten und zu vergleichen. Jede Kategorie wurde mit unterschiedlichen Werkzeugen bewertet, dazu gehören numerische Gebäudesimulationsumgebungen, genauso wie normative Berechnungsverfahren. Auch Standardwerke für die Kostenberechnung wurden für die Durchführung entsprechender Abschätzungen herangezogen.

Hinsichtlich der Resultate kann folgendes festgehalten werden: Werden Konstruktions-Details mit ähnlicher thermischer Performance verwendet, wird die grundlegende thermische Performance des Dachbodens im Winterfall nicht wesentlich von der Art der Konstruktion bestimmt. Thermischer Komfort ist aber auch in der Sommersaison wichtig. Bei nicht angemessenen Konstruktionsformen können – zieht man Wiener Klimabedingungen heran - Innentemperaturen von 37°C und mehr auftreten. Es versteht sich von selbst, dass solche Temperaturen nicht akzeptabel sind. Ein wesentlicher Aspekt ist daher – wenn man Holzbaulösungen in Dachgeschossausbauten einsetzen möchte, die Kontrolle der Sommertauglichkeit. Die Ergebnisse dieser Arbeit haben gezeigt, dass bei durchdachten massiven Holzkonstruktionen die Anzahl der Stunden mit sommerlicher Überhitzungstendenzen signifikant gesenkt werden kann.

Bei Ökobilanzierung von "Cradle-to-Gate" haben alle untersuchten Konstruktions-Lösungen einen geringen ökologischen Fußabdruck gezeigt. Die Implementierung bestimmter Holzbaugruppen kann jedoch die relativen ökologischen Auswirkungen im Vergleich zu anderen Lösungen um 50% reduzieren. Der Hauptunterschied zwischen den Konstruktionsarten kann (dann) in der Kostenbewertung gesehen werden.

Aufbauend auf den Erkenntnissen dieser Arbeit kann festgehalten werden, dass die Hauptherausforderungen für die integrale Bewertung von Dachgeschosserweiterungen der Einsatz und die Verfügbarkeit unterschiedlicher Bewertungswerkzeuge, die Untersuchung der Machbarkeit von Bauelementen und eine präzise Gebäudeplanung und –dokumentation sind.

Schlagwörter

Holzbaukonstruktionen, integrale Bewertung, Energieeffizienz-Bewertung, thermischer Komfort, Ökobilanzierung, Cradle-to-Gate, Sommertauglichkeit, Kosten-Zeit-Analyse.

ABSTRACT

Due to the increasing demand of habitable space in the city of Vienna and generally in central Europe, and the restrictions limiting building in the central area, the refurbishment of the existing building stock has played an important role – for instance by performing rooftop extensions – in the building environment's development of the 21st century. In this context, the great potential of wood constructions solutions is under scrutiny. In principle, wood constructions are considered to be fast-assembly solutions as well as eco-friendly, due to the positive eco-balance of wood. Moreover, the favorable building physics characteristics of wood and wood-based materials enable high-energy efficient performance of building elements and constructions. In this master thesis, this will be tested and further developed for an attic extension, in order to cover the need for a fast-assembly and environmental friendly solutions, and to promote energy efficient performance of building elements.

In detail, this master thesis focuses on an integral assessment of different rooftop solutions for a representative reference building in Vienna. This study aims to evaluate and compare the performance of six roof alternatives in terms of thermal behavior, ecological impact, and cost-time efforts. Each category has been assessed by the implementation of different methods such as numerical building simulation and building standards procedures. Moreover, reference works were used for the realization of appropriate estimations for the cost calculation.

Regarding the results of the study, the following can be stated: by implementing construction details with similar thermal characteristics, the thermal performance in winter of the attic space is not significantly influenced by the type of construction. However, thermal comfort is important to be considered in the summer period. In cases where the building design is not appropriate – and given the prevailing Viennese climatic conditions –, an attic space's indoor temperature can reach 37°C. A control of the summer overheating is essential in this type of renovations. The results have shown that by implementing massive wood solutions, discomfort hours can be significantly reduced in comparison to other solutions.

While performing a "cradle-to-gate" ecological evaluation, all details have shown an absolute low ecological footprint. However, the implementation of certain wood assemblies can reduce 50% the relative ecological impact values in comparison to other solutions. The main difference between the details can be seen (therefore) in terms of cost evaluation.

Based on the findings of this works, it can be stated that the main challenges of the integral assessment of rooftop extension are the implementation and availability of different software assessment tools, the feasibility study of building elements and an accurate building design and documentation.

Keywords

Wood construction alternatives, Integral assessment, Energy performance evaluation, Thermal comfort, Life Cycle Assessment, “Cradle-to-gate”, Summer overheating, Cost-time analysis.

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CONTENTS

1 INTRODUCTION

1.1 Overview

The city of Vienna has a population of 1.797.337 inhabitants and it is expected to increase to 2 million by 2029. The actual built-area is approximately 35,6% of the total area of the city, assigning a 64,4% to green areas, bodies of water and streets (Magistrat der Stadt Wien). According to statistics (Norris and Shiels 2004), 50% of the residential buildings in European countries were built before 1970. Unexceptionally, 1/5 of Vienna's total building stock are historical buildings, leading to two important facts: the heritage protection of the so-called "Gründerzeit" – buildings constructed between 1848 and 1918 with a historical-conserving value –, and the consequently limitation of the construction of new buildings in the central area of the city.

Due to the need of more habitable spaces in the consolidated city and, at the same time, complying with buildings' energy requirements and quality, the city of Vienna has invested in the refurbishment of existing older stock. In that sense, the extension of rooftops or attic spaces in existing buildings has become a partial solution to the densification of the city.

According to statistics from 2004 (Stadtenwicklung Wien 2004), an average of 400 attic extensions per year are performed in Vienna. From all the existing "Gründerzeit" buildings, only 14% have already been renovated. Considering that approximately 2 or 3 apartments can be built per rooftop extension, there is a construction potential of 30.000 to 40.000 apartments. That means an increase of the existent habitation from approximately 3,3% to 5% (Figure 1).

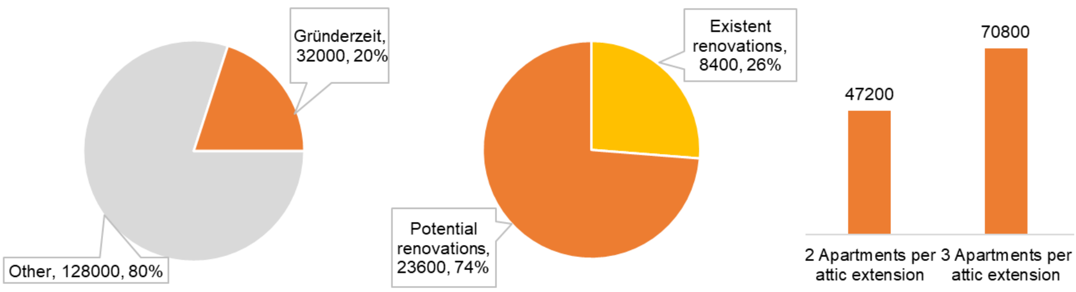


Figure 1: Habitation in Vienna and historical buildings (left), attic renovations (center), potential apartment (right)

Therefore, the construction of rooftops plays an important role on an urban level and its process should be carefully assessed. Different aspects need to be considered in the renovation process, including people (occupants, neighbors), regulations, investor's budget, building location and space availability, and traffic situation. All these parameters have an impact on the building solution and, therefore, on the renovation process.

Another important aspect is the impact on the users. Taking into consideration that either the occupant is living in the building during the construction phase or the time he/she should move until the dwelling can be occupied again – which may involve lengthy timeframes; in both cases the renovation process should impact at a minimum extent possible on occupants' comfort and privacy. In this regard, the users' friendliness concept should be introduced as a parameter in building renovation development (Coydon et al. 2015).

On the other hand, the retrofit process includes the analysis of main parameters such as energy performance and thermal comfort. Previous studies show that 70% of the heat gain of the building is through the roof (Yew et al. 2013), mainly due to the impact of solar radiation. Therefore, the utilization of different building elements for the roof construction has a great impact on the variation of the above-mentioned parameters.

Regardless of the type of construction, the energetic crisis led to use sustainable materials for building applications (Asdrubali et al. 2017). Undoubtedly, emissions of building materials need to be considered, and according to Pacheco-Torgal 2014, energy efficiency is the most cost effective way to reduce them. It is also mentioned that *"the impact of climate change will result in a shift from heating energy to cooling energy for buildings in temperate climates''* (Pacheco-Torgal 2014, p. 155).

Considering all the above, an optimal design of rooftop extensions is of great importance. Therefore, what would be a suitable solution which covers the above-mentioned aspects and how would be these implemented into such suggested solution?

1.2 Motivation

The design process of building details requires not only the consideration of the different building elements' assembly, but also the study of materials' performance and properties. New materials are available and selected by professionals, but the utilization of wood in building constructions is undoubtedly the one with the longest tradition in the market.

Wood building constructions date from Paleolithic times and since then, wood has been widely used. Many reasons can explain its long-term use, such as material availability, structural possibilities and diversity of building elements' configurations to reach thermal and acoustical needs. However, its favorable carbon footprint has been lately one of the main benefits by using wood as a building construction material. Embodied energy has been taken more importance and consideration in the life cycle energy.

As mentioned before, users' comfort during the construction phase should be taken into account. The implementation of wood in rooftop extensions could reduce the construction duration. As a mayor benefit of dry constructions, using wood is considered a faster mounting process because of the possibility to use prefabricated elements, among others.

Another factor of great importance is, in most cases, the unknown conditions of the structure and the materials of the existing building. One of the benefits of lightweight constructions is that allows to reduce the impact of the new construction and the possibility of performing an independent structure as well.

Despite the great potential of wood solutions for building applications, the building tradition in Vienna in terms of attic extensions is dominated by steel constructions (proHolz Austria 2015). Without questioning its benefits mainly in terms of fast-mounting process, vast experience of contractors, lightweight structures' malleability and flexibility, and its consolidated market in Vienna, it is under discussion whether this building type is the most suitable due to its higher costs, ecology impact and thermal behavior.

All in all, testing and comparing different solutions for attic extension aims not only to fulfill building requirements in terms of heating and cooling demand and summer overheating, but also to contribute to a more efficient construction phase, and a user's and environmental friendly process.

1.3 Background

Many studies have been developed in order to, for instance, find the optimal position of the insulation layer in roof details (Ozel and Pihtili 2007), study the impact of roof orientation or of different covering and insulation materials on heating and cooling demands (Jayasinghe et al. 2003).

Schöberl and Handler (2011) have shown that highly energy-efficient building concepts are applicable in attic renovations in “Gründerzeit” buildings, by developing an energetic design and a technical building concept.

The report provides the documentation of the planning, as well as the presentation of the used technologies and building materials in order to facilitate the implementation of such concepts in future projects. However, the building material selection is limited as it does not include different type of constructions.

An integral assessment on rooftops performance in Vienna may provide the possibility of comparing existent and alternative building solutions, as well as of weighting different evaluation aspects according to the selected building material.

1.4 Objective

The objective of this thesis is to properly study different rooftop solutions’ advantages and disadvantages by introducing different construction types. As above mentioned, a thermal performance analysis, as well as an ecological impact and cost-mounting efforts’ assessment are important aspects to be considered while selecting a building technology.

As there is a panoply of possible different solutions that can be performed, a selection of the most commonly used and suggested details will be evaluated for a study case. Each mentioned category will be assessed by the implementation of different methods, such as building simulation, building standards and market research.

At the end, a comprehensive comparison of the results will be performed, showing the potentials and drawbacks of each detail. A final conclusion may provide an efficient assessment to professionals for further implementation in the design phase.

2 STATE OF RESEARCH

2.1 Standards and requirements

According to Austrian Standards ÖNORM and OIB-Richtlinie, a specific set of regulations apply to new constructions and renovations in historical buildings. A short summary will describe the main considerations in terms of thermal, acoustical, fire protection, geometry and conservation aspects. Further requirements regarding structural and earthquake (seismic) aspects, will not be considered for the purposes of this thesis.

Fire protection

According to Kirchmayer et al. (2011), attic extensions in “Gründerzeithäuser” in Vienna are usually building class GK5, which means the maximal building level is between 11 and 22 meters. Therefore, the following requirements are in correspondence to that assumption.

According to the Österreichisches Institut für Bautechnik OIB-330.2-011/15, the requirements for fire resistance of building elements related to rooftop extensions are: class R60/REI90 for bearing walls, class R60 for the pitched roof and class EI 60 and A2 for openings in the roof area.

According to the Austrian Standards ÖNORM B 3806: 2012 10 01 and Austrian Standards ÖNORM B 3800-1: 1988 12 01, the reaction to fire of building materials muss fulfill the following requirements: class A2 for sheathing and supporting structure, and B for the insulation layer for room walls. In pitched roofs, class A2 is required for the roofing materials, waterproofing membrane and insulation layers.

Sound insulation

According to Austrian Standards ÖNORM B 8115-2: 2006 12 01 and Österreichisches Institut für Bautechnik OIB-330.5-002/15, the minimum requirements for sound proofing insulation [dB] for exterior building elements depend on the building type and the weighted sound pressure level (LA,eq) values.

For residential buildings (Class D) the minimum values are: $38<R'_{res,w}$ (resulting sound reduction index) for the compound exterior building components, $43<R_w$ (weighted sound reduction index) for opaque exterior elements (5 dB higher than $R'_{res,w}$), and $33<R_w$ (5 dB below $R'_{res,w}$) for windows. These values correspond to an equivalent $L_{A,eq}$ [dB] for an outside sound level from 51 to 55 during day and from 41 to 45 during

night for urban residential area (Class 3) according to the Ministerium für ein Lebenswertes Österreich 2017.[1]

Energy consumption and thermal insulation

The requirements and specifications for the elaboration of an energy certificate are provided by the Österreichisches Institut für Bautechnik OIB-330.6-009/15. In the case the analyzed rooftop extension does not correspond to an exception to perform an energy certificate, the following requirements apply:

- The minimum requirements for thermal insulation of the different building elements are specified in terms of U-value [$W.m^{-2}.K^{-1}$] as follow[2]: exterior wall (0,35); pitched roof (0,20); windows (1,40); neighbor wall (0,50).
- The energy requirements for residential buildings are categorized by new buildings and renovations, for which apply different maximum values for heating and energy demands. In most cases, rooftop extensions apply to the building renovations category (Kirchmayer et al. 2011). For those cases, the heating demand ($HWB_{Ref,RK}$) [$kWh.m^{-2}.a^{-1}$] – calculated to a reference weather data – muss not exceed $21 \times (1 + 2,5 / \ell c)$.

Moisture protection and air exchange

According to Österreichisches Institut für Bautechnik OIB-330.6-009/15 the air exchange rate n50 (pressure difference of 50 Pa between out- and indoors) for naturally ventilated buildings must not exceed the value 3 h^{-1}.

As stated in the Österreichisches Institut für Bautechnik OIB-330.3-009/15 and Österreichisches Institut für Bautechnik OIB-330.6-009/15, the importance of air tightness in buildings for moisture protection is partially related to the correctly installation of water vapor barriers.

Summer overheating and heat storage

According to Austrian Standards ÖNORM B 8110-3: 2012 03 15, the verification for the avoidance of summer overheating in buildings specifies the maximum inner temperature during the day of 27°C and during night below 25°C, for an average outdoor temperature of 23°C. The simplified one-day calculation does not constitute a whole year simulation.

[1] The mentioned values apply to the attic extension that is being analyzed.
[2] The mentioned building elements apply to the analyzed attic extension.

Summer overheating is influenced by different parameters such as ventilation, energy income and heat storage. In order to reduce this effect, the mentioned standard relates the total immission area to the volume air exchange ($V_{L,s}$) [$m^3.h^{-1}.m^{-2}$] and to the total heat storage of the building elements ($m_{w,I}$) [$kg.m^{-2}$], setting the limit values for both of them.

Room geometry

According to the Österreichisches Institut für Bautechnik OIB-330.3-009/15, the light entrance area from windows muss be at least 10% from the room area. If the room deepness is more than 5 meters, the window area must be increased 1% per meter room deepness.

In terms of design, the flap tile should be at least 120cm height. In terms of room height, the usable interior must have at least 2,5m height from half of the total area. According to the information provided by proHolz Austria (2012) a roof pitch lower than 3° is likely to cause puddles, as standing water on the roof can cause damage. In case of pitched roofs, an inclination higher than 20° is common for housing in central Europe (Nusser and Teibinger 2013).

Weight

The type of rooftop extensions in Vienna is mainly differentiated between a decisive or non-decisive intervention of the existent building, also known as “lightweight attic extension” where a maximum load of 720 $kg.m^{-2}$ can be introduced, and “massive attic extension” when the attic heightening has a load higher than 720 $kg.m^{-2}$. In the second case, the buildings’ safety by applying the correspondent load has to be considered for the static proofs (Kirchmayer et al. 2011).

2.2 Thermal evaluation

2.2.1 Thermal properties

In order to evaluate the impact of a building element on the energy performance of a building is essential to understand its materials' behavior, which depends in part on its characteristics and thermal properties.

When referring to wood structures and wood related materials, one of the most relevant parameters is the **moisture content**, as many physical and mechanical properties of wood depends on it. This concept can be express according to the following equation:

$$M = \frac{mwet - mdry}{mdry}\,(100\%) \tag{1}$$

where m_{wet} is the mass of the specimen at a given moisture content
m_{dry} is the mass of the oven dry specimen

The moisture content varies from different types of wood according to their density and specific gravity (relative density), and it is a function of relative humidity and temperature. In order to prevent huge content changes, the drying process brings it to the expected value that the product will have in service.

Despite this variability, a standard reference basis of moisture content is used – generally 12% - for comparison purposes of different wood products, for example in terms of thermal conductivity (Forest Products Laboratory 2010).

As moisture content is dependent on temperature, the **density** of a material is given at certain moisture content. At constant temperatures, certain materials' density maintains constant as they do not absorb moisture, and for materials that do not change volume, the relationship between moisture content and density is linear (e.g. brick and stone). In contrast to these materials, the behavior of wood is different as both mass and volume are dependent on moisture content.

As density, moisture content and temperature increase so does the **thermal conductivity** of wood materials. In general, thermal conductivity of structural wood is lower than metals[3], and two to four times that of common insulation materials (Forest Products Laboratory 2010).

[3] General values for wood are 0,10 to 0,14 $W.m^{-1}.K^{-1}$, compared to 216 for aluminum, 45 for steel, 0,9 for concrete, 1 for glass, 0,7 for plaster, and 0,036 for mineral wool.

One important characteristic of materials is the energy storage capability. Likewise other properties, the heat storage varies according to other parameters. In the case of wood, the **specific heat capacity** [J.kg^{-1}.K^{-1}] depends principally on moisture content, temperature and the direction of the grains, and not much on density (Tenwolde et al. 1988).

In 2 the relationship between specific heat capacity for a certain mass in terms of temperature variation is shown:

$$c = \frac{Q}{m \,.\, \Delta\theta} \qquad (2)$$

where Q is the heat [J]
m is the mass [kg]
$\Delta\theta$ is the temperature difference [K]

Specific heat capacity can also be analyzed in terms of moisture content. In the case of moist wood, an additional apparent specific heat is *"due to the energy absorbed by the wood-water bonds and can be represented by a correction term"* (Tenwolde et al. 1988):

$$c = A + \frac{c0 + 0{,}01M\ cw}{1 + 0{,}01M} \qquad (3)$$

where c_0 is the specific heat of dry wood [kJ.kg^{-1}.K^{-1}]
c_w is the specific heat of water 4,186 kJ.kg^{-1}.K^{-1} approximately
M is the moisture content [%]
A is the correction term [kJ.kg^{-1}.K^{-1}]

There are different approaches to calculate the specific heat capacity of a material, depending on the moisture content and temperature (Brigola 2010). In Table 1 different values for solid wood at different temperatures and moisture content can be seen:

Table 1: Heat capacity of solid wood at selected temperatures and moisture contents (Forest Products Laboratory 2010)

Temperature		Heat capacity (kJ kg^{-1} K^{-1} (Btu lb^{-1} °F^{-1}))			
(K)	(°C (°F))	Ovendry	5% MC	12% MC	20% MC
280	7 (44)	1.2 (0.28)	1.3 (0.32)	1.5 (0.37)	1.7 (0.41)
290	17 (62)	1.2 (0.29)	1.4 (0.33)	1.6 (0.38)	1.8 (0.43)
300	27 (80)	1.3 (0.30)	1.4 (0.34)	1.7 (0.40)	1.9 (0.45)
320	47 (116)	1.3 (0.32)	1.5 (0.37)	1.8 (0.43)	2.0 (0.49)
340	67 (152)	1.4 (0.34)	1.6 (0.39)	1.9 (0.46)	2.2 (0.52)
360	87 (188)	1.5 (0.36)	1.7 (0.41)	2.0 (0.49)	2.3 (0.56)

Usually it is assigned between 100 and 800 [J.kg^{-1}.K^{-1}] for metals, 800–1.200 [J.kg^{-1}.K^{-1}] for masonry materials, such as brick and concrete, and 4176 [J.kg^{-1}.K^{-1}] to water, which has the highest value (Szokolay 2008). Values for standard materials are tabulated by International Organization for Standardization ISO 10456:2007 and Austrian Standards ÖNORM B 8110-7: 2013 03 15.

For different building applications, wood has a high specific heat capacity, ranging from 1.200 to 2.500 [$J.kg^{-1}.K^{-1}$]. The importance of this property relies on the capacity to storage energy and, consequently, to influence the heat conduction (4).

$$c = \frac{\lambda}{a \, . \, \rho} \qquad (4)$$

where λ is the conductivity [$W.m^{-1}.K^{-1}$]
a is the thermal diffusivity [$m^2.s^{-1}$]
ρ is the density [$kg.m^{-3}$]

Because of the low thermal conductivity and moderate density and heat capacity of wood, the **thermal diffusivity (a)** of wood is much lower than other structural materials, such as metal, brick, and stone. Wood structures have usually a value of $1{,}6 \times 10^{-7}$ $m^2.s^{-1}$, while steel has 1×10^{-5} $m^2.s^{-1}$ and stone and mineral wool 1×10^{-6} m^2 s^{-1}.

The relationship between specific heat capacity of a material at a given density is express by the **heat storage capacity** [$J.m^{-3}.K^{-1}$]:

$$s = c \, . \, \rho \qquad (5)$$

where c is the specific heat capacity [$J.kg^{-1}.K^{-1}$]
ρ is the density [$kg.m^{-3}$]

Likewise, for a certain volume [m^3], the **effective storage mass** or heat mass [$J.K^{-1}$] can be expressed as the specific heat capacity [$J.kg^{-1}.K^{-1}$] per material's weight [kg]. According to the Austrian Standards ÖNORM EN ISO 13786: 2008 04 01, the maximum depth of penetration of the effective storage capacity is calculated as the half of the total building element thickness or until the first insulation layer (in the direction of the heat transmission).

A study of the TUGraz (Kouba 2001) compares a wood timber wall, a solid wood wall and a brick wall in terms of cooling hours, until the wall surface reaches 0°C (Figure 2). The analyzed building elements have similar thickness but different U-value. The solid wood construction cools down 144% slower than the brick wall and 454% than the wood timber construction.

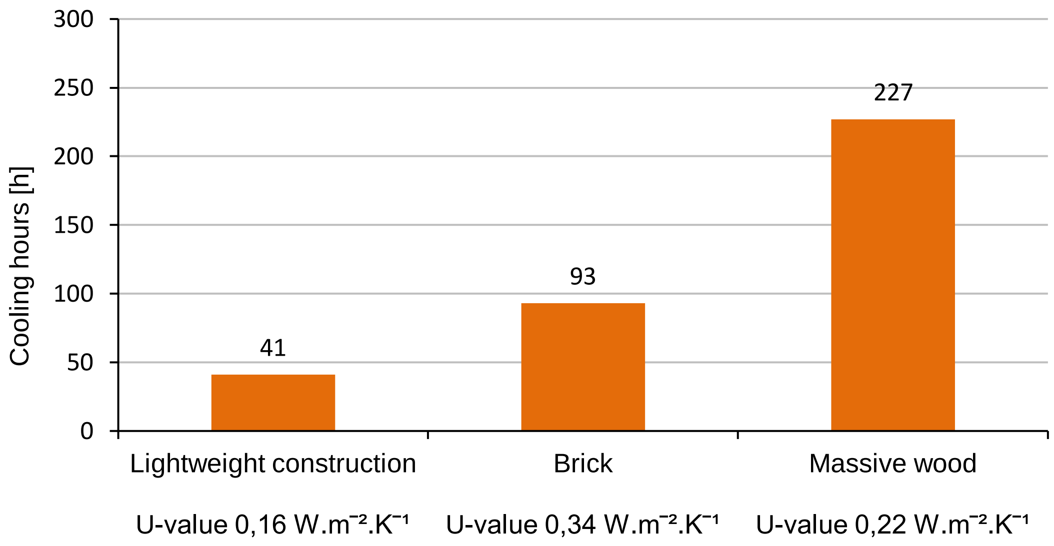


Figure 2: Cooling hours for different wall alternatives without insulation (Kouba 2001)

As shown in Figure 3, the same study was performed adding an insulation layer to reach a similar U-value for the three cases. The solid wood construction cools by far slower than other constructions (200% slower than brick and 1.795% than timber frame constructions).

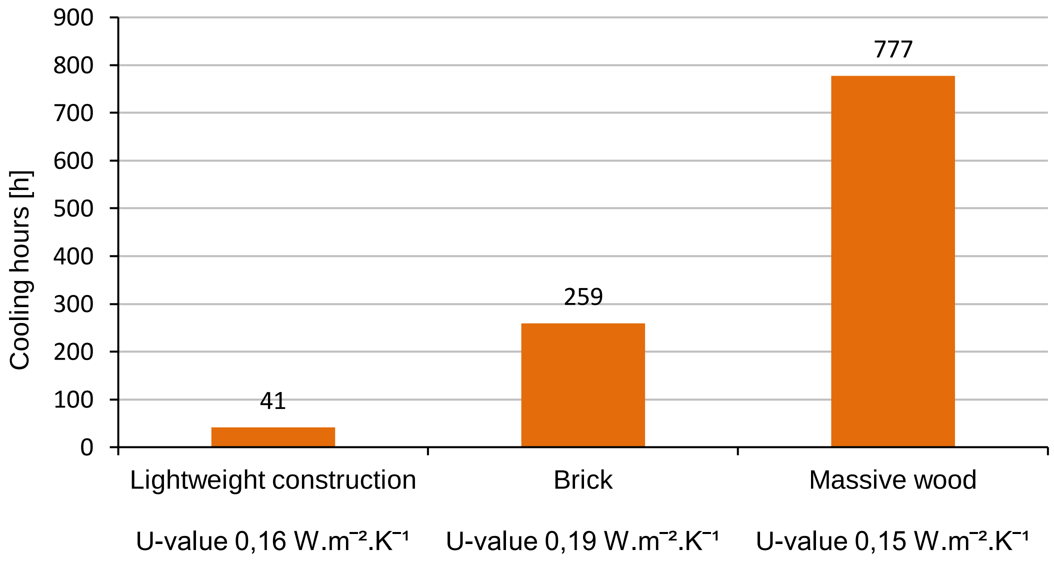


Figure 3: Cooling hours for different wall alternatives with additional insulation (Kouba 2001)

Even though the building elements have the same thermal conductivity, the heat transmission is delay due to the energy "stored" within the material. This behavior is explained due to the impact of the heat storage capacity of the materials, influencing the thermal behavior of building elements.

2.2.2 Thermal comfort

Energy consumption of buildings is not only influence by the design and operation conditions of the building, but also by the indoor conditions criteria and performance. The reciprocal relationship between energy use and occupancy behavior is strongly dependent on indoor perception.

Several factors influence individuals' thermal perception: mainly environmental characteristics, such as air temperature, air movement, humidity, radiation, and personal characteristics and preferences (activity level, clothing value, etc.).

In order to design and evaluate the indoor environment, a set of standards specifies the main parameters and calculations for the building energy performance and thermal comfort.

The adaptive model approach proposed by the European Standard BS EN 15251:2007 and ASHRAE Special Publications is intended for use in naturally ventilated buildings, determining an acceptability range of indoor conditions given the monthly mean outside temperature (ASHRAE Special Publications) or weekly weighted outdoor temperature (European Standard BS EN 15251:2007). Different categories of acceptability are defined with their correspondent temperature limits (Figure 4) by relating it to the outdoor climate, so it is not necessary to estimate the clothing values for the space.

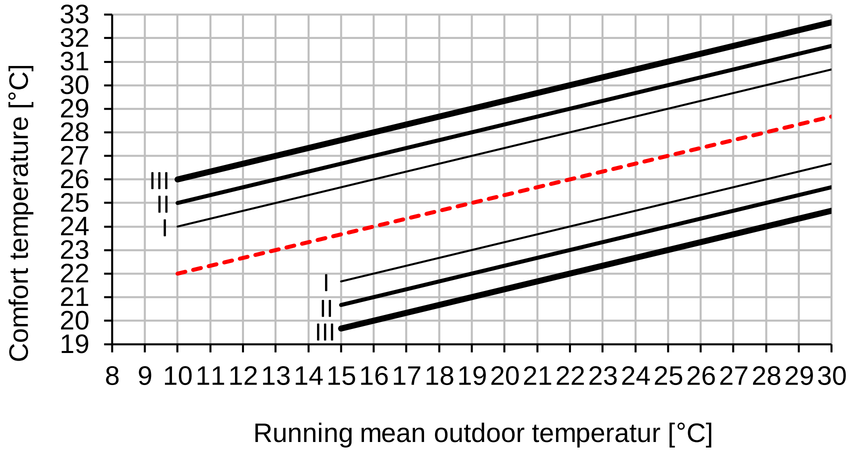


Figure 4. Acceptable operative temperatures ranges for naturally conditioned spaces (European Standard BS EN 15251:2007)

The European Standard BS EN 15251:2007 suggests in Annex F different ways for long-term evaluation of the general thermal comfort conditions: simple indicator (criteria of a category is 95% met), hourly criteria (number of hours when the criteria of PMV-PPD is met), degree hours criteria (degree hours outside the upper or lower boundary) and weighted PMV criteria.

The ASHRAE-55 Handbook (ASHRAE Special Publications) defines the main influencing factors for thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity (steady state conditions). By means of the PMV-PPD index calculation, it is possible to set the requirements for indoor thermal conditions, which requires a satisfaction of the occupants of at least 80%. By assigning values to the above-mentioned factors, a comfort zone is defined in terms of an operative temperatures range that provide acceptable thermal environmental conditions. The main difference with the adaptive model is that the indoor temperature comfort zone does not change with seasonality, considering an all-year constant setpoint. This means that occupants do not adapt to different outdoor temperatures.

Independent of the approach, it is desirable to maintain a balance between energy demand and thermal comfort, which is directly influenced by building design and behavior criteria. Brigola (2010) describes the main influencing factors on indoor temperatures for a roof area as internal gains, room storage mass, duration of warm season, shading, night ventilation, insulation materials and floor construction.

For purposes of this study, the influence of the material selection is specially assessed. In the above mentioned study (Kouba 2001) a comparison of 17 different building elements in terms of cooling period and thermal satisfaction is performed. The results showed a significant difference in the thermal perception for those building elements with slower cooling response (Figure 5).

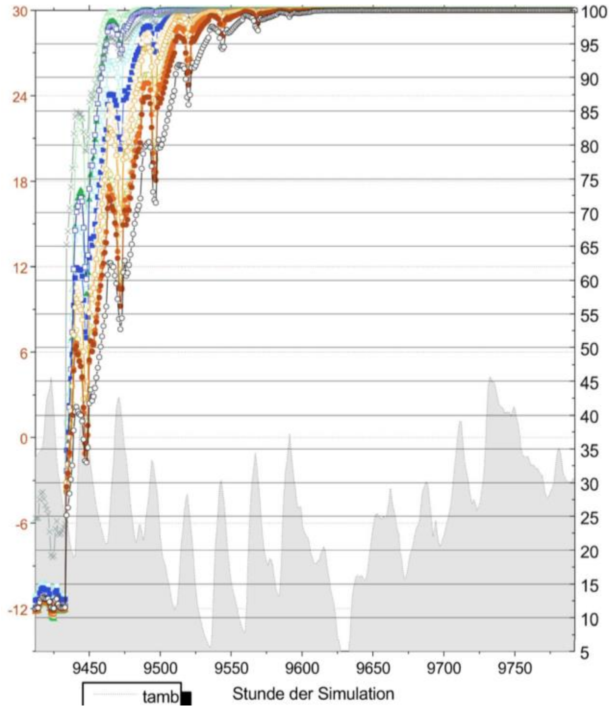


Figure 5: Tendency of the thermal comfort during the cooling process (Kouba 2001)

2.2.3 Thermal bridges

The consideration of hygrothermal conditions in construction detailing is very important due to the risk of mold growth, the appearance interstitial condensation and even materials' corrosion. Thus, the consideration of thermal bridges is directly related to materials durability and may also have an impact on the heating demand due to the increase of heat loss.

Thermal bridges are generated due to a variation of geometry or materials in the analyzed detail. The directions of the isolines or different conductivities result in a change in the heat flow rate and in the inner surface temperature.

Usually thermal decoupling and the continuity of the insulation around the construction are techniques used to avoid hygrothermal problems. However, joints must be carefully assessed as *"Pihelo et al. [62] show that risk of mould growth and longer dry out periods are higher when the thermal transmittance of the wall is lower (high thicknesses of insulation)."* (Asdrubali et al. 2017, p. 318). In that cases, the use of wind and vapor barriers in wood constructions are used for wall assemblies.

In order to determine the risk of mold growth or surface condensation, the Austrian Standards ÖNORM B 8110-2 Bbl 1: 2003 07 01 defines the limit values in standard indoor and outdoor conditions (T_i= 20ºC; RH=55%; T_e=-10ºC; R_{si}=0.25 $m^2.K.W^{-1}$) for the temperature factor (f_{Rsi}): when $f_{Rsi} \geq 0{,}71$ there is mold growth, and $f_{Rsi} \geq 0{,}69$ surface condensation.

In general, thermal bridges are assessed by experience or thermography, and in certain cases, through a numerical simulation. The procedures to determine the numeric calculation method are defined by the International Organization for Standardization DIN EN ISO 10211:2008-04. Both 2D and 3D geometrical models of a thermal bridge can be simulated and assessed by the calculation of the thermal coupling coefficients L^{2D} and L^{3D} for two-dimensional and three-dimensional junctions, respectively.

Viot et al. (2015) exemplifies the importance of assessing thermal bridges as part of the building design process: *"The results for wood stud thermal bridges showed that the values that are mainly used by engineering offices often lead to important errors due to the standard method and rounding choice."*

2.3 Acoustical evaluation

There are several parameters to characterize the acoustical properties of a material: Airborne Sound Insulation (R_w), the Impact Sound Insulation (L_n) and Sound Absorption coefficient (α). As mentioned before, the minimum requirements of a building element are determined in Austria by national standards.

Even though acoustical evaluations require major efforts, several tests have been developed for building applications. By means of field measurements, Nusser et al. (2016) has tested the competence of timber constructions in terms of airborne sound insulation in accordance to procedures in the International Organization for Standardization ISO 140-7:1998 and International Organization for Standardization ISO 717-1:2013.

Similarly, Theocharis (2015) has tested the impact sound insulation of an existing and renovated wood floor construction according to the measurement test procedures in the International Organization for Standardization ISO 16283-2:2015. Alternatively, the use of the Finite Element simulation tool allows facing low frequency vibroacoustic issues.

In wooden buildings, usually a sufficient level of sound insulation can be achieved by using multi-layered constructions. By making wooden battening or by positioning a porous absorption material (e.g. thermal insulation) behind the paneling, low sounds (usually problematic for light structures) can be dampened, while in floors it is convenient a footstep insulation improved with a so-called floating surface. In renovated buildings, the impact sound noise is more problematic than the airborne sound in the refurbishment of old-stock (Theocharis 2015).

2.4 Ecological criteria

Although the evaluation of the environmental impact of single materials or elements related to the entire building is still under development due to its complexity, the use of Life Cycle Assessment (LCA) tools to assess environmental performance is increasingly spreading and taking more relevance. The evaluation criteria are highly diverse and can be analyzed according to different impact categories, such as resources, global warming potential and ozone depletion, among many others.

It has been widely proved the favorable impact of the utilization of wood in buildings in terms of environmental performance. In Figure 6, a comparison of three identical and hypothetical buildings with different types of construction systems (wood, steel and concrete) showed that wood houses have the smallest environmental impact (Asdrubali et al. 2017).

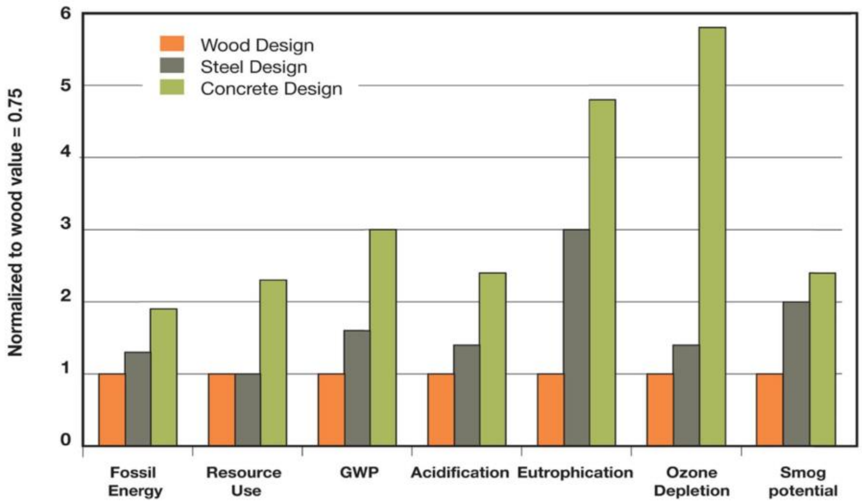


Figure 6: Impacts of three hypothetical buildings normalized to wood value (Asdrubali et al. 2017, p. 323)

Although wood is commonly considered a sustainable material, the consideration of certain issues such as forest management, manufacturing methods and site assembly, distance required for transportation and use of glues, are main factors to evaluate its sustainability. For instance, the choice of a construction material is highly influence by the region background, as the its local production would directly reduce the transportation environmental impact.

Another important aspect in the LCA is the reuse of materials for new buildings. For example, *"the potential of reusing steel structures has been estimated as a saving of 81% in the initial embodied energy"* (Asdrubali et al. 2017). Even though in the case of wooden materials the reutilization for building use is not very common, the reuse in furniture or as combustible materials in place of fossil fuels, leads to potential global warming savings.

Pajchrowski et al. (2014) assess 4 single-family residential buildings and divides the LCA in 7 stages: production of building materials, transport of building materials, construction processes, use, demolition, transport of demolition waste and final disposal of demolition waste. Depending on the type of building technology and energy standard (conventional or passive building), the results showed that in general around 92-96% of the total impact on the life cycle account for the use stage, between 3-8% for material production and less than 0,7% for transport and construction stages.

Moreover, it has been shown how the environmental benefit of wood on the production process *"has been directly connected with the effect of photosynthesis and absorbing* *carbon dioxide, positive for the global warming, which takes place in the ''cradle'', i.e. during tree growth in the forest"* (Pajchrowski et al. 2014, p. 435).

A study in Sweden (Kuittinen et al. 2013) compares the same building with different wood systems in terms of primary energy and greenhouse gas (GHG) emissions over the life cycle. A cross-laminated timber (CLT) system; a beam and column system with laminated veneer lumber (LVL) and glulam as main structure; and a volumetric modules system with individual volumetric elements prefabricated off-site, are the three analyzed wood constructions.

The LCA analysis includes production, operation, end-of-life phase and the complete life cycle assuming a life span of 50 years. The impact of each category depending on the wood construction (both conventional and with passive house standards) can be seen in Figure 7. The operation phase accounts for a large share of the primary energy, while the material production dominates the GHG emissions. In general, the CLT has lower life cycle primary energy use and emissions compare to the other systems.

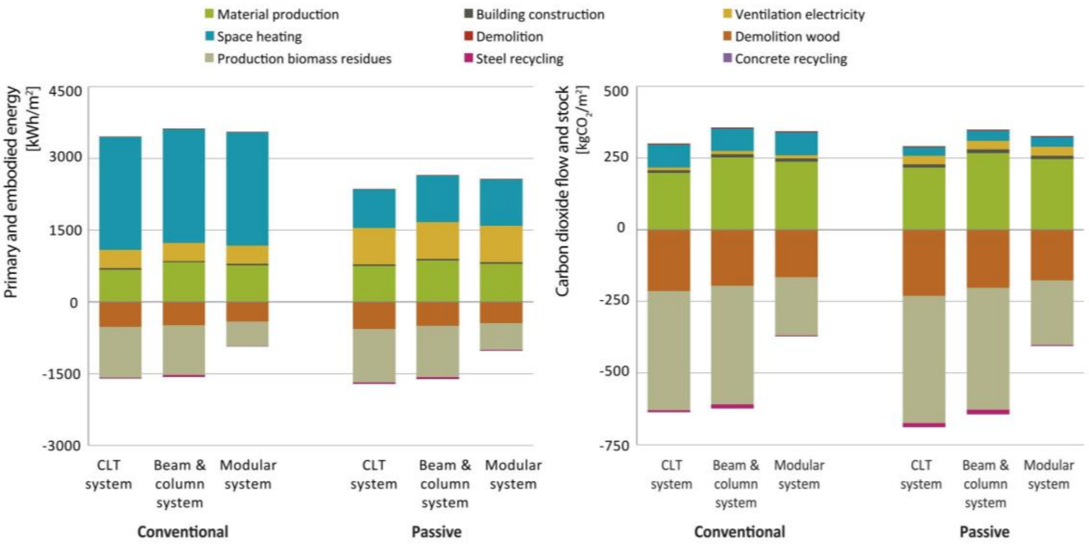


Figure 7: Primary energy use (a) and GHG emission (b) for the life cycle phases (Kuittinen et al. 2013, p. 120)

The increasingly studies on the evaluation of sustainable materials for building use has been sharing a growing tendency of tenants to care about the sustainability of building materials and life encompassed (Mikado 2013). Even though there is still a lack of regulations and normative (Kuittinen et al. 2013), there are several efforts to develop and motivate sustainability as a part of the design process.

2.5 Time, cost and mounting efforts criteria

2.5.1 Prefabrication

Prefabrication is a manufacturing process where materials are formed as a component of the final installation. In the last 10 years, it has been widely regarded not only as a time-efficient but also as a sustainable construction method, mainly in terms of waste reduction (Li et al. 2014).

Tam et al. (2007) synthesizes the main advantages of adopting prefabrication in construction, such as a frozen early stage design required for the manufacture of the building elements, better products' quality, lower construction costs and time, better environmental performance, and project's integrity from the design and construction phases. The main disadvantages of applying prefabrication are the lack of change possibilities of the design and its limitations, higher initial costs and time, bigger space required for placing building components, and lack of experience on contractors.

Both benefits and drawbacks of applying prefabrication have different levels of significance, being better quality and inflexible for design changes the most relevant ones for each case. Time and cost play also an important role on the decision of adopting prefabrication.

There are different forms of prefabricated constructions modules, such as semi-prefabricated non-structural elements, structural prefabricated elements such as columns, beam, load-bearing walls, roof sheathing, etc., and modular buildings. Haziq Bin HJ Zariful, M. (2015) has exemplified different ways of implementing prefabrication such as precast concrete systems, steel framing and formwork systems, prefabricated timber framing systems, and block work systems.

Different companies like Ecococon Straw Panels and ModCell Panels, commercialize prefabricated elements turning to a more sustainable direction, by incorporating renewable materials such as straw bale layers in wall panels.

For roof assemblies, steel and wood structures are usually performed. The prefabrication of a roof modular structural wood system has been also structurally proved (Fiorelli et al. 2012). Even though prefabricated modules are not extensively used in attic extensions in Vienna, some examples can be found (Figure 8).

Figure 8: Massive attic extension with prefabricated wood system (Kirchmayer et al. 2011)

2.5.2 Cost

The definition of the construction costs is defined by the Austrian Standards ÖNORM B 1801-1: 2015 12 01 (Figure 9). The first category includes the structural assembly costs such as building structure, services and finishing processes. The constructions costs represent the second category, including also the equipment and gardening works. The third category includes professional fees, incidental costs and reserves (insurance fees, building permission and legal requirements, arising costs, governmental fees). The final total costs include the construction site and the provision of services.

<table>
<tr><td>0. Construction Site</td><td></td><td></td><td></td><td rowspan="5">Total costs</td></tr>
<tr><td>1. Provision of services</td><td></td><td rowspan="3">Construction costs</td><td rowspan="4">Building Costs</td></tr>
<tr><td>2. Building structure
3. Building services
4. Building finishing</td><td>Construction costs (structural assembly costs)</td></tr>
<tr><td>5. Equipment
6. Gardening</td><td></td></tr>
<tr><td>7. Proffesional fees
8. Incidental costs
9. Reserves</td><td></td><td></td></tr>
</table>

Figure 9: Summary of building costs (Schöberl and Handler 2011)

In general, additional costs account for 15-20% of the total building costs. Additional factors that may increase the cost ranges are site access, construction site conditions and specifications and finishes (RIAI 1998). According to Schöberl and Handler (2011), a conventional attic extension cost between 2.000 €.m$^{-2}_{EBF}$ und 2.500 €.m$^{-2}_{EBF}$ of gross heated area[4].

[4] In German “Energiebezugsfläche”.

2.6 Building elements

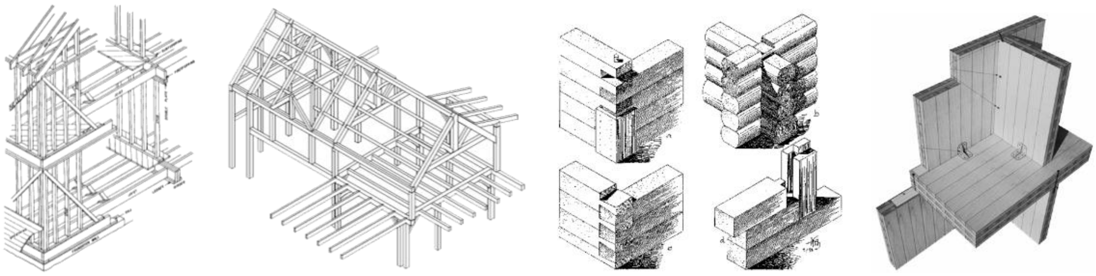
In a publication from proHolz Austria (2012), the authors suggest the following considerations and recommendations while performing roof structures:

- planning across trades to avoid execution defects at the interfaces between the trades.
- maintenance of the roof at regular intervals.
- use of weatherproof protection at the end of the workday to prevent the entry of moisture during the construction phase.
- aim for maximum tightness: professional work regarding the water and air tightness of the roof elements is a prerequisite for a durable, high-quality roof construction.
- avoidance of cavities in the thermal insulation, so that moisture cannot accumulate.
- avoidance of subsequent penetration or, if necessary, use cuffs for sealing.
- avoidance of building moisture: the construction process must be planned and coordinated accordingly. Elements' prefabrication prevents any penetrating moisture from being spread over large areas in the roof and allows a quick sealing of the roof tightness.
- performance of dynamic moisture protection calculations to ensure the functional capability and risk assessment of non-certified building elements, especially with the use of moisture-adaptive vapor barriers.
- avoidance of structures with high diffusion resistance on the outside and inside.

Load-bearing material

In residential buildings, there are different types of wood structures typologies. Nowadays, the ones that are mainly performed are platform frame structures, timber frame structures, Block-Bau System and X-LAM structures.

Timber frame structures (Figure 10a) employ timber beams and columns jointed with mortises and tenor joints, and additional diagonal bracing is also used for structural purposes. Platform frame structures (Figure 10b) are composed by pins interrupted by horizontal platforms which are the floors. With more limitations in the design, the Block-Bau system (Figure 10c) creates walls by employing square-section trunks that overlay and connect each other with snap fit joints at the corners. More recently used, X-LAM or Cross Laminated Timber (CLT) structures (Figure 10d) consist in solid wood panels as the load bearing material, which are composed by crossed layers of planks, nailed and glued (Asdrubali et al. 2017). One of the main benefits of cross laminated panels is its ability to absorb diagonal forces – acting as a static stiffening element –, and the uncomplicated processing and design flexibility of the wood construction material during the entire construction process (proHolz Austria 2008). Remarkable solutions for attic extensions in Vienna are performed with wood timber skeleton and with solid wood as the structural material.



(a) (b) (c) (d)

Figure 10: Different structural typologies: Timber frame (a) (Timber Frame HQ 2018), Platform frame (b) (Spiess 2018), Block-Bau system (c) (Krauth, T., Meyer, F. 2008), X-LAM (d) (Fat Pencil Studio 2018)

Hybrid systems are based on the combination of wood and steel materials for the building structure. Wood can not only be used as load bearing element but also as a bracing element, reducing the percentage of steel elements in the whole construction (Figure 11).

Figure 11: Details of hybrid construction (Obenauf 2018)

As before mentioned (Tam et al. 2007), cost and time are important factors when choosing a certain technology. Therefore, concrete prefabricated reinforced concrete solutions are a suitable choice regarding construction cost reduction in comparison to conventional steel solutions (Figure 12). Moreover, concrete roof solutions are suitable for cold climates due to its thermal properties which allow the absorption of thermal energy for long periods of time. Moreover, Alvarado et al. (2009)

demonstrates that, with adequate passive cooling techniques, the implementation of concrete roofs can also reduce the building's cooling loads.

Figure 12: Massive attic extension with prefabricated lightweight concrete building elements (Kirchmayer et al. 2011)

Insulation material

Traditional thermal insulation materials include expanded polystyrene, mineral wool, extruded polystyrene, expanded chipboard cork, rigid foam of poly-isocyanurate or polyurethane, rock wool, cellulose, fiber glass, urethane foam and vermiculite.

"On the basis of temperature, it can be categorized as, low temperature insulation – EPS, PUF, glass wool, expanded polyethylene, etc. and high temperature insulation – ceramic wool, rock wool, perlite concrete, etc."[5] (Kumar and Suman 2013). In terms of moisture conditions, the use of wood fiber insulation as well as glass wool shows a good thermal performance (Asdrubali et al. 2017).

The use of vacuum insulation panels (VIPs) has been widely used due to the benefits of a lower thickness for the same thermal performance of other common insulation materials. As disadvantages, it is easily damaged and its use is associated with thermal bridges effects (Pacheco-Torgal 2014).

Recently, the incorporation of straw as an insulation material has been tested and used for some residential buildings. *"Despite what might seem logical, properly constructed walls made from straw bales have proven to be more flame retardant than conventional wood-frame construction. This is because the bales are dense and tend to just smolder when the ignition source is removed."* (Syncronos Design Inc. 2015). According to Stroh & Lehm (2017), official structural tests were carried out for straw bale walls in Germany and Austria and gave the following results: a fire protection of

[5] The range of application temperature for high temperature insulation is generally between 600-1.500°C and between 20-600°C for low temperature insulation, depending on the insulation material. (ECFIA 2014)

F90, building element class B2 (normal inflammable) and a thermal conductivity value of 0,0456 $W.m^{-1}.K^{-1}$.

Jayasinghe et al. (2003) has evaluated the performance of an insulation layer with the incorporation of a reflective layer. Results have shown that the maximum indoor temperature can be significantly lowered. Moreover, the *"aluminum foil glued to fiberglass or rockwool blanket could be suspended directly on the underside of the roof"* (Ong 2011, p. 2405). Radiant heat barriers and reflective insulation systems reduce radiant heat gains, and combined with insulation materials, can reduce attic temperatures by 5.5°C. An experiment showed by Winiarski and O'Neal showed heat flux reductions of between 29% and 37% for the summer period (Ong 2011).

Al-Sanea (2002) has evaluated the heat transmission in a roof detail by using a polystyrene layer as the insulation material and the results have shown a higher reduction of the heat transfer than with the use of a polyurethane material; while Han et al. (2009) has shown that the impact of using polyurethane in cooling loads allows a bigger reduction than when using glass wool, which has a higher thermal conductivity. The latter was performed for a hot humid climate and a lightweight aluminum roof type.

In terms of finding the optimal position of the insulation layer in roof details, authors such as Ozel and Pihtili (2007) and Han et al. (2009) have evaluated for different roof types the efficiency of placing the insulation material close to the façade outside surface. Furthermore, the insulation layer under the cavity of the ventilated roof performs better than above it (Gagliano et al. 2012).

In terms of embodied energy, some wood based materials, such as mineralized wood fibers, show a value (per functional unit) as high as synthesized materials like EPS or glass wool, but much lower than expanded polyethylene or expanded polyurethane (Asdrubali et al. 2017, p. 325). *"In recent years some investigations have focused on thermal insulation materials based on natural materials like hemp fibres or flax"* (Pacheco-Torgal 2014, p. 154). Although they show high performance, they are not cost effective as glass or mineral fibers. In the case of straw bales, they are biodegradable and have a low-embodied energy, as the manufacture of the product requires little energy in comparison to other insulation materials. Sunlight is the main energy source for growing plant and additional energy is needed just in the bailing process (Gruber & Partner KG 2016).

Inner finishing

"In order to meet fire safety requirements concrete and mass wood structures can be encapsulated with gypsum board layers" (Asdrubali et al. 2017, p. 327). Moreover, providing airtightness of the attic floor, for example by using a plastic film (vapor barrier), can prevent condensation. The use of smart vapor barriers (moisture adaptive) allows less moisture to diffuse in winter and to diffuse significantly in summer. In the roof structure in the Radetzkystraße, Vienna (proHolz Austria 2012), a moisture-adaptive vapor barrier with a variable Sd-value of 0,2 to 5 meters on the room side has been applied. The author explains that depending on the humidity and air temperature, this membrane changes its vapor resistance by up to 25 times.

It is of great importance that the airtight layer is placed on the warm side of the insulation, as it allows the re-drying of existing moisture with high outside diffusion resistance (proHolz Austria 2012).

Outdoor finishing

The incorporation of ventilated roofs contributes to the reduction of solar heat gains on the indoor environment, respect to a non-ventilated roof with same thermal resistance value. They need a tilt angle of more than 20° at least (Gagliano et al. 2012), which is also *"more or less robust against diffusion moisture damages"* (Nusser and Teibinger 2013).

The use of house wrap with increased rain resistance on pitched roofs allows the moisture within the ventilated layers to escape (proHolz Austria 2012). Moreover, the wind barrier in the outside layer allows the vapor to be dried out and, as an effect, increases the temperature of the internal insulating material reducing its relative humidity (Asdrubali et al. 2017).

Han et al. (2009) found that the type of insulation materials used for construction of roof has a more significant effect on indoor temperatures than the effect from the exterior roof surface color. Contrarily, Jayasinghe et al. (2003) explains that the light color tiles perform better than the black ones in terms of reducing the indoor temperature and light color roof surfaces (e.g., off-white) can achieve indoor thermal conditions comparable to those of the insulation materials.

3 METHOD

3.1 Overview

In this chapter, six roof building details are selected and the methodology for the thermal, ecological and cost evaluation is explained.

In chapter 3.2, the different details' layers, thickness and main characteristics of the building elements are shown. The building elements' properties were calculated with Archiphysik 14.0 (Archiphysik 2015). In chapter 3.3, the methodology for the thermal performance analysis is explained. The chosen software used for this evaluation is Energy Plus 8.6. (EnergyPlus 2018) due to its free accessibility and its recognized validation. The simulated results were processed and represented in Matlab R2015b (Matlab 2018). The ecological performance analysis is explained in chapter 3.4, which is performed with Archiphysik 14.0 due to its free accessibility and its recognized IBO standard values for the materials' database. Finally, in chapter 0 the evaluation method for cost and time calculation is described.

As this study focuses on the comparison of building elements' performance in generic roof extensions, an acoustical evaluation of the new roof and a thermal bridges evaluation will be not assessed due to the detailed information required for both assessments (e.g. specific building details' design). Considerations will be taken according to previous studies on building elements.

3.2 Construction details

According to the description, criteria and in fulfillment of the requirements mentioned in chapter 2, the details were designed and selected. For purposes of this work, the assemblies mainly differ in the load-bearing material and the insulation material, while the inner and outdoor finishing will be common for all of them[6].

[6] Note: the details were designed for comparison purposes, taking common dimensions, minimum thickness and separation of building elements from current roof examples, excluding loads calculations.

3.2.1 Lightweight Timber construction

Usually a particleboard is incorporated on the outside, acting as a wind bracing material (Asdrubali et al. 2017). Viennese companies such as *Obernauf GmbH* and *Dietrich* (proHolz Austria 2012) have implemented this system. Different solutions of this typology can be obtained also from Dataholz (2018) and baubook GmbH (2018).

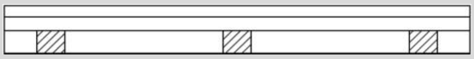
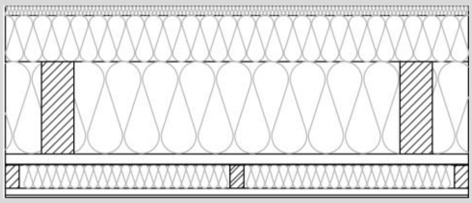
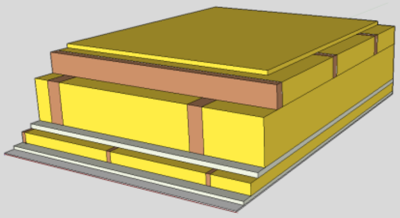
Lightweight timber wood with mineral wool (TMW)			
	10 mm 30 mm 50 mm	Roof tiles Battens Ventilated air layer between counter battens Rain and wind protection foil	
	20 mm 100 mm 200 mm 20 mm 2 mm 50 mm 15 mm 5 mm	Wood fiber insulation Glass wool insulation between battens Mineral wool insulation between beams MDF plate Vapor barrier PE Mineral wool insulation between battens Fire protection plasterboard Gypsum plaster inside	
	50,2 0,134 48,41 118,9	cm $W.m^{-2}.K^{-1}$ $kJ.m^{-2}.K^{-1}$ $Kg.m^{-2}$	Total thickness U-Value Heat Storage Weight

Figure 13: Lightweight timber construction with mineral wool as insulation material

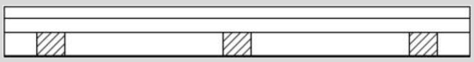
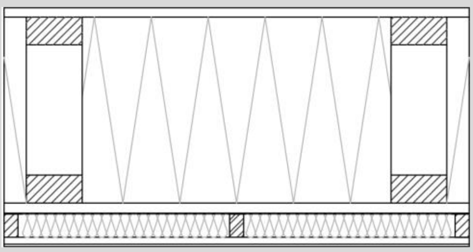
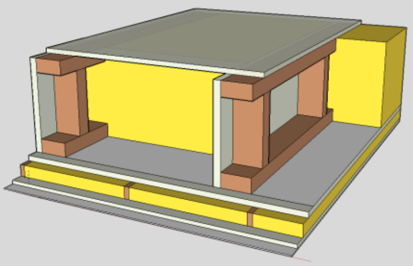
Lightweight timber wood with straw (TSI)			
	10 mm 30 mm 50 mm	Roof tiles Battens Ventilated air layer between counter battens Rain and wind protection foil	
	20 mm 400 mm 20 mm 2 mm 50 mm 15 mm 5 mm	MDF plate Straw insulation between beams MDF plate Vapor barrier PE Mineral wool insulation between battens Fire protection plasterboard Gypsum plaster inside	
	60,2 0,135 48,43 168,7	cm $W.m^{-2}.K^{-1}$ $kJ.m^{-2}.K^{-1}$ $Kg.m^{-2}$	Total thickness U-Value Heat Storage Weight

Figure 14: Lightweight timber construction with straw as insulation material

3.2.2 Massive wood construction

The variation of the thickness of the X-LAM layers has shown a different thermal behavior (Kouba 2001). Usually, in X-LAM an insulation sheathing is placed in the outside before the air gap (Asdrubali et al. 2017). Examples of massive wood can be seen in attic extensions from *Dietrich* and *Lutter Architektur* (proHolz Austria 2011, 2004).

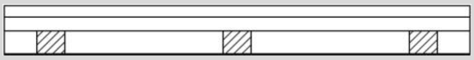
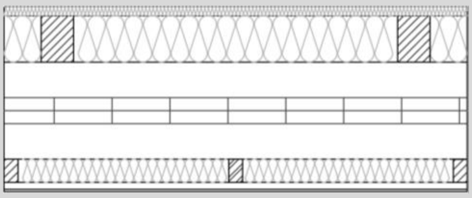
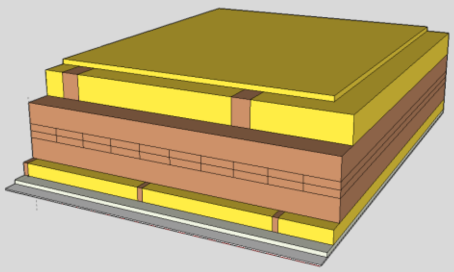
Massive wood with one-layer insulation (MOI)			
	10 mm 30 mm 50 mm	Roof tiles Battens Ventilated air layer between counter battens Rain and wind protection foil	
	20 mm 100 mm 210 mm 2 mm 50 mm 15 mm 5 mm	Wood fiber insulation Glass wool insulation between battens Cross laminated timber Vapor barrier PE Mineral wool insulation between battens Fire protection plasterboard Gypsum plaster inside	
	49,2 0,203 48,44 192,5	cm $W.m^{-2}.K^{-1}$ $kJ.m^{-2}.K^{-1}$ $Kg.m^{-2}$	Total thickness U-Value Heat Storage Weight

Figure 15: Massive wood construction with one insulation layer

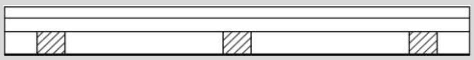
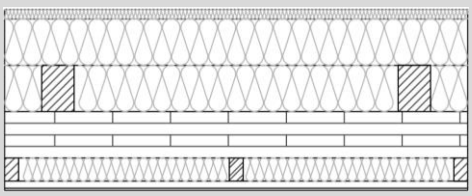
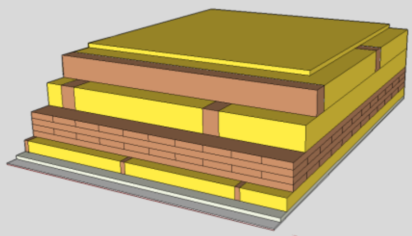
Massive wood with two-layer insulation (MTI)			
	10 mm 30 mm 50 mm	Roof tiles Battens Ventilated air layer between counter battens Rain and wind protection foil	
	20 mm 100 mm 100 mm 100 mm 2 mm 50 mm 15 mm 5 mm	Wood fiber insulation Glass wool insulation between battens Glass wool insulation between battens Cross laminated timber Vapor barrier PE Mineral wool insulation between battens Fire protection plasterboard Gypsum plaster inside	
	48,2 0,152 48,44 149,6	cm $W.m^{-2}.K^{-1}$ $kJ.m^{-2}.K^{-1}$ $Kg.m^{-2}$	Total thickness U-Value Heat Storage Weight

Figure 16: Massive wood construction with two insulation layers

3.2.3 Hybrid construction

Structural metal roofs commonly use a type of rigid insulation above the main insulation layer, which *"not only increases the overall thermal insulation of the roof, but reduces any thermal bridging which may have arisen from gaps and spaces in the first layer of insulation."* (Buchinger et al. 2014). Examples of hybrid systems can be seen in the attic extension performed by *Schöberl&Pöll GmbH*, *Obenauf GmbH* and *Holodeck Architects*.

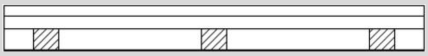
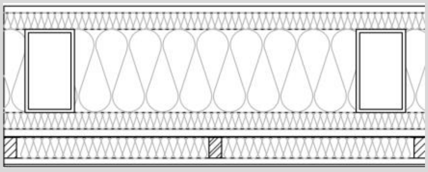
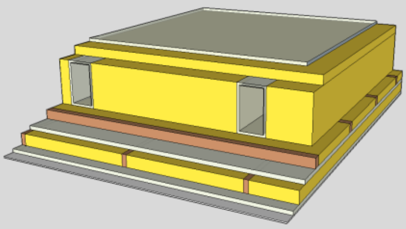
Hybrid system with steel and wood (HS)			
	10 mm	Roof tiles	
	30 mm	Battens	
	50 mm	Ventilated air layer between counter battens	
		Rain and wind protection foil	
	16 mm	MDF plate	
	100 mm	Glass wool insulation between battens	
	200 mm	Mineral wool insulation between steel profile	
	100 mm	Glass wool insulation between battens	
	20 mm	MDF plate	
	2 mm	Vapor barrier PE	
	50 mm	Mineral wool insulation between battens	
	15 mm	Fire protection plasterboard	
	5 mm	Gypsum plaster inside	
	59,8	cm	Total thickness
	0,169	$W.m^{-2}.K^{-1}$	U-Value
	48,55	$kJ.m^{-2}.K^{-1}$	Heat Storage
	138,1	$Kg.m^{-2}$	Weight

Figure 17: Hybrid system with steel and wood elements

3.2.4 Concrete construction

For concrete roof solutions, the increase of the thermal resistance contributes to cool down the ceilings during the daytime in summer conditions (Tong et al. 2014). This technology is hardly implemented in Vienna due to existent buildings' regulations on heavy structures. However, some attic examples can be found with prefabricated reinforced concrete structures (Kirchmayer et al. 2011).

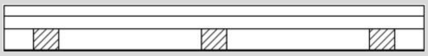
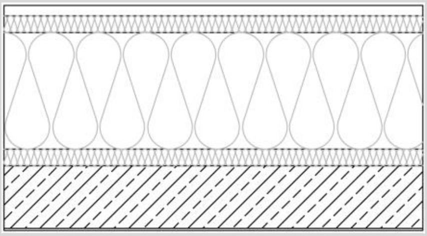
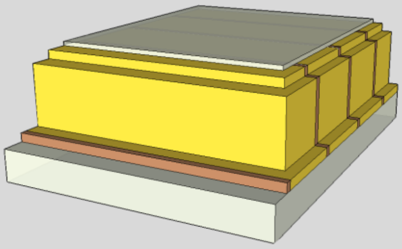
Reinforced concrete (RC)			
	10 mm 30 mm 50 mm	Roof tiles Battens Ventilated air layer between counter battens Rain and wind protection foil	
	25 mm 40 mm 280 mm 40 mm 150 mm 5 mm	MDF plate Glass wool insulation between battens Mineral wool insulation between battens Glass wool insulation between battens Reinforced concrete Gypsum plaster inside	
	63,0 0,103 268,91 499,3	cm W.m^{-2}.K^{-1} kJ.m^{-2}.K^{-1} Kg.m^{-2}	Total thickness U-Value Heat Storage Weight

Figure 18: Reinforced concrete construction

3.3 Thermal performance analysis

3.3.1 Reference building

The different details were analyzed for a typical residential building from 1889 in the 1st district of Vienna. The building has 5 floors, a two-level basement and the possibility of performing an attic extension. The building has two blocks: a north-south oriented block with a maximum level of approximately 28 m, and the back block with east-west orientation of approximately 23 m height (Figure 19).

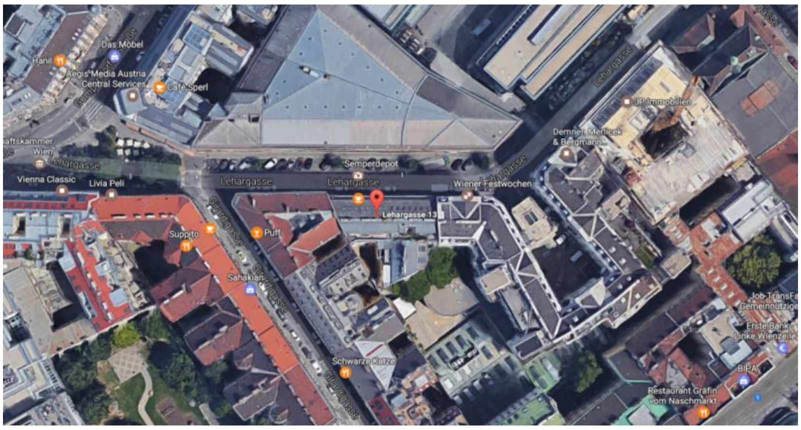


Figure 19: Location of the reference building

In Figure 20 and Figure 21, the plans and sections of the renovated attic are shown. The renovation from 1998 was taken as a reference for the design of the attic extension (roof and windows design and room arrangement). The existent ceiling and wall materials are unknown. Nevertheless, according to the year of construction it can be assumed that the building's façade is made of stucco, solid-brick for the outside walls and a "Dippelbaumdecke"[7] for the ceiling. The requirements from chapter 2.1 were considered for the window design, slope of the roof and heights.

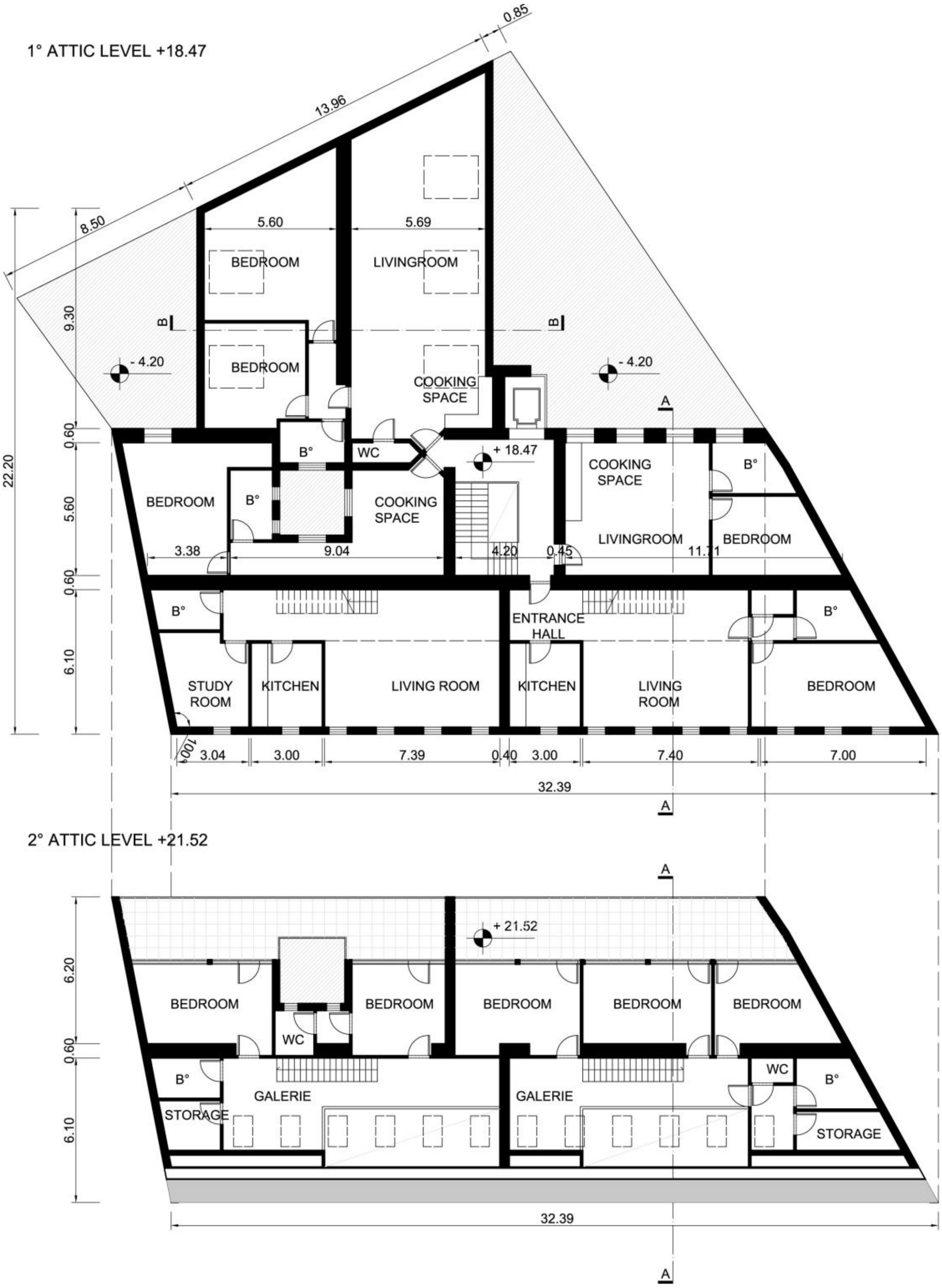


Figure 20: Attic extension in Lehargasse 13, 1060, Vienna. Plans of 1° and 2°attic levels.

[7] Typical wood ceiling construction for "Gründerzeit" buildings in Vienna.

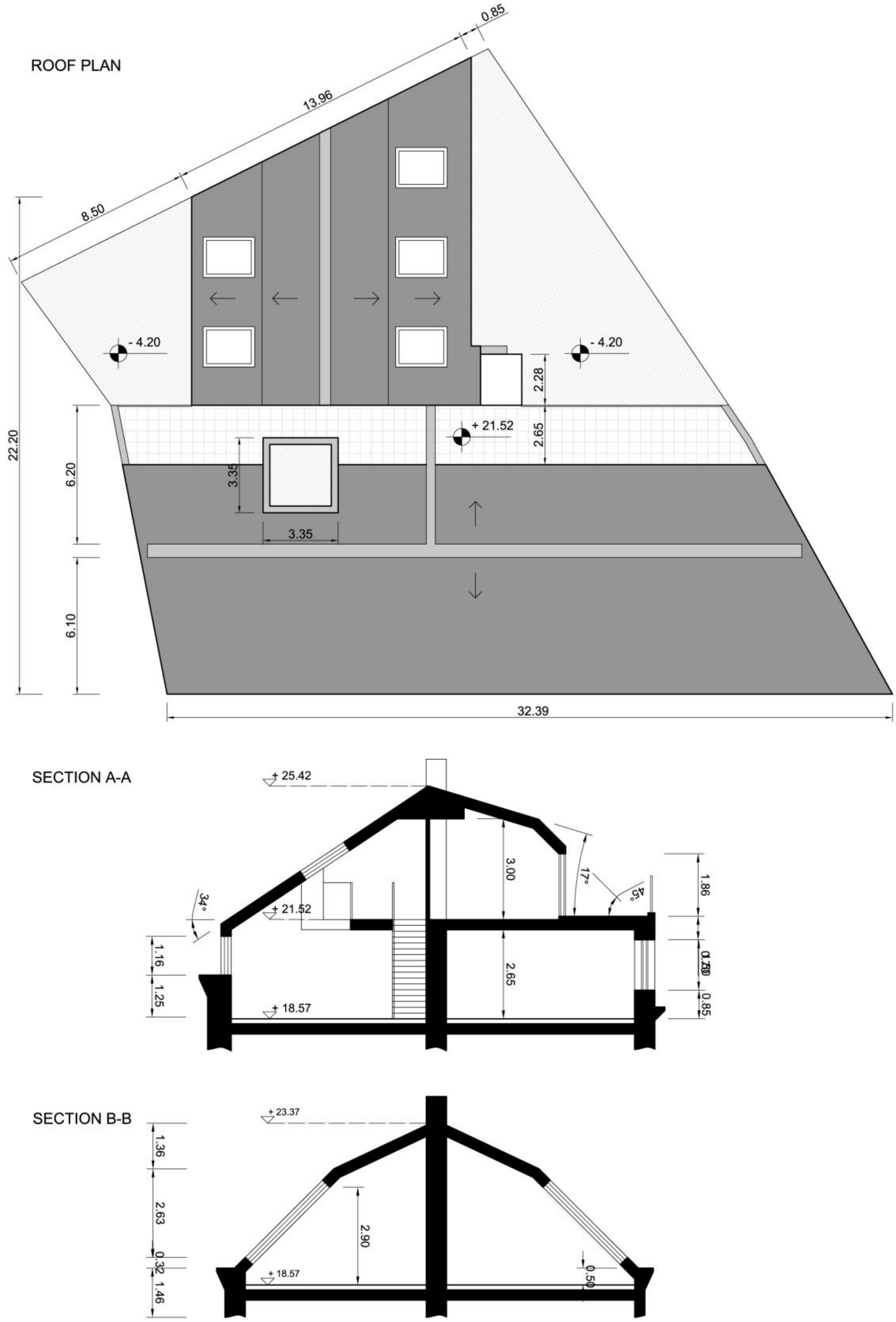


Figure 21: Attic extension in Lehargasse 13, 1060, Vienna. Roof plan and sections.

The attic roof was divided in six zones according to the use and the different apartments (Figure 22). The heating demand was analyzed for the whole building, while the summer overheating analysis was evaluated on the different zones separately. All the zones are conditioned with exception of the green zone which corresponds to the building staircase (zone 4).

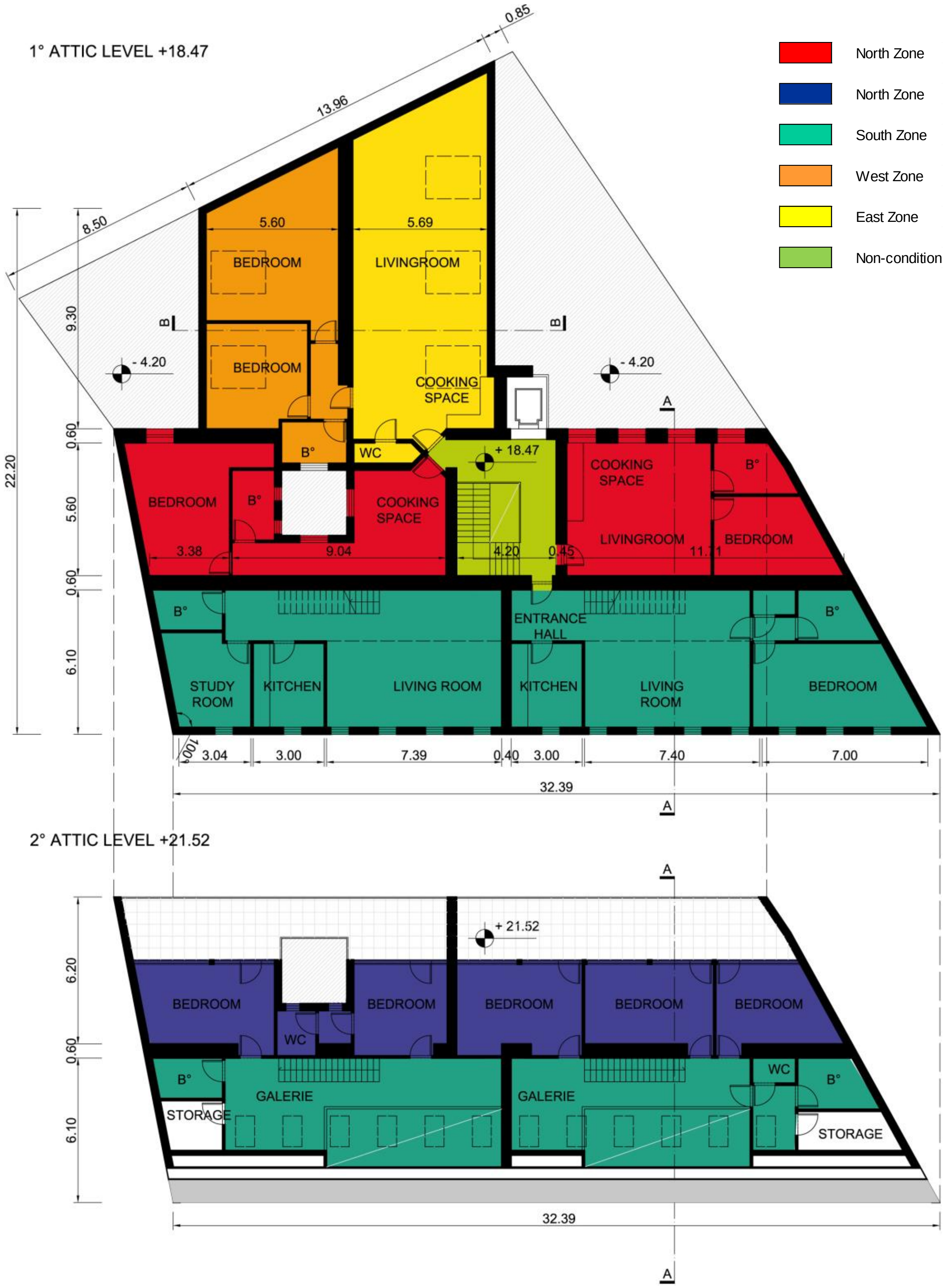


Figure 22: Different zones in attic extension in Lehargasse 13, 1060, Vienna

3.3.2 Weather data

The weather data corresponds to the city of Vienna and is a “typically year” weather file taken from Energy Plus (EnergyPlus 2018). In Figure 23, the annual outside temperatures are shown. The gray area shows the summer period considered for the simulation (05/01-09/30) while the white area corresponds to the winter period (01/31-04/30; 10/01-12/31).

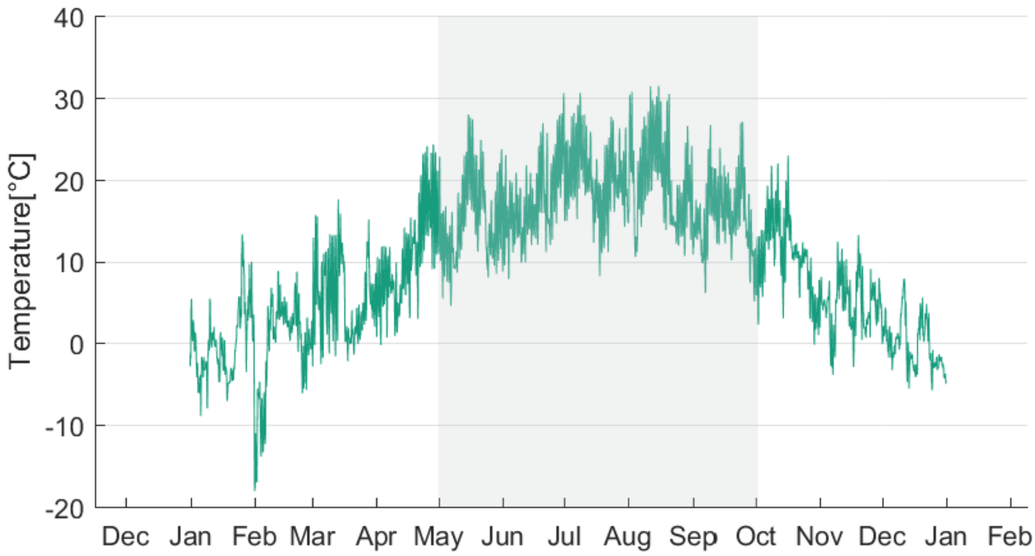


Figure 23: Vienna’s weather data (EnergyPlus 2018)

3.3.3 Internal gains, ventilation and shading

The internal gains (Table 2) were taken from Austrian Standards ÖNORM B 8110-3: 2012 03 15 and Austrian Standards ÖNORM B 8110-6 Bbl 1: 2015 11 15 for residential use for summer and winter periods, respectively. The values for winter are according to a weighting calculation based on the annual average values for internal loads (3,75 W.m-2).

The ventilation rates (Table 3) for summer were taken from Austrian Standards ÖNORM B 8110-3: 2012 03 15. In order to capture a more realistic occupant behavior for the window operation in the winter period, the ventilation rates were taken from the Passivhaus Institut (Passivhaus Institut 2015). According to Feist (2003) at least four intermittent airing from 5 to 10 minutes with the window totally opened during the day guaranties occupant’s comfort in a healthy environment. In order to represent a realistic occupant daily schedule, two daily intervals of 10 minutes were assigned before and after working hours (8:00 and 17:00). The detailed ventilation rates for each thermal zone are shown in Table 18 from the Appendix.

Table 2: Summer and winter values for internal loads

	Internal Loads [W.m^{-2}]	
Daytime (until h)	Summer (ONORM 8110-3:2012)	Winter (ONORM 8110-6)
1:00	5,52	2,80
2:00	5,43	2,75
3:00	5,56	2,82
4:00	5,56	2,82
5:00	6,37	3,23
6:00	9,52	4,82
7:00	8,85	4,48
8:00	9,00	4,56
9:00	7,78	3,94
10:00	7,24	3,67
11:00	6,61	3,35
12:00	5,04	2,55
13:00	4,41	2,23
14:00	6,15	3,12
15:00	8,18	4,14
16:00	9,12	4,62
17:00	10,52	5,33
18:00	10,47	5,31
19:00	10,02	5,08
20:00	9,12	4,62
21:00	8,08	4,09
22:00	6,87	3,48
23:00	6,46	3,27
0:00	5,74	2,91
Average	7,40	**3,75**
Max value (100%)	**10,52**	5,33

Table 3: Summer and winter values for ventilation rate

	Ventilation rate [h^{-1}]	
Daytime (until h)	Summer (ONORM 8110-3:2012)	Winter (Passivhaus Institut)
9:00	0,56	2/24 hs; 6 h^{-1} in 10min (8:00-8:10; 17:00-17:10)
15:00	0,14	
19:00	0,42	

3.3.4 Building elements

The roof details were modelled as described in chapter 3.2. The exterior walls were modeled as with the same materials as the roof, with an outside plaster instead of the ventilated air gap and roof tiles. In the case of the ceiling, a retrofitted floor was built above the existent wooden slab; interior walls and neighbor walls were taken from Dataholz (2018). The details' building elements can be seen in Figure 49 from the Appendix.

3.3.5 Model assumptions

Each building material's properties (conductivity, density, thickness and storage capacity) needed as inputs to the model are specified in Table 17 from the Appendix. In order to model inhomogeneous materials, an average value – "virtual value" – was assigned according to the percentage of each material in the inhomogeneous layer. These materials are shown in Table 16 from the Appendix.

The ventilation layers under the roof tiles were modeled as still air with a resistance of 0,16 [$m^2.K.W^{-1}$], as they do not contribute to the thermal storage of the building element and they are smaller than 6-10 cm (Nusser and Teibinger 2013; Susanti et al. 2011), which means they do not represent a significant air flow.

According to Wurm (2016), the inclusion of night ventilation and shading in residential buildings has shown better results in terms of thermal behavior in the summer period. For that purpose, an exterior shading was modeled and the night ventilation – previously shown – was taken as an assumption to the model.

For a more realistic representation of the shading operation, a control system is regulated by sensor setpoints according to the indoor temperature (25°C) and the incident solar radiation on the window surface. In case of the solar radiation, an average value of 150 $W.m^{-2}$ was taken from different database sources. (Weiss; SolarGis)

The heating system was modelled as an ideal load system without limited capacity, which provides the necessary energy to meet the required setpoint. There is no active cooling for the model. For comparison purposes, an additional active cooling model was simulated with an ideal cooling system and a setpoint of 27°C.

Table 4 summarizes the assumptions which were taken for the model:

Table 4. Summary of assumptions for thermal model

Weather data	Vienna Running time: yearly
Seasons	Winter (01/31-04/30; 10/01-12/31) Summer (05/01-09/30)
Zones	5 conditioned; 1 unconditioned
Internal gains	Summer: ÖNORM 8110-3:2012 (See table 2) Winter weighted according to summer values with average value 3,75 $W.m^{-2}$, ONORM 8110-6 (See table 2)
Infiltration	Air exchange rate 0,3 h^{-1} (Zeller 2013) Running time: always
Shading	Exterior shade Running time: always (by sensors) System and control: indoor zone temperature setpoint 25°C and incident radiation on window setpoint 150 $W.m^{-2}$
Windows and frames	Double glazing (LoE) with argon 13mm System and control: according to ventilation rates
Inhomogeneous materials	Weighted conductivity, spedific heat and density
Ventilation	Summer: ÖNORM 8110-3:2012 (See table 3) Winter: Passive Haus Institut (See table 3) Running time: always System and control: natural ventilation
Heating	Zone heating Running time: always (by demand) System and control: ideal heating system and seatpoint 20°C (ÖNORM 8110-5)
Cooling	No active cooling

3.3.6 Scenarios and indicators

For purposes of analyzing the performance implications of the constructions' behavior, an additional baseline model with different ventilation assumptions was evaluated. In this case, the summertime natural ventilation is represented as an air economizer that introduces outdoor air to the building as high as 8 ACH when the outdoor air is cooler than the indoor air.

The thermal performance of the six details was evaluated and compared in terms of heating and cooling demand [$kWh.m^{-2}.a^{-1}$]. For the evaluation of the thermal comfort, an analysis of summer overheating was performed.

3.4 Ecological analysis

The Austrian OI3 (IBO GmbH) environmental indicator, drawn up by the Austrian Institute of Healthy and Ecological Building, was used for the comparison of the analyzed details. It is based on three environmental categories for different envelope boundaries: global warming potential (GWP), primary energy consumption from non-renewable energy sources (PEC n.r.), and acidification potential (AP).

The impact and relationship between the above-mentioned indicators is expressed by the $OI3_{KON}$ calculation for one square meter of a structure of building material (**Fehler! Verweisquelle konnte nicht gefunden werden.**) and the ΔOI3 for one layer of a building material (7), indicating by how many OI3 points the layer raises the $OI3_{KON}$ of structure.

$$\mathrm{OI3KON} = \frac{1}{3}\,\mathrm{OIPECnr} + \frac{1}{3}\mathrm{OIGWP} + \frac{1}{3}\mathrm{OIAP} \qquad (6)$$

$$\Delta\mathrm{OI3BS} = \frac{1}{3}\left[\frac{1}{10}(\mathrm{PECnr})\mathrm{BS} + \frac{1}{2}(\mathrm{GWP})\mathrm{BS} + \frac{100}{0{,}25}(\mathrm{AP})\mathrm{BS}\right] \qquad (7)$$

Furthermore, the OI3 results can be expressed according to different parameters: thermal building envelope ($OI3_{BGX}$) shown in 8, characteristic length ($OI3_{BGX,lc}$) shown in 9, gross floor area ($OI3_{BGX,BGF}$) and thermal retrofit ($OI3_{STGH}$).

$$\mathrm{OI3BGX} = \frac{\sum_{i=1}^{n} Ai \;\; . OI3\ KON, i}{\sum_{i=1}^{n} Ai} \qquad (8)$$

where $\sum_{i=1}^{n} Ai$ is the structure area
$OI3\ KON, i$ is the $OI3_{KON}$ of the i-th structure
Ai is area of the structures [m^2]

$$\mathrm{OI3BGX, lc} = 3\,.\frac{OI3BGX, lc}{(2 + lc)} \qquad (9)$$

where lc is the typical length of the building (Volume/Area)

The comparison of the details was analyzed in the previously described building. The following table summarizes the assumptions which were taken for the model:

Table 5: Summary of assumptions for ecological model

OI3 Standard	Material production - Cumulative step until shipping
Volume	2139,13 m^3
Total opaque building area	827,74 m^2
Total transparent building area	77,68 m^2
Characteristic length	2,36 m
Sources	Baubook / IBO
Definition	BG2 Boundary (envelope and interior walls)

The building materials were assessed by means of a cumulative-step life cycle assessment up to the shipment, including all processes upstream up to that point. *"For each step in the process, the material, transportation and energy inputs, as well as the emissions into the air, soil and water, and waste, are calculated. The downstream stages (sale, integration into buildings, etc.) are not assessed, as these depend on the place of sale, place of use and the chosen structure. Also, the disposal and recycling scenarios and reliable data as to the useful life of the products are lacking."* (IBO GmbH)

3.5 Cost and time analysis

The cost analysis considers only the building costs, excluding the categories mentioned in chapter 2.5.2. The Calculation Atlas (WEKA 2014) was used for the calculation of the cost and construction time. For each building category (concrete, steel, dry construction, etc.) the correspondent values for time, materials' cost, salary, machinery's cost and external (contracted) services are assigned.

The total cost values of each detail were calculated per m^2 by summing each layer's cost which constitutes the detail. The comparison is focused on the main structure elements. The waterproofing and roofing – including battens and insulation above the rafters – were not considered for the calculation of the costs as they are common for all details. Windows, connections, installations, joinery and special joints were not taken into consideration. All values are net prices.

4 RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the results and findings of the different evaluations are shown. In chapters 4.2, 4.3 and 4.4 the findings of the thermal performance, ecological and cost analysis are described, respectively. In chapter 4.5 the possible sources of error due to uncertainties are discussed. In chapter 4.6, a general comparison between the categories' evaluation is shown.

4.2 Comparison thermal performance

4.2.1 Scenarios

Before analyzing the thermal performance of the details, a comparison of two baseline models – explained in chapter 3.3.6 – was performed: a ventilation system with an air economizer (model 1) and a natural ventilated building (model 2). A comparison between the models was performed in the summer period for the lightweight with mineral wool insulation detail in both cases (Figure 24). In terms of indoor temperatures, the model with the air economizer showed a higher value of frequency of temperatures from 25°C to 27°C, while the natural ventilated model showed higher values of frequency of temperatures above 28°C, representing a 500% increase of values in comparison to model 1.

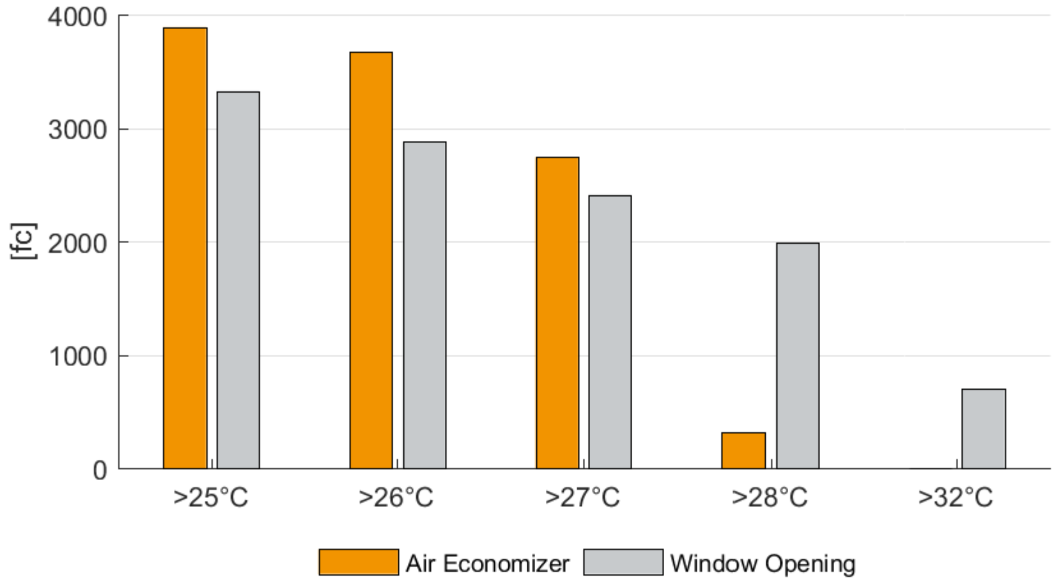


Figure 24: Temperature frequency in summer period for both models, west zone, TWI detail

When comparing the temperature frequency above 28°C in kelvin hours between all assemblies (Figure 25), the model 1 – assuming a higher ventilation rate – has shown better performance in terms of lower values of temperature frequency above the threshold value.

Moreover, the profile of temperatures in both models showed differences on the behavior of the hybrid system and the reinforced concrete. In model 1, the impact of the heat storage capacity of the reinforced concrete detail is higher than in the model 2 (lower ventilation rate), as its high thermal mass allows maintaining low indoor temperatures influenced by an effective cooling during nighttime. The steel construction behaves similarly to the wood lightweight details in the model with higher ventilation rate. In this case, the influence of the ventilation rate on indoor temperatures is higher than the building materials' behavior.

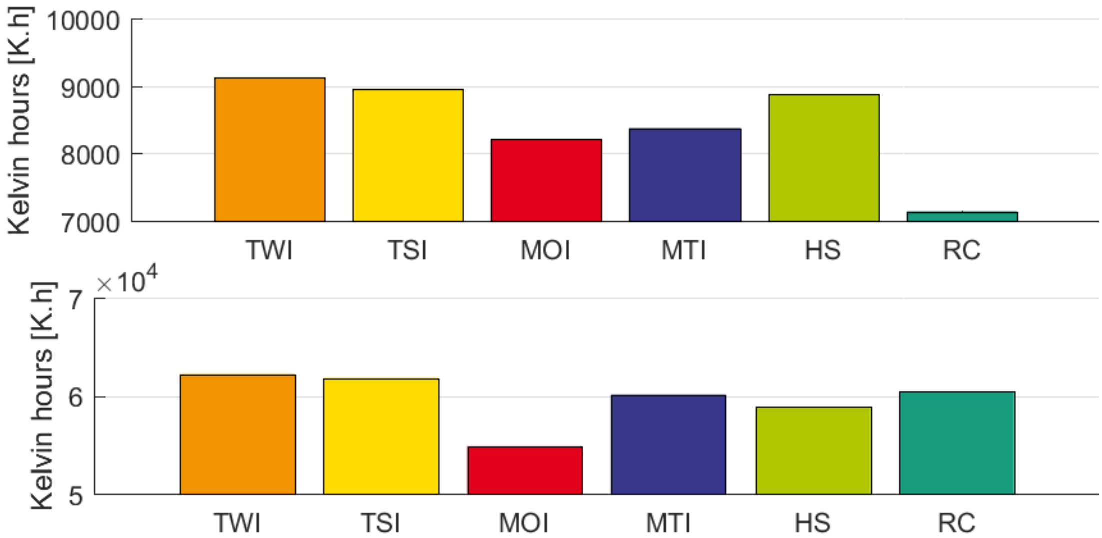


Figure 25: Temperature frequency above 28°C in summer period in west zone for model with air economizer (top) and natural ventilation (bottom) in Kelvin hours [K.h]

The variation of each detail from the mean value and the increase between the lowest and highest values in each model are shown in Table 6. The increase in model 1 is almost the double in comparison to model 2 (28 and 13% respectively). In the model 1, the reinforced concrete has the lowest value with a difference of approximately 1.000 K.h from the massive wood with one insulation layer and a variation from the mean value of -15%. In contrast, in model 2 the massive wood with one insulation layer has the lowest value with a variation of -8% from the mean value.

Table 6: Temperature frequency values, variation from mean value and increase between details for model 1 and 2 for all assemblies

Details	Air Economizer [K.h]	Variation [%]	Natural ventilation [K.h]	Variation [%]
TWI	9.129,00	8%	62.202,00	4%
TSI	8.959,00	6%	61.825,00	4%
MOI	8.206,00	-3%	54.846,00	-8%
MTI	8.373,00	-1%	60.122,00	1%
HS	8.878,00	5%	58.884,00	-1%
RC	7.140,00	-15%	60.455,00	1%
Mean	**8.447,50**		**59.722,33**	
Increase	**28%**		**13%**	

In Figure 26, a comparison of the annual heating and cooling demands for each construction detail is shown. In terms of heating demand values, the increase from model 1 to model 2 is between 10-30%, and in terms of cooling demand values is between 300-340%.

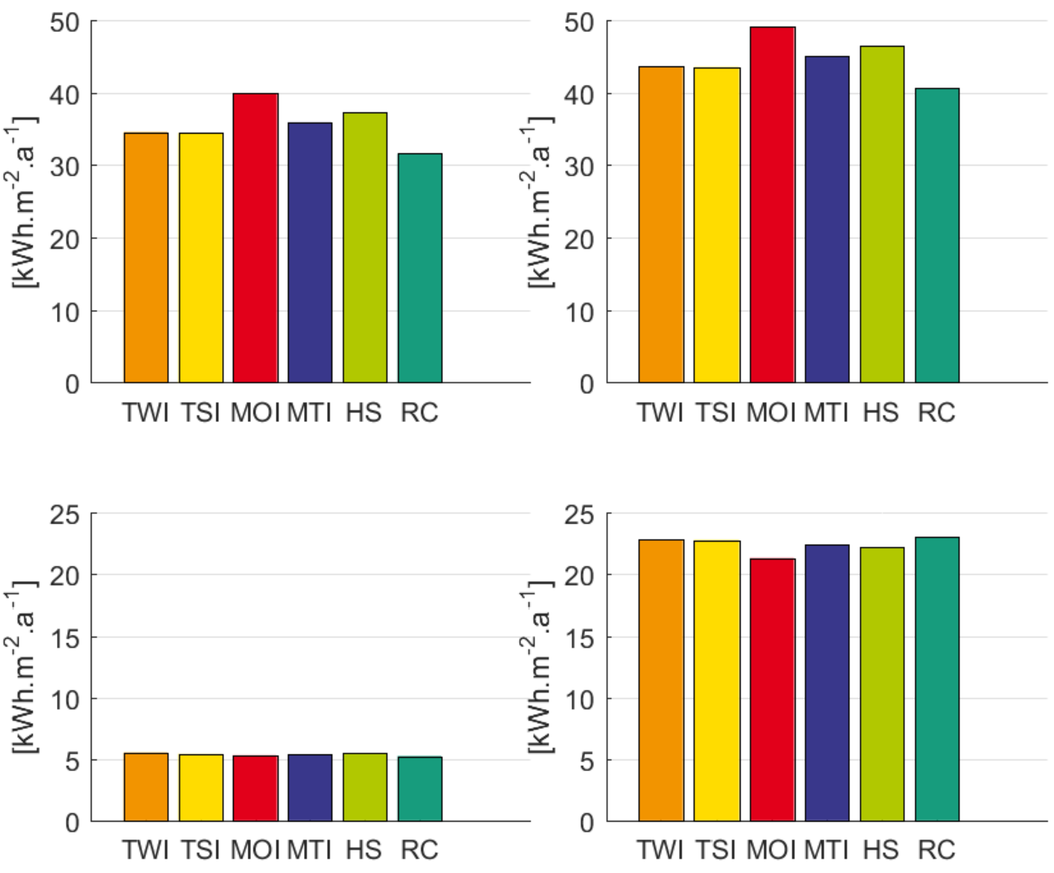


Figure 26: Annual heating demand for model 1 (left, top) and model 2 (right, top) and annual cooling demand for model 1 (left, bottom) and model 2 (right, bottom)

The performance of each construction detail is different according to the ventilation rate that is considered. **In this sense, the ventilation assumption can have high implications – especially in the summer period – in such an extreme scenario, like using an air economizer.**

For the comparison of the details, the natural ventilated model was taken as the baseline model. Even though the indoor summer temperatures are considerably higher in comparison to the model with the air economizer, mechanical ventilation is not commonly used in attic extensions, so the window operation represents more realistically the dwellings' ventilation strategy.

4.2.2 Heating and cooling demand

In Figure 27 the heating demand of the attic space enclosed by specific construction assemblies was calculated. The heating demand with the reinforced concrete roof is the lowest one with 40,63 $kWh.m^{-2}.a^{-1}$ which represents a 9% reduction from the mean value, while the highest heating demand corresponds to the massive wood with one insulation layer detail with 49,03 $kWh.m^{-2}.a^{-1}$ which represents a 10% increase from the mean value and an approximately 20% increase from the reinforced concrete value. In Table 19 from the Appendix, values for the annual heating and cooling demand are shown.

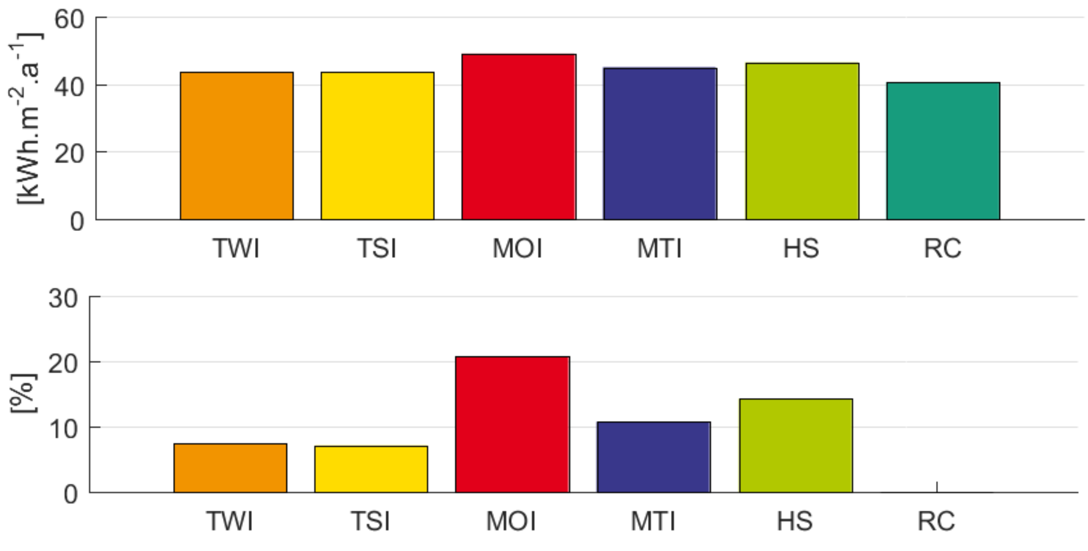


Figure 27: Annual heating demand of the different building elements, all zones (top); Comparison to RC – Increase (bottom)

In case of including an active cooling (Figure 28), the lowest cooling demand corresponds to the massive wood with one insulation layer detail with 21,23 $kWh.m^{-2}.a^{-1}$, while the reinforced concrete roof has the highest value with 22,96 $kWh.m^{-2}.a^{-1}$, which represents a 3% increase from the mean value and an approximately 7,5%

increase from the massive wood with one insulation layer. In contrast to the heating demand, there are no significant differences in terms of cooling (8% variation from the lowest and the highest values).

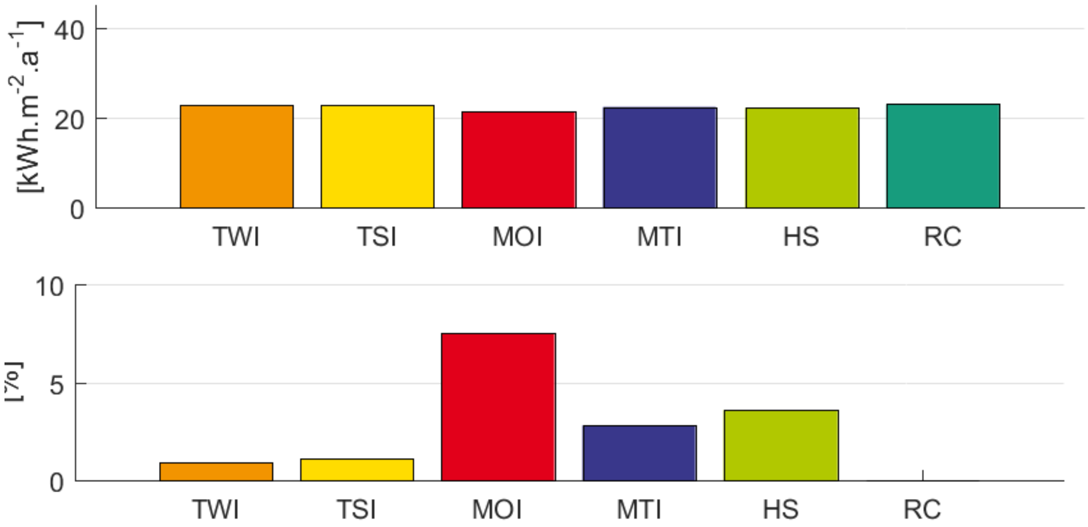


Figure 28: Annual cooling demand of the different building elements, all zones (top); Comparison to RC – Decrease (bottom)

The thermal analysis has shown that in terms of heating demand the values range between 40 and 49 kWh.m^{-2}.a^{-1}, which corresponds to a "category B" in accordance to the Austrian energy standards. The relatively low values can be explained as all details are in accordance to the minimum required U-values for building elements, ranging from 0,103 to 0,203 W.m^{-2}.K^{-1} for the roof details (Table 7).

Table 7: Heating demand and cooling demand of the attic space enclosed by specific construction assemblies, and U-value of all assemblies

Details	Heating demand [kWh.m^{-2}.a^{-1}]	Cooling demand [kWh.m^{-2}.a^{-1}]	U-Value [W.m^{-2}.K^{-1}]
TWI	43,63	22,75	0,134
TSI	43,52	22,70	0,135
MOI	49,03	21,23	0,203
MTI	44,99	22,31	0,152
HS	46,41	22,13	0,169
RC	40,63	22,96	0,103

In Figure 29 the linear relationship between the U-values and the heating and cooling results is shown. The better the U-value, the lower the heating demand and the higher the cooling demand. In the case of the cooling, the linear relationship shows a slightly different behavior of the reinforced concrete detail and the hybrid system.

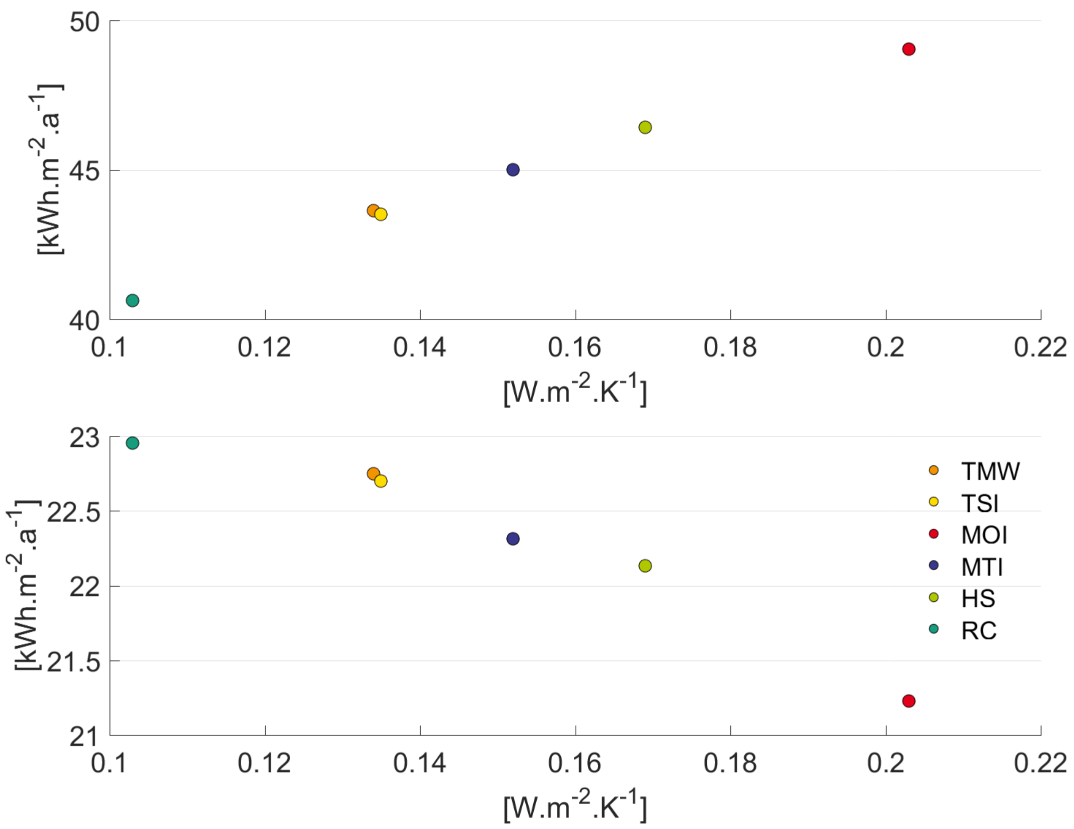


Figure 29: Comparison annual heating demand (top) and cooling demand (bottom) with U-values for all assemblies

4.2.3 Thermal comfort

The summer overheating was analyzed for the thermal zones facing south and west orientation, as they have the highest impact of solar radiation on the roof construction. (Jayasinghe et al. 2003)

For the evaluation of the thermal comfort, a threshold value of 28°C was taken for the indoor temperature and a comparison of the frequency values in kelvin hours above that threshold was calculated (Figure 30).

The reinforced concrete detail and both lightweight constructions show the highest values of temperature frequency above 28°C in both orientations, while the massive wood with one insulation layer shows the lowest value of temperature frequencies in kelvin hours. These results are consistent with the above-mentioned results for the cooling demand.

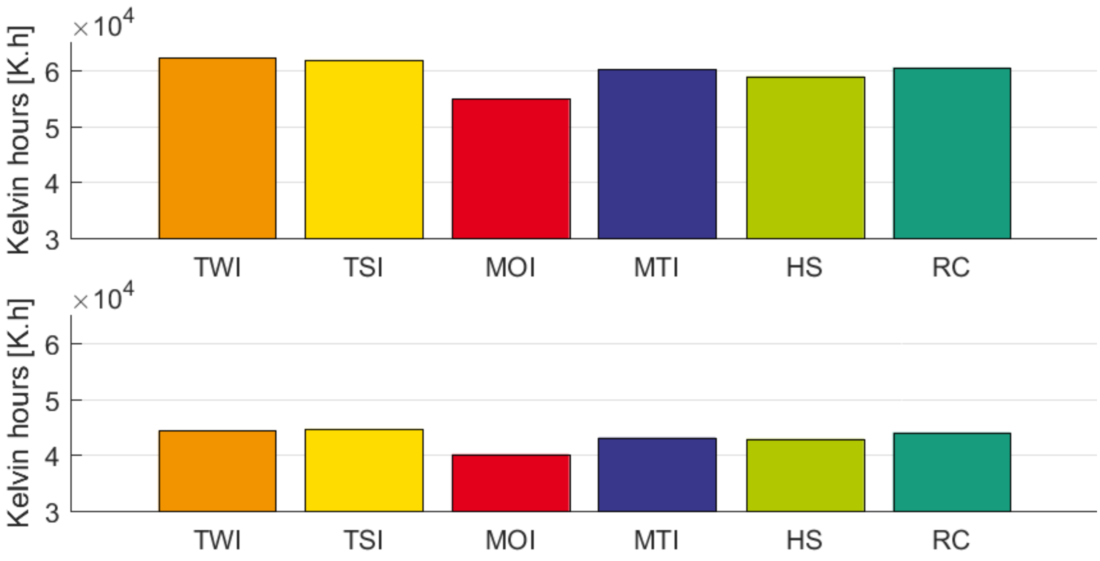


Figure 30: Temperature frequency above 28°C in west zone (top) and south zone (bottom) in kelvin hours [K.h]

The cumulative distribution function's profile for the temperatures' frequencies on the west and south orientations are shown in Figure 31 and Figure 32. In the west zone, 80% of the temperature values are lower than 31°C and the highest reached temperature is 37°C, while in the south zone 80% of the temperature values are below 29°C and the highest reached temperature is 34°C.

All details shown a similar distribution in each orientation, expect from the reinforced concrete detail. The temperatures below 26 and 28°C (south and west orientation, respectively) of the reinforced concrete detail showed lower values of frequency in comparison to the other details. In that sense, the reinforced concrete maintains indoor temperatures more constant (between 28°C and 33°C for west orientation and 26°C and 30°C for south orientation) in comparison to the other details.

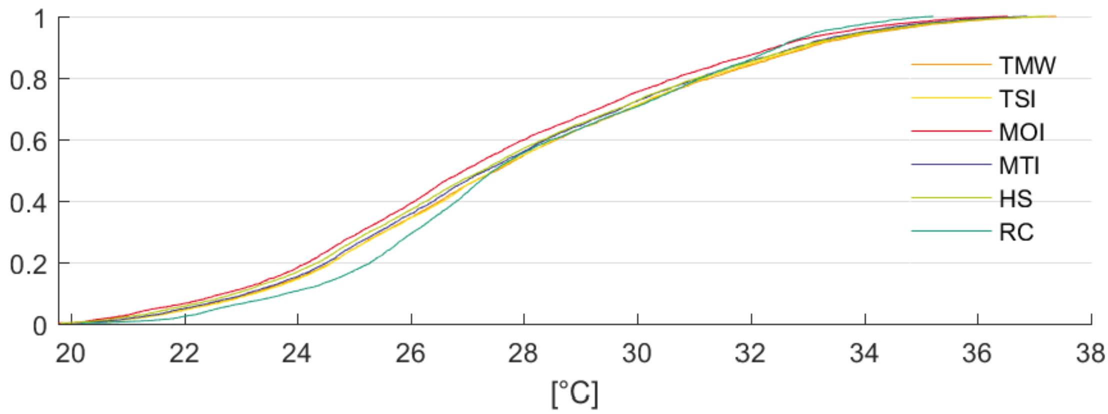


Figure 31: Cumulative distribution frequency of temperatures in summer period for west zone

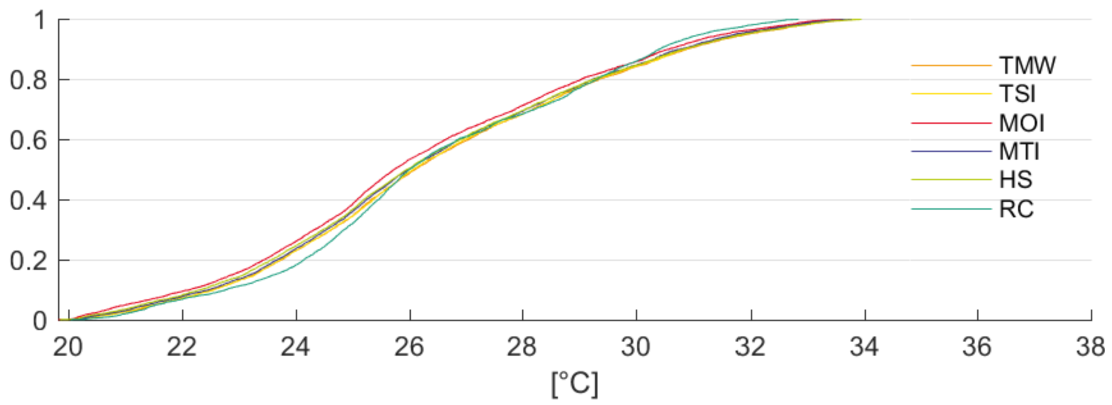


Figure 32: Cumulative distribution frequency of temperatures in summer period for south zone

In order to see the behavior on the hottest period of the year, a comparison of the temperature variation for west and south orientations was performed on the week from 8th to 18th August (Figure 33 and Figure 34). The profiles from zones north and east are shown in Figure 50 from the Appendix.

Although indoor temperatures on the west zones reach 37°C while on the south zone do not exceed 33°C, the temperature profiles from all constructions are similar in both orientations. However, the west zone shows more daily temperature fluctuations in all details than the south zone. **Namely, the roof orientation impacts mostly on indoor temperatures and each detail's profile rather than on the constructions' performance, due to the incident solar radiation**.

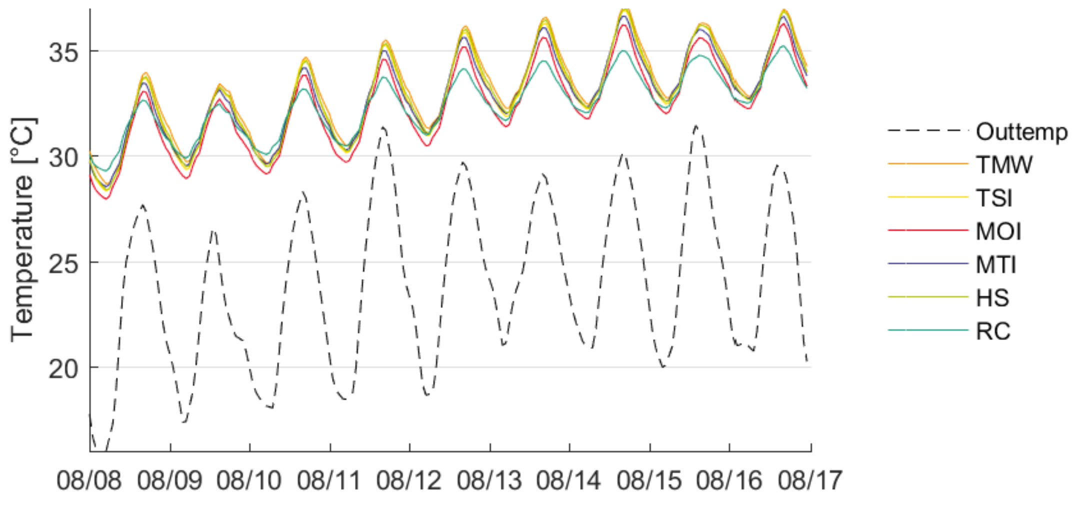


Figure 33: Temperature variation in hottest week for west zone

All details show similar behavior, expect from the reinforced concrete which has the profile with less fluctuations, especially with higher outdoor temperatures. The massive wood with one insulation layer detail has the lowest temperatures during night and the reinforced concrete during day.

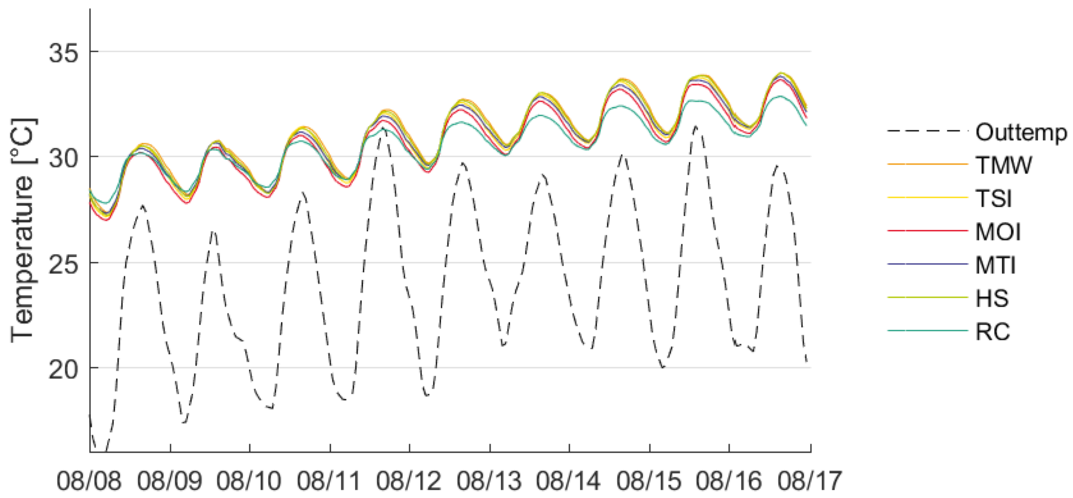


Figure 34: Temperature variation in hottest week for south zone

The temperature difference profile with reference to the reinforced concrete detail evaluated in the same week for the south orientation is shown in Figure 35 (the profiles from zones north and east are shown in Figure 51 from the Appendix). In general, the differences are not significantly high, showing a maximal difference of almost 1,4°K. However, some aspects on the constructions' behavior can be observed.

When the minimum outdoor temperature is lower than approximately 28°C – from 8th to 11th as seen in Figure 33 and Figure 34 –, all details have slightly lower temperatures during the night than the reinforced concrete detail, showing the latter higher temperatures. On the contrary, when the outdoor temperature is higher than 28°C during the day and higher than 20°C during the night, the reinforced concrete shows the lowest temperatures.

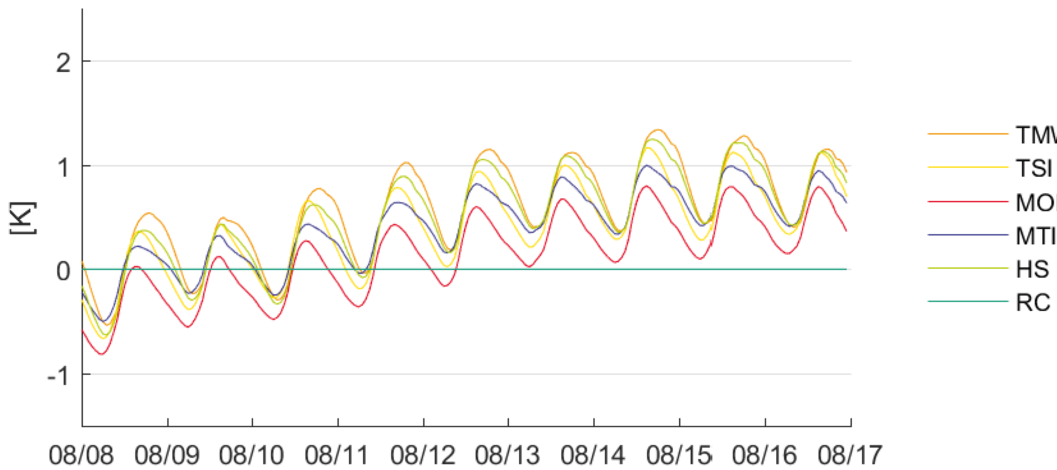


Figure 35: Temperature difference to RC (reference) in hottest week for south zone

As previously mentioned, the west orientation shows more daily fluctuations. Those fluctuations can be seen clearly seen in Figure 36, where the differences are higher than in the south zone, reaching 2°K in the hottest days.

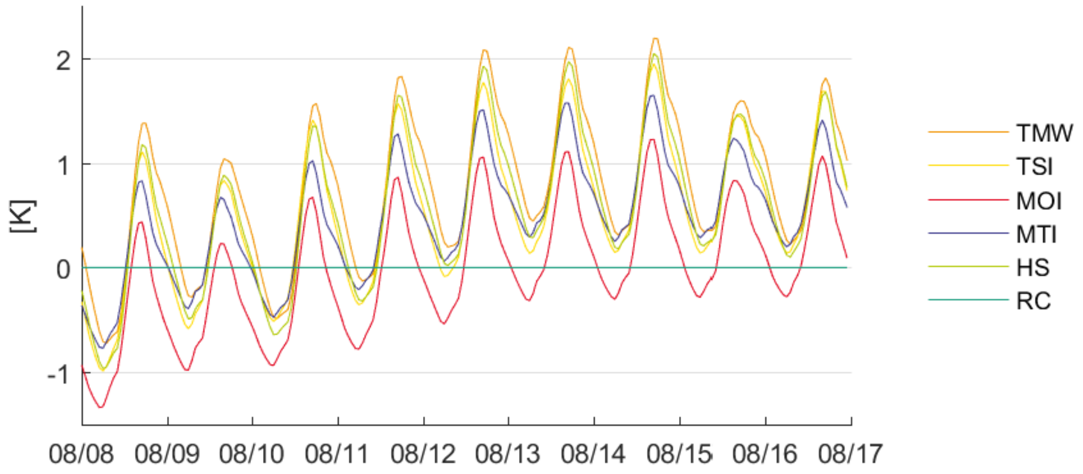


Figure 36: Temperature difference to RC (reference) in hottest week for west zone

In both orientations, can be seen that both massive wood constructions show a similar profile among them, as well as the three lightweight constructions between themselves. The behavior of the hybrid system is slightly different in comparison to those details. During night, it reaches lower temperatures than the massive wood with two insulation layers (with better U-value), but during the day it reaches higher temperatures than most of the details with worse U-value.

As seen before, there is a linear relationship between the cooling demand and the U-values of the roof details, with a slight difference in the case of the hybrid system. As a matter of fact, the steel beams in the hybrid system have a higher thermal diffusivity (See chapter 2.2.1) which allows the construction to release the heat faster during the night and increase temperature faster during the day, showing consequently the highest fluctuations.

In Figure 37 a daily profile comparison on a typical day (12^{th} August) can be seen. In general, wood constructions show the same temperature profile but with different temperatures. The main difference can be seen in the reinforced concrete's profile, due to its storage capacity (268,91 $kJ.m^{-2}.K^{-1}$), which is almost 5 times higher than the other details, and consequently experiencing the less temperature fluctuations.

Furthermore, when the temperature is starting to rise around 7:00 am all details show almost the same temperatures until midday when outside temperatures exceed approximately 28°C. From that point until the cooling period, the details behave differently and the impact on the indoor temperature of the materials' properties (U-value, heat storage capacity and thermal diffusivity) can be seen.

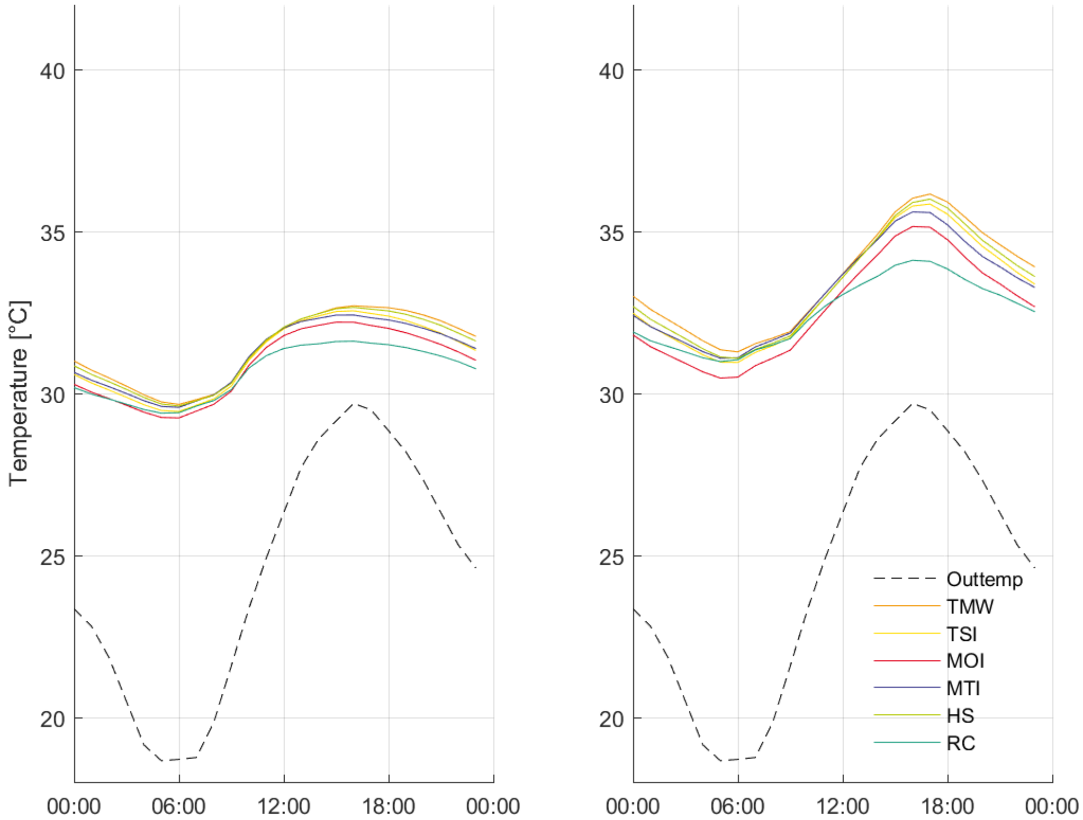


Figure 37: Daily temperature profile for south zone (left) and west zone (right)

Even though the performance of the details has shown different behaviors in the temperature profile, **there are no significant indoor temperature differences between the details, showing a maximal difference of 2°K along the summer days**.

4.3 Comparison ecological performance

As mentioned before, the assessment though the OI3 evaluation (Austrian standard) is focus on the material production. The results of the general OI3 evaluation show values between 8 and 22 points (Figure 38). This evaluation can be interpreted in a similar way as the scale for energy certificates, where values around 15 points correspond to an "acceptable" building performance. The wood lightweight with straw insulation has the best result with 8 points, followed by the wood lightweight with mineral wool insulation (13 points). Both massive assemblies have the same values (15 points), while the hybrid system and the reinforced concrete have the worst results in comparison to all assemblies (20 and 22 respectively).

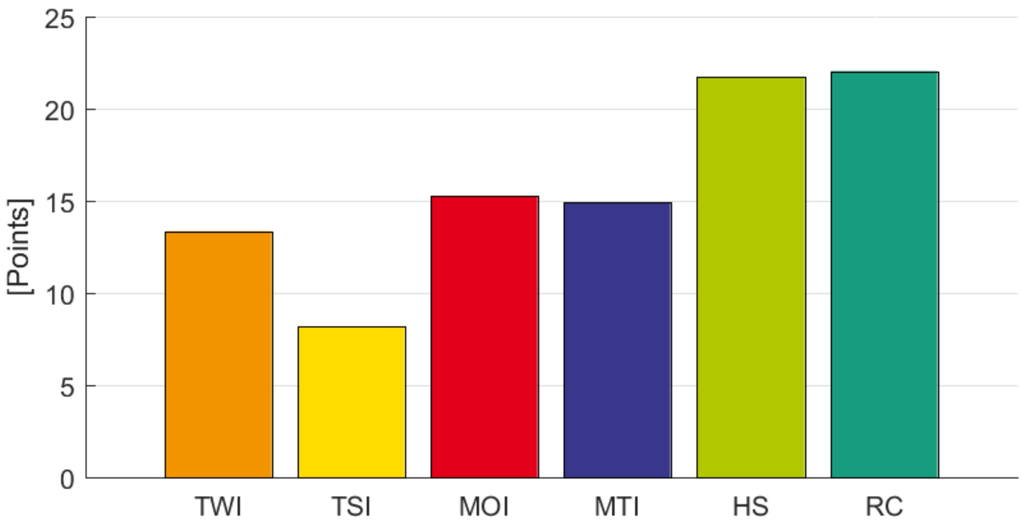


Figure 38: General OI3 evaluation for all assemblies

In general, wood details have shown lower ecological impact in comparison to steel and concrete. Even though the building study cases differ from each other, the results are consistent to previous works' results, such as Asdrubali et al. (2017) and Pajchrowski et al. (2014). **Wood and wood-based materials have shown a positive environmental impact on the production stage ("cradle-to-gate")**.

The evaluation was also analyzed for each indicator separately. In terms of Primary Energy Content (PEC n.r.), the massive wood construction with one insulation layer shows the highest value with 2.120.658 MJ, and the lower values correspond to both timber wood constructions (mineral wool and straw insulation) with 1.842.089 and 1.811.983 MJ (Figure 39) which represent a decrease of 13-15%.

In this last case, the impact of the straw on the timber wood construction reduces the PEC n.r value by approximately 30.000 MJ. Similarly, there is an impact of the insulation on the two massive wood constructions. By incorporating two insulation layers and reducing the thickness of the cross laminated timber structure, the total PEC n.r. decreases by 7%.

In general, the impact of wood structures is higher than the insulation layers – either straw or mineral wool. Moreover, both steel and reinforced concrete structures show relative high values in comparison to lightweight wood structures.

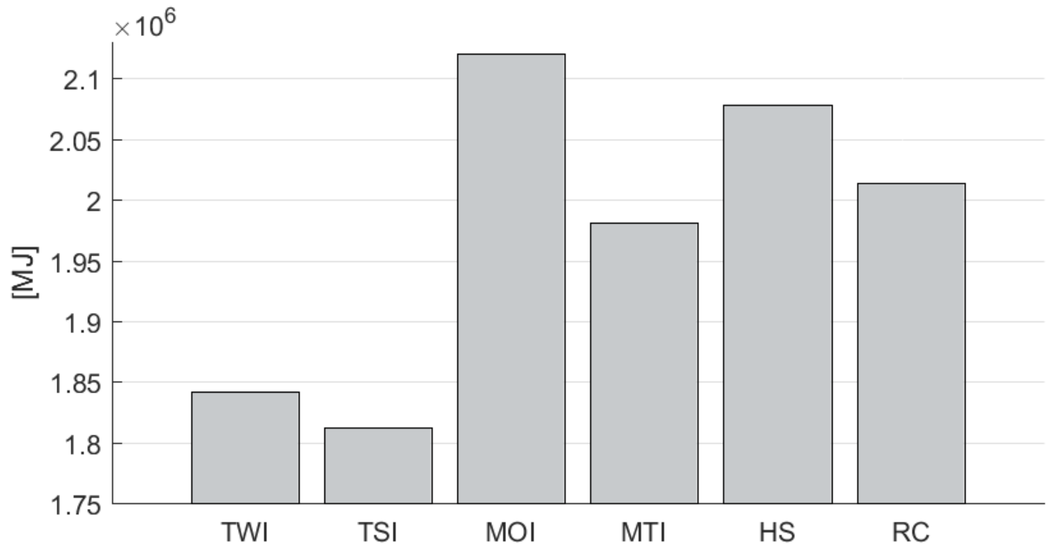


Figure 39: Primary energy content non-renewable (PEC n.r.) for all assemblies

Contrary to the PEC n.r., the massive wood with one insulation layer (MOI) shows the best results in terms of Global Warming Potential (GWP). The reinforced concrete detail has the worst result with -126 tons, which represents an increase of 47% in comparison to the MOI detail (Figure 40). In the same comparison, both hybrid system and timber wood with one insulation layer show a similar impact on the GWP of approximately 41-43%; the timber wood with straw insulation and the massive wood with one insulation have also a similar behavior.

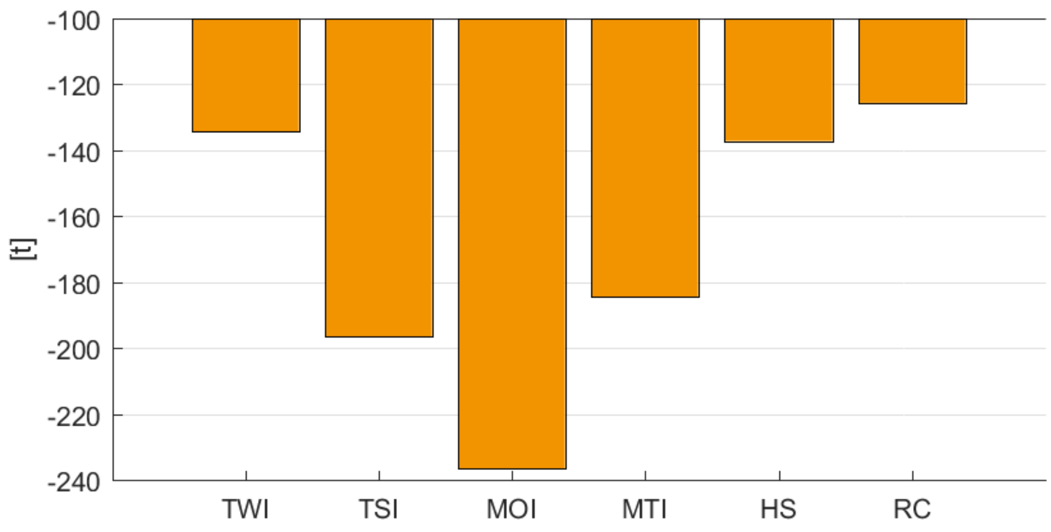


Figure 40: Global warming potential (GWP) for all assemblies

Generally, the incorporation of the mineral wool layer in lightweight constructions has a higher impact in terms of GWP (-134 tons for TWI and -137 tons for HS) in comparison to straw insulation (-196 tons for TSI) and massive constructions (-236 tons for MOI and -184 tons for MTI).

The Acidification Potential (AP) evaluation shows a similar profile and percentages decrease as the PEC n.r. (Figure 41). The MOI has the highest value with 490 kg, while the best results correspond to the wood lightweight constructions with 405 and 417 kg, which means a 15-17% decrease in comparison to the highest value from the MOI. The reinforced concrete has also a high value (473 kg). In general, the AP has a higher impact on massive constructions (massive wood and reinforced concrete).

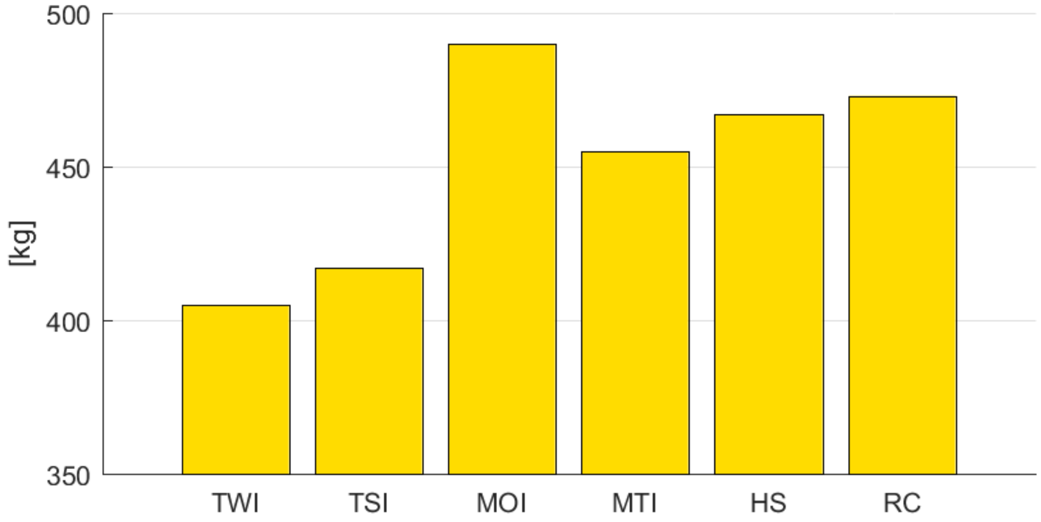


Figure 41: Acidification potential (AP) for all assemblies

In order to analyze the impact of all three indicators in the whole building, all values were compared in terms of points according to **Fehler! Verweisquelle konnte nicht gefunden werden.**. Figure 42 shows the points for each indicator in the different assemblies. The red bars are the total OI3 points previously shown in Figure 38.

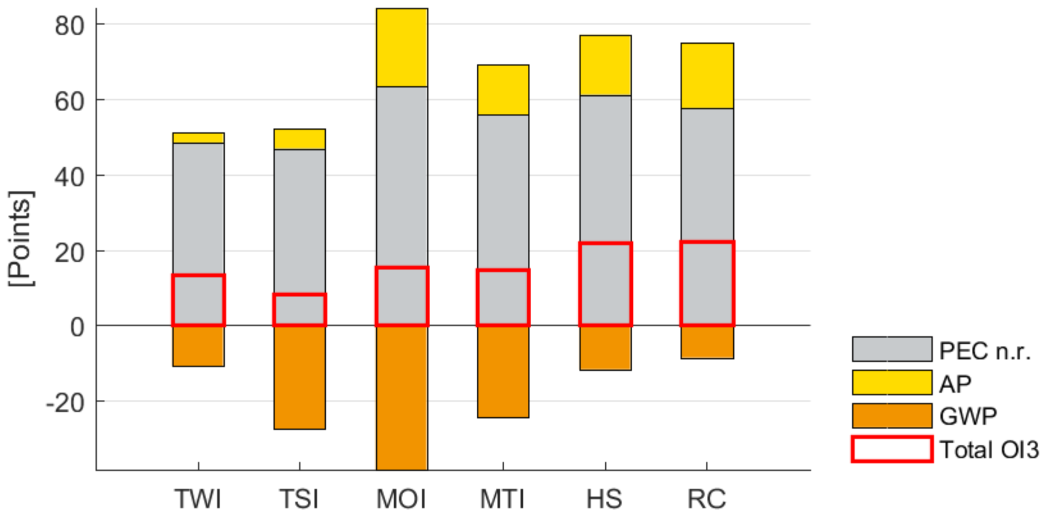


Figure 42: OI3 evaluation of the 3 indicators for all assemblies

In general, the absolute impact of the PEC n.r. is the highest of all indicators, but the values do not vary more than +/-15% between constructions. The AP and GWP values have a lower absolute impact but higher relative variation between assemblies (Table 8). As mentioned before, **the overall OI3 values for all assemblies have shown absolute low results in terms of ecological impact, despite the relative variation between assemblies reaches 87%.**

Table 8: Absolute and relative impact of different assemblies.

Impact	PEC nr [point]	GWP [point]	AP [point]	Total OI3 [point]
Absolute	55	-20	12	16
Relative	30%	53%	125%	87%

In Figure 43 the impact of the layers that vary between each detail was analyzed. The layers' selection and the detailed calculation is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** from the Appendix. On an individual calculation, the steel from the hybrid system has a higher value (approximately 131 points) in comparison to the rest of the details (between 16 and -33 points). However, in the overall evaluation (Figure 38) the impact of each material is compensated by its relative percentage, and the performance of the details is not highly different. In **Fehler! Verweisquelle konnte nicht gefunden werden.** from the Appendix all values of the OI3 evaluation and the OI3 indicators are shown.

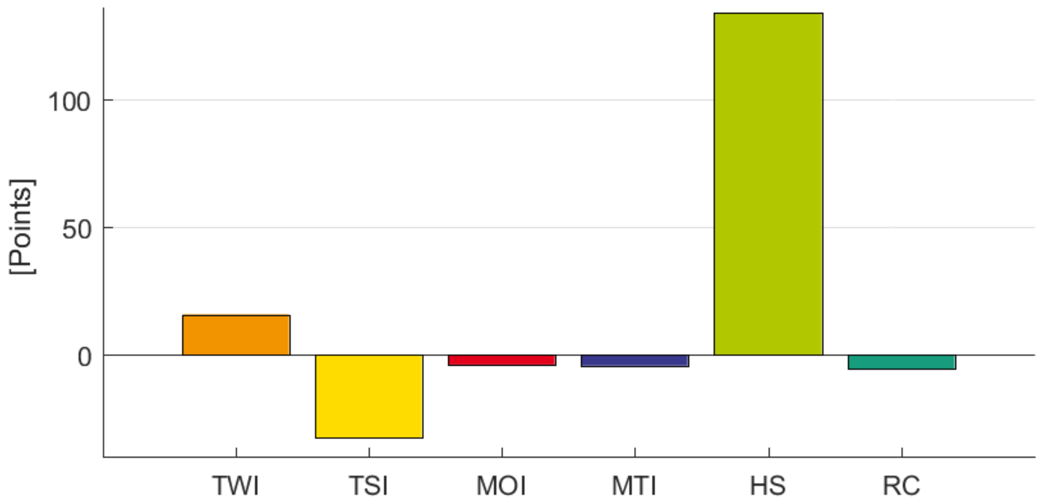


Figure 43: Delta OI3 for all assemblies

4.4 Comparison costs, time and mounting efforts

In Table 9 the calculation of each detail is shown. The description of each component and work and its correspondent values can be seen in Table 22 and Table 23 from the Appendix. In this analysis, the inclusion of precast concrete (PC) was also evaluated to compare to in-situ reinforced concrete solutions.

Table 9: Cost calculation of each details' layer

Detail	Layer	Components/Work	Unit	Per m² (*)	Labor [€]	Material [€]	Machinery [€]	[€.unit⁻¹]	Material Cost [€.m⁻²]	Time [h]	Time per m² [h]	from [€.m⁻²]	middle [€.m⁻²]	to [€.m⁻²]
1. TWI	1.1.Wood fiber insulation	1.1.1.Material and assembly	m2	1,00	7,38	4,50	0,00	11,88	11,88	0,20	0,20	9,74	11,32	14,32
	1.2.Glas wool btw battens	1.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		1.2.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	1.3.Mineral wool btw beams	1.3.1.Wood delivery	m3	0,04	0,00	12,92	0,00	323,00	12,92	0,00	0,00	10,89	12,95	16,21
		1.3.2.Wood assembly	m	2,00	16,24	0,00	0,00	8,12	16,24	0,22	0,44	9,62	15,22	17,64
		1.3.3.Insulation material and assembly	m2	0,80	5,90	8,08	0,00	17,48	13,98	0,20	0,16	11,66	13,74	16,23
	1.4.MDF/OSB Plate	1.4.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	1.5.Vapor barrier	1.5.1.Material and assembly	m2	1,00	2,95	2,00	0,00	4,95	4,95	0,08	0,08	4,77	5,39	6,74
	1.6.Inner sheathing	1.6.1.Material and assembly	m2	1,00	28,58	26,52	0,00	55,10	55,10	0,75	0,75	48,38	56,61	63,96
					78,37	**101,12**	**0,00**		**179,50**		**2,10**	**155,20**	**183,62**	**209,85**
2. TSI	2.1.MDF/OSB Plate	2.1.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	2.2.Straw btw beams	2.2.1.Wood delivery	m	2,00	0,00	37,00	0,00	18,50	37,00	0,00	0,00	32,98	38,50	40,64
		2.2.2.Wood assembly	m	4,00	32,48	0,00	0,00	8,12	32,48	0,22	0,88	19,24	30,44	35,28

		2.2.3.Insulation material and assembly	m2	0,80	5,90	13,81	1,36	26,34	21,07	0,20	0,16	17,29	21,27	25,26
	2.3.MDF/OSB Plate	2.3.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	2.4.Vapor barrier	2.4.1.Material and assembly	m2	1,00	2,95	2,00	0,00	4,95	4,95	0,08	0,08	4,77	5,39	6,74
	2.5.Inner sheathing	2.5.1.Material and assembly	m2	1,00	28,58	26,52	0,00	55,10	55,10	0,75	0,75	48,38	56,61	63,96
					84,67	**101,93**	**1,36**		**187,96**		**2,27**	**157,78**	**190,43**	**214,02**
3. MOI	3.1.Wood fiber insulation	3.1.1.Material and assembly	m2	1,00	7,38	4,50	0,00	11,88	11,88	0,20	0,20	9,74	11,32	14,32
	3.2.Mineral wool btw battens	3.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		3.2.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	3.3.Massive wood structure	3.3.1.Wood delivery	m3	0,21	0,00	114,92	0,00	547,25	114,92	0,00	0,00	109,95	119,75	135,64
		3.3.2.Wood assembly	m2	1,00	22,14	0,00	0,00	22,14	22,14	0,60	0,60	22,45	28,66	35,90
	3.4.Vapor barrier	3.4.1.Material and assembly	m2	1,00	2,95	2,00	0,00	4,95	4,95	0,08	0,08	4,77	5,39	6,74
	3.5.Inner sheathing	3.5.1.Material and assembly	m2	1,00	28,58	26,52	0,00	55,10	55,10	0,75	0,75	48,38	56,61	63,96
					70,99	**183,75**	**0,00**		**254,73**		**1,90**	**237,87**	**271,02**	**310,23**
	4.1.Wood fiber insulation	4.1.1.Material and assembly	m2	1,00	7,38	4,50	0,00	11,88	11,88	0,20	0,20	9,74	11,32	14,32
	4.2.Mineral	4.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28

4. MIT	wool btw battens	4.2.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	4.3.Mineral wool btw battens	4.3.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		4.3.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	4.4.Massive wood structure	4.4.1.Wood delivery	m3	0,10	0,00	53,23	0,00	532,32	53,23	0,00	0,00	49,77	55,47	64,28
		4.4.2.Wood assembly	m2	1,00	22,14	0,00	0,00	22,14	22,14	0,60	0,60	22,45	28,66	35,90
	4.5.Vapor barrier	4.5.1.Material and assembly	m2	1,00	2,95	2,00	0,00	4,95	4,95	0,08	0,08	4,77	5,39	6,74
	4.6.Inner sheathing	4.6.1.Material and assembly	m2	1,00	28,58	26,52	0,00	55,10	55,10	0,75	0,75	48,38	56,61	63,96
					80,93	**157,86**	**0,00**		**238,79**		**2,17**	**220,27**	**256,03**	**292,54**
5.HS	5.1.MDF/OSB Plate	5.1.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	5.2.Mineral wool btw battens	5.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		5.2.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	5.3.Steel structure	5.3.1.Profil	m	2,00	66,46	142,04	0,00	104,25	208,50	0,75	1,50	182,96	208,00	222,56
		5.3.7.Insulation material and assembly	m2	0,80	5,90	8,08	0,00	17,48	13,98	0,20	0,16	11,66	13,74	16,23
	5.4.Mineral wool btw battens	5.4.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		5.4.2.Mineral wool	m2	0,88	5,52	27,98	0,00	38,07	33,50	0,17	0,15	32,24	36,27	39,39
	5.5.MDF/OSB Plate	5.5.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07

	5.6.Vapor barrier	5.6.1.Material and assembly	m2	1,00	2,95	2,00	0,00	4,95	4,95	0,08	0,08	4,77	5,39	6,74
	5.7.Inner sheathing	5.7.1.Material and assembly	m2	1,00	28,58	26,52	0,00	55,10	55,10	0,75	0,75	48,38	56,61	63,96
					138,53	**272,85**	**0,00**		**411,38**		**3,43**	**368,05**	**420,54**	**458,97**
6. RC	6.1.MDF/OSB Plate	6.1.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	6.2.Glas wool between battens	6.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		6.2.2.Mineral wool	m2	0,92	5,77	29,26	0,00	38,07	35,02	0,17	0,16	33,71	37,92	41,18
	6.3.Mineral wool between beams	6.3.1.Wood delivery	m3	0,06	0,00	18,09	0,00	323,00	18,09	0,00	0,00	15,25	18,12	22,70
		6.3.2.Wood assembly	m	2,00	16,24	0,00	0,00	8,12	16,24	0,22	0,44	9,62	15,22	17,64
		6.3.3.Insulation material and assembly	m2	0,80	5,90	8,08	0,00	17,48	13,98	0,20	0,16	11,66	13,74	16,23
	6.4.Glas wool between battens	6.4.1.Battens	m	2,00	5,90	6,20	0,00	6,05	12,10	0,08	0,16	10,34	12,40	14,90
		6.4.2.Mineral wool	m2	0,92	5,77	29,26	0,00	38,07	35,02	0,17	0,16	33,71	37,92	41,18
	6.5.Reinforced concrete	6.5.1.Pitched roof slab	m2	1,00	6,22	17,10	1,48	24,80	24,80	0,16	0,16	14,76	23,08	27,04
		1.5.2.Reinforcement	t	0,01	5,88	4,99	0,00	1552,86	10,87	21,60	0,15	8,36	10,48	13,07
		6.5.3.Formwork	m2	1,00	35,01	8,24	0,00	43,25	43,25	0,90	0,90	35,10	41,20	47,90
	6.6.Gypsum plaster	6.6.1.Material and assembly	m2	1,00	9,03	4,07	0,28	13,38	13,38	0,25	0,25	12,03	14,55	18,08
					107,52	**144,40**	**1,76**		**253,68**		**2,85**	**212,43**	**256,76**	**295,28**

7. PC	7.1.MDF/OSB Plate	7.1.1.Material and assembly	m2	1,00	7,38	11,30	0,00	18,68	18,68	0,20	0,20	17,56	19,11	21,07
	7.2.Glas wool between battens	7.2.1.Battens	m	2,00	4,42	7,82	0,00	6,12	12,24	0,06	0,12	10,34	13,02	14,28
		7.2.2.Mineral wool	m2	0,92	5,77	29,26	0,00	38,07	35,02	0,17	0,16	33,71	37,92	41,18
	7.3.Mineral wool between beams	7.3.1.Wood delivery	m3	0,06	0,00	18,09	0,00	323,00	18,09	0,00	0,00	15,25	18,12	22,70
		7.3.2.Wood assembly	m	2,00	16,24	0,00	0,00	8,12	16,24	0,22	0,44	9,62	15,22	17,64
		7.3.3.Insulation material and assembly	m2	0,80	5,90	8,08	0,00	17,48	13,98	0,20	0,16	11,66	13,74	16,23
	7.4.Glas wool between battens	7.4.1.Battens	m	2,00	5,90	6,20	0,00	6,05	12,10	0,08	0,16	10,34	12,40	14,90
		7.4.2.Mineral wool	m2	0,92	5,77	29,26	0,00	38,07	35,02	0,17	0,16	33,71	37,92	41,18
	7.5.Precast concrete	7.5.1.Pitched roof slab	m2	1,00	31,51	36,69	5,89	74,09	74,09	0,81	0,81	60,11	70,09	81,32
	7.6.Gypsum plaster	7.6.1.Material and assembly	m2	1,00	9,03	4,07	0,28	13,38	13,38	0,25	0,25	12,03	14,55	18,08
					91,92	**150,76**	**6,17**		**248,85**		**2,45**	**214,32**	**252,09**	**288,58**
(*) See Appendix "Inhomogenous layers"														

In Figure 44 the average cost values as well as the deviation of each detail are shown. The wood lightweight with mineral wool construction has the lowest average cost value, followed by the timber wood with straw insulation with 4% higher average costs. In a second cost group can be found both concrete details and the massive wood with two insulations with 37-39% higher cost values than the lowest one, and the massive wood with one insulation with 48%. The hybrid system is the most expensive detail with 130% increase from the lowest average cost value.

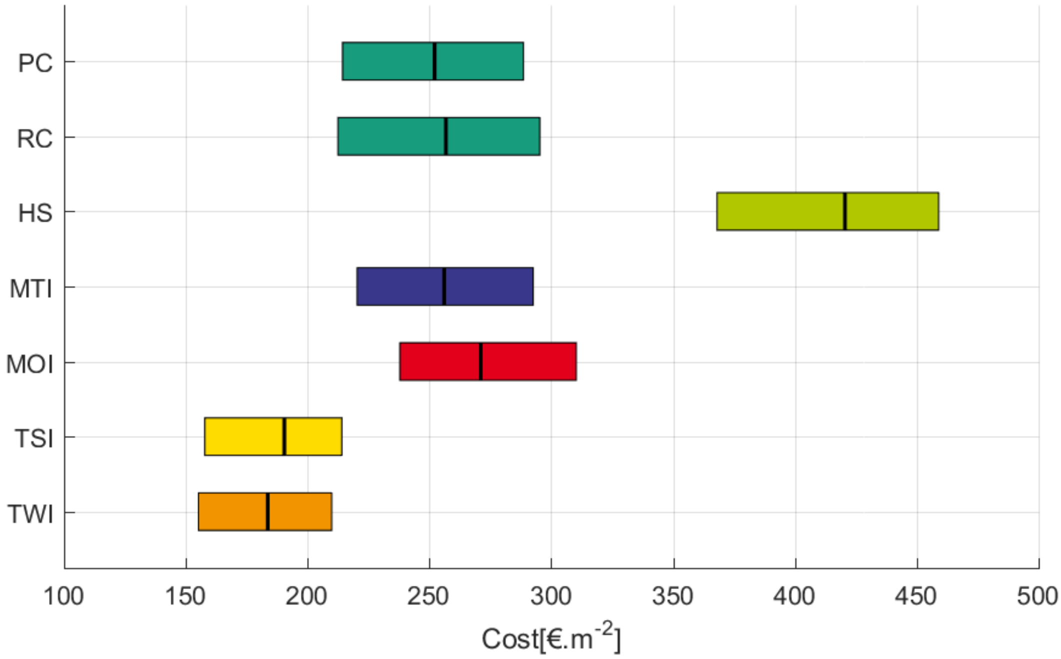


Figure 44: Minimum, middle and maximum cost values of each detail

Even though the concrete solutions and the massive wood with two insulation layers are approximately 30% more expensive than the wood timber solutions, their minimum cost values reach the maximum cost values from the lightweight wood details.

According to Walberg et al. (2015) concrete solutions implicate more transport costs and extra costs can be charged for small and particular objects. The form-work and the concrete pump needed make them more expensive in comparison to other solutions. However, the in-situ concrete construction has not shown a cost difference higher than 2% in comparison to the prefabricated concrete detail.

In Table 10 the deviation of the mean cost value and the difference between maximum and minimum are shown. The deviation from all details is between 11-16%. Even though the hybrid system has the highest cost values and difference between extreme values, it has the lowest deviation in comparison to the other details. Both massive constructions have a deviation of around 13-14%, and both lightweight wood details and the prefabricated concrete construction around 15%. The reinforced concrete has the highest deviation cost value.

Table 10: Mean, maximum and minimum cost values, difference and deviation from cost values

Description	from [€.m^{-2}]	mean [€.m^{-2}]	to [€.m^{-2}]	Difference [€.m^{-2}]	Deviation [€.m^{-2}]
TWI	155,20	183,62	209,85	54,64	0,15
TSI	157,78	190,43	214,02	56,25	0,15
MOI	237,87	271,02	310,23	72,36	0,13
MTI	220,27	256,03	292,54	72,27	0,14
HS	368,05	420,54	458,97	90,92	0,11
RC	212,43	256,76	295,28	82,85	0,16
PC	214,32	252,09	288,58	74,26	0,15

In Figure 45 the divided costs according to labor, material cost and machinery are shown. In general, there are higher differences between material costs (174 € difference between maximal and minimal value) than labor costs (68 €) in all the details. Machinery costs correspond only to concrete details, which represent between 1-2% of the total costs of those details.

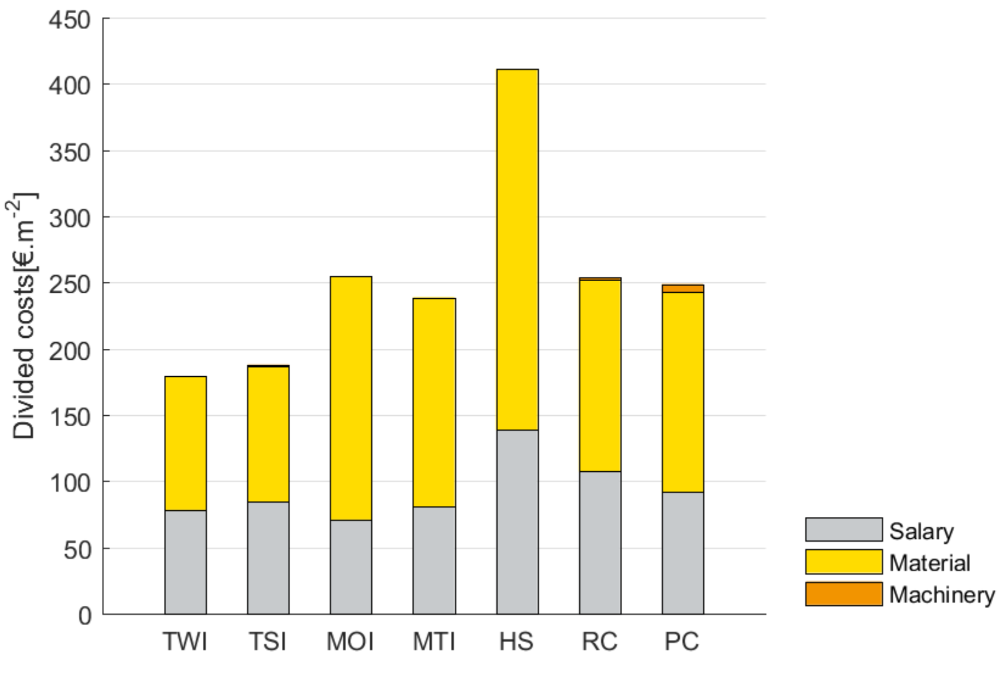


Figure 45: Divided costs for all assemblies

In Table 11 the increase values are shown in comparison to the lower cost values. The wood lightweight with mineral wool detail has the lowest material costs, although there is no significant difference with the straw insulation detail. Both concrete details have around 43-49% higher material costs. The impact on material costs of both massive wood constructions increments the cost from 52% to 82% depending on the thickness of the CLT plate. The use of the steel beams makes a huge impact on the material costs for the roof detail (170% higher material cost values).

The massive wood with one insulation layer has the lowest labor cost, followed by the lightweight wood with mineral wool. The massive wood with two insulation layers requires more labor cost (14%) than with just one insulation layer, even though the CLT plate is lighter for the montage process. The straw detail requires a bigger wood beam than the one with mineral wool – almost double height – due to thickness of the straw bales and consequently a more complex structure, increasing the labor cost to 19%. The precast concrete detail has around 29% higher labor costs in comparison to lowest labor value, having a considerable difference in comparison to the in-situ concrete detail with 51%, due to the non-prefabricated building elements. The hybrid system detail has the higher labor costs (95%) due to the need of specialized workforce.

Table 11: Divided costs and increase percentages

Description	Labor [€]	Material [€]	Machinery [€]	Labor Increase from (*) [%]	Material Increase from (*) [%]
TWI	78,37	101,12	0,00	10	(*)
TSI	84,67	101,93	1,36	19	1
MOI	70,99	183,75	0,00	(*)	82
MTI	80,93	157,86	0,00	14	56
HS	138,53	272,85	0,00	95	170
RC	107,52	144,40	1,76	51	43
PC	91,92	150,76	6,17	29	49

In Table 12 the values of the divided cost and its correspondent percentage in each detail is shown. In the case of both lightweight wood constructions and the in-situ reinforced concrete the percentage relation is similar, around 42-44% for labor and 56-57% for material costs, which means an almost 1 to 1 relation. The massive wood with two insulations and the hybrid system have the same relation with 34% labor costs and 66% material costs. In this last case, the presence of the steel beams and the CLT makes an influence on the material costs two times the labor costs. The prefabricated concrete detail has also a similar relation to the previous described. The massive wood with one insulation has the higher labor-material relation difference, as the material represents a 72% of the total costs.

Table 12: Percentage of cost within each detail

Description	Labor [%]	Material [%]	Machinery [%]
TWI	44	56	0
TSI	45	54	1
MOI	28	72	0
MTI	34	66	0
HS	34	66	0
RC	42	57	1
PC	37	61	2

In Figure 46 the amount of time required for the assembly process is shown. For 1m^2 of roof detail, time values range from 1,9 to 3,4 hours. The hybrid system requires more number of hours, followed by the in-situ reinforced concrete. The difference between the in-situ and the precast concrete details is of 16%. Wood details have the lowest time values ranging from 1,9 to 2,3 h.m^{-2}. The massive wood with one insulation layer detail requires less number of hours, almost 80% less time than the hybrid system.

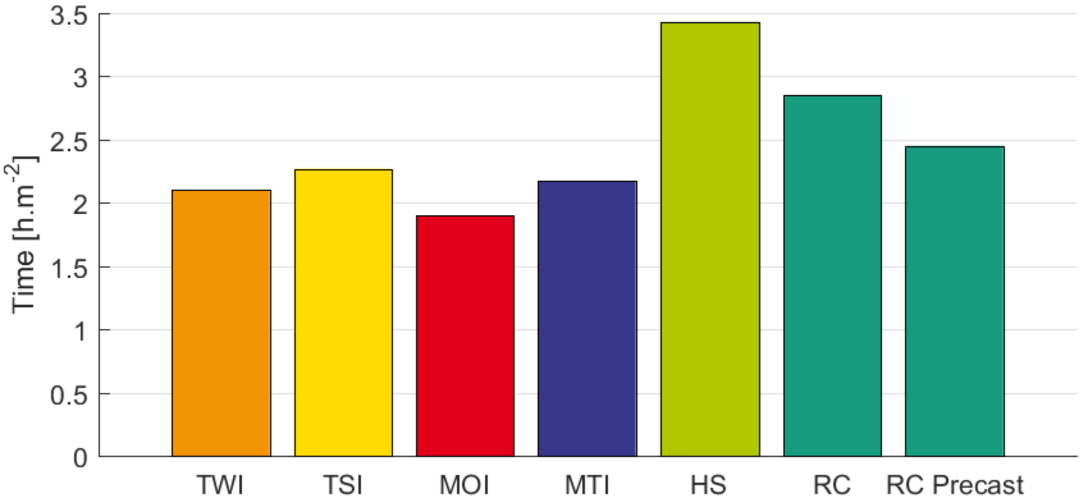


Figure 46: Average hours per m^2 of each detail

In Figure 47, the relationship between cost and time values for each detail is shown. The graph has shown that there is a linear relationship only between both lightweight wood constructions. The precast concrete solution requires less time and has lower cost values in comparison to the in-situ concrete roof, although the difference is not higher than -16% and -2% for time and cost, respectively. The massive wood with one insulation layer requires less time but it has higher costs than the massive wood with two insulation layers with reciprocal results. The hybrid system has the highest time and cost values.

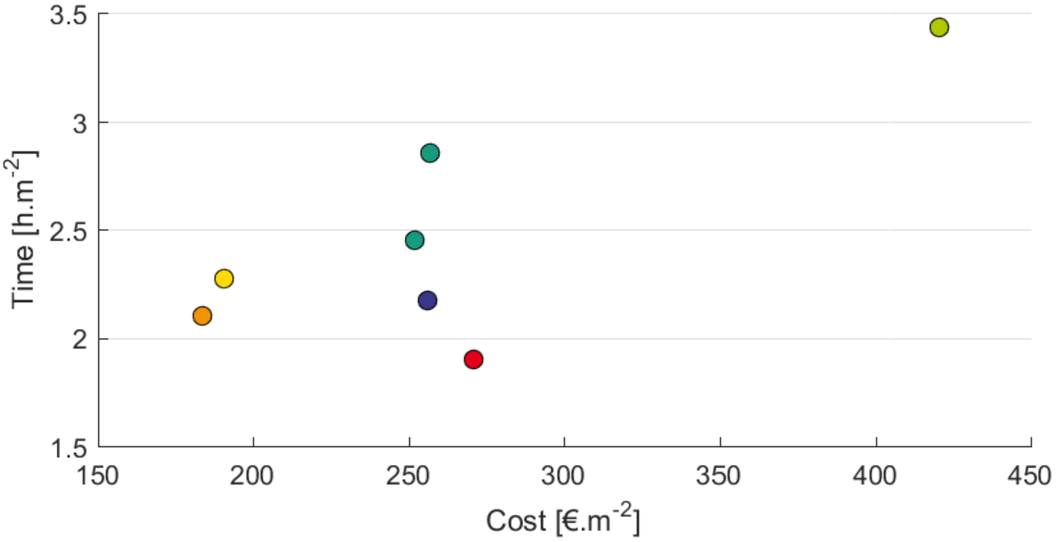


Figure 47: Cost and time relationship

4.5 Uncertainties

Ecological Analysis

As mentioned before, there are different impact categories for the ecological analysis. This thesis is focused on only three categories and on one stage of the life cycle assessment.

As studied by Kuittinen et al. (2013) the environmental impact on different stages can be dominated by diverse indicators. Moreover, each stage of the life cycle assessment has a different impact on the total analysis. By making those distinctions and elaborating a deeper analysis, different results may be encountered (Pajchrowski et al. 2014). Some aspects that may impact on the analyzed study cases are:

- Transportation of building materials: indicators related to the transport of building materials from the production or sale location to the building site can be decreased because of a lower load weight. For example, CLT may have a higher impact in comparison to wood and steel beams.
- Assembly: the assembly process of reinforced concrete structures may require more time and in-situ resources, which means a higher ecological impact in terms of transportation and natural resources, such as water.
- Disposal material waste: the entire “cradle-to-grave” process is not considered, which leads to partial results. In the previous analysis (chapter

4.3), the impact of the steel material in the disposal phase is not visible in the final results, as the assembly has similar performance results to the other assemblies.

- Reuse of material: especially steel beams and some wooden elements may be reutilized rather than concrete structures.

Another aspect of relevance is that the database used for this work was taken from IBO GmbH and baubook GmbH (2018) baubookGmbHÉ. The comparison with other sources may show differences on the values assigned for each material and consequently the final results might vary.

Cost analysis

The cost analysis has been evaluated for a m^2 of structure. Specific attic details were not considered, such as window connections, roof's ridge, hip, valley and eave details. In those cases, costs regarding labor, material and time may vary according to the building technology used.

The cost analysis considers the machinery's cost for the assembly disregarding the building's location and shape, such as attic's height, which may influence on the machinery needed. For instance, a massive wood detail requires fewer pieces of building elements but due to the CLT weight, the use of a crane may be of necessity. Contrarily, for steel or timber wood constructions usually scaffolds are sufficient for the mounting process.

For the time analysis, the number of hours for the preparation and mounting processes are considered. Previous and post-process, such as material transportation time, are not taken into account and may lead to different time results.

4.6 General comparison

The categories in Table 13 represent the main results of the different analysis. For the ecological analysis, the general OI3 evaluation [Points] is considered as the final ecological value indicator. The thermal analysis results are shown in terms of specific energy demand [kWh.m-2] but differentiating between cooling and heating demand to capture the behavior in the different seasons. The thermal comfort is represented by the discomfort hours [K.h] – temperature above 28°C in summer period. The average cost values [€.m-2] are also included in the comparison.

Table 13: Values of each analyzed category for all assemblies

Details	Heating demand [kWh.m^{-2}.a^{-1}]	Cooling demand [kWh.m^{-2}.a^{-1}]	Temperature > 28° (west zone) [K.h]	OI3 Evaluation [Points]	Cost [€.m^{-2}]
TWI	43,63	22,75	62.202	13,35	183,62
TSI	43,52	22,70	61.825	8,16	190,43
MOI	49,03	21,23	54.846	15,26	271,02
MTI	44,99	22,31	60.122	14,90	256,03
HS	46,41	22,13	58.884	21,74	420,54
RC	40,63	22,96	60.455	22,04	256,76

In Table 14, the increase between the maximum and minimum values within each category is shown. The increase values of the thermal energy and comfort categories are lower than 21%, while the ecological and cost categories the difference is significant (170% and 129% between the minimum and the maximum values).

Table 14: Maximum, minimum and increase values of each analyzed category

	Heating demand [kWh.m^{-2}.a^{-1}]	Cooling demand [kWh.m^{-2}.a^{-1}]	Temperature > 28° (west zone) [K.h]	OI3 Evaluation [Points]	Cost [€.m^{-2}]
Max value	49,03	22,96	62.202	22,04	420,54
Min value	40,63	21,23	54.846	8,16	183,62
Mean	44,70	22,35	59.722	15,91	263,07
Difference	8,41	1,73	7.356	13,88	236,92
Increase	21%	8%	13%	170%	129%

In order to compare the values from different categories or “populations”, all categories’ values were normalized with a typified unit calculation:

$$z = \frac{x - \mu}{\mu} \quad (10)$$

where z is the normalized value
x is the analyzed value
μ is mean value

By normalizing the values (Table 15), all values are referenced to the mean value, which is set to zero, without losing the deviation in each category. Those results are illustrated in the spiderchart from Figure 48. The farther the lines are from the diagram’s center, the worse the performance is: higher costs, worse ecological values, higher heating and cooling demand and higher discomfort hours.

Table 15: Normalized values and standard deviation

Details	Heating demand [kWh.m^{-2}.a^{-1}]	Cooling demand [kWh.m^{-2}.a^{-1}]	Temperature > 28° (west zone) [K.h]	OI3 Evaluation [Points]	Cost [€.m^{-2}]
TWI	-0,02	0,02	0,04	-0,16	-0,30
TSI	-0,03	0,02	0,04	-0,49	-0,28
MOI	0,10	-0,05	-0,08	-0,04	0,03
MTI	0,01	0,00	0,01	-0,06	-0,03
HS	0,04	-0,01	-0,01	0,37	0,60
RC	-0,09	0,03	0,01	0,39	-0,02
Std Deviation	**0,06**	**0,03**	**0,04**	**0,30**	**0,30**

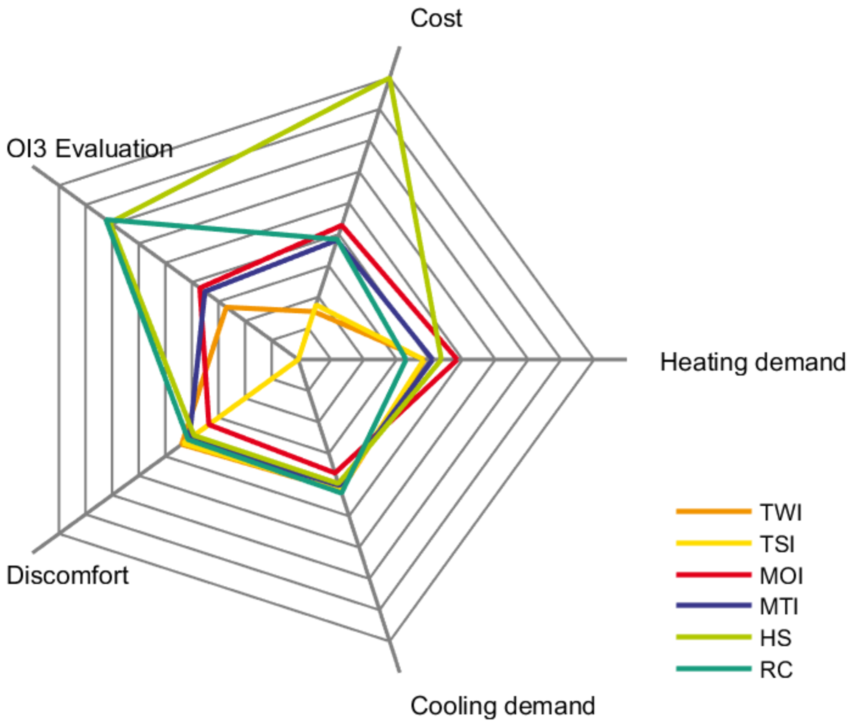


Figure 48: Comparison of normalized values of each category for all assemblies

All details show similar values for cooling and discomfort categories, which are closer to the mean value. The results for heating demand are also close to the mean value but the standard deviation is slightly higher. The highest standard deviation corresponds to the OI3 and cost results. In the latter, three groups can be identified with similar behavior: wood lightweight details with the lower values; massive wood details and reinforced concrete assembly with values closer to the mean value; and the hybrid system showing the highest value. Similarly, OI3 results can be divided in three groups of similar behavior: wood lightweight with straw insulation with the lowest value; wood lightweight with mineral wool insulation and massive wood details with values close to the mean; and the hybrid system and reinforced concrete details showing the highest values.

Both massive wood details show values close to the mean in all categories. Both wood lightweight details show acceptable performance in terms of costs and the wood lightweight with straw insulation assembly has the best performance in terms of ecological analysis. The reinforced concrete shows slightly better results in terms of heating demand and significantly worse results in terms of ecological performance. Similarly, the hybrid system shows high ecological values and a significant increase in terms of costs, showing the highest value.

In this representation a comparison of all categories is visually comprehensible. However, the qualitative nature of each value – meaning how “good” or “bad” the value is – is not represented. For instance, all heating demand, cooling demand and ecological values are within “good” performance results, despite the variety in results between assemblies. Contrarily, values for cost and discomfort are not categorized and can be only analyzed by comparing the details.

5 CONCLUSION

This master thesis focuses on a general assessment of different roof building assemblies for typical attic extensions in Vienna (and comparable European cities). The main objective is to perform a comprehensive comparison between details with different load-bearing and insulation materials. Three main aspects were subject of comparison: ecological, thermal and cost performance. Through the selection of a representative reference building, 6 assemblies were evaluated.

Regarding the thermal results, numeric simulations have identified high indoor temperatures (higher than 35°C in hottest days) in the rooftop area during the summer period, especially in the west and south orientations. Consequently, cooling demand and frequency of discomfort hours became crucial aspects to be considered in this construction type.

The building details' thermal behavior was evaluated by proving the linear relationship between thermal transmittance (represented by the U-value) and heating and cooling demand values. Due to similar thermal transmittance values, the heating and cooling demand does not vary more than 20% between details.

For the thermal comfort analysis, the influence of the details' heat storage capacity on thermal discomfort was evaluated. Despite differences in the indoor temperature profile of the details, the heat storage capacity has not shown a significant influence on reducing discomfort hours. In comparison to other building factors and occupant behavior, such as the possibility and application of passive ventilation during night times, the type of construction does not show a very high influence on the thermal performance of the attic space.

Wood assemblies have shown a better performance in terms of ecological impact. A significant relative reduction within wood constructions can be achieved by changing the insulation material from mineral wool to natural material-based insulations, such as straw bales. However, such a change needs to be considered in the building construction detailing. Regarding the scope of this analysis, the difference between choosing a lightweight steel structure and a lightweight wood structure with the same insulation material can reduce the ecological impact values by 50% for the latter case. Nevertheless, while performing a “cradle-to-gate” evaluation, all details have shown low ecological impact in absolute numbers.

The main difference between the details can be seen in terms of cost evaluation. Lightweight wood structures are the less expensive ones, independent from the type of insulation. Applying a hybrid system to the roof construction may increase the costs by 130%.

Beyond quantitative aspects, selecting a building technology for an attic extension is influenced by the building elements' feasibility, such as the construction weight, which may restrict the use of reinforced concrete and massive wood structures. Furthermore, building traditions of Vienna play a large role in the design phase. In praxis, steel is commonly used for this construction type and the lack of knowledge and trust on working with other materials, such as wood and straw bales, limits the implementation of new materials and construction technologies.

All in all, an integral assessment for a rooftop extension in Vienna has presented different challenges in terms of:

- the complexity of using different sources and software for each analyzed category, lacking an integral evaluation tool.
- the limitation of including building design's particularities in the general evaluation.
- the appropriate selection of feasible and comparable assemblies' design.

Further steps in future research will concern the possibility to deepen knowledge about strategies and constructions solutions for attic extensions design considering in detail the following aspects:

- a comparison of different ecological data sources to validate previous results.
- a full life cycle ecological assessment to capture further chain's phases, such as materials' disposal.
- the empirical experimentation with new materials and technologies.
- a comprehensive cost analysis, including material transportation and ancillary services.

6 INDEX

6.1 List of Figures

6.2 List of Tables

6.3 List of Equations

6.4 List of Abbreviations

$L_{A,eq}$	Weighted sound pressure level [dB]
$R'_{res,w}$	Resulting sound reduction index [dB]
R_w	Weighted sound reduction index [dB]
$HWB_{Ref,RK}$	Heating demand calculated to a reference weather data [$kWh.m^{-2}.a^{-1}$]
$V_{L,s}$	Total immission area to the volume air exchange [$m^3.h^{-1}.m^{-2}$]
$m_{w,I}$	Total heat storage of the building elements [$kg.m^{-2}$]
m_{wet}	Mass of the specimen at a given moisture content
m_{dry}	Mass of the ovendry specimen
c	Specific heat capacity [$J.kg^{-1}.K^{-1}$]
Q	Heat [J]
m	Mass [kg]
$\Delta\theta$	Temperature difference [K]
c_0	Specific heat of dry wood [$kJ.kg^{-1}.K^{-1}$]
c_w	Specific heat of water [$kJ.kg^{-1}.K^{-1}$]
M	Moisture content [%]

A	Correction term [$kJ.kg^{-1}.K^{-1}$]
λ	Conductivity [$W.m^{-1}.K^{-1}$]
a	Thermal diffusivity [$m^2.s^{-1}$]
ρ	Density of a material [$kg.m^{-3}$]
s	Heat storage capacity [$J.m^{-3}.K^{-1}$]
PMV-PPD	Predicted Mean Vote – Predicted Percentage Dissatisfied
T_i	Interior air temperature [ºC]
RH	Relative humidity [%]
T_e	Exterior air temperature [ºC]
R_{si}	Thermal resistance of the interior surface [$m^2.K.W^{-1}$]
f_{Rsi}	Temperature factor [-]
L2D	Thermal coupling coefficient for two-dimensional junctions [-]
L3D	Thermal coupling coefficient for three-dimensional junctions [-]
R_w	Airborne Sound Insulation
L_n	Impact Sound Insulation
α	Sound Absorption coefficient
LCA	Life Cycle Assessment
GHG	Greenhouse gas emissions
LVL	Laminated veneer lumber
CLT	Cross-laminated timber
X-LAM	Cross-lam
EBF	Gross heated area (“Energiebezugsfläche”)
EPS	Expanded polystyrene
PUF	Polyurethane Foam
VIPs	Vacuum insulation panels
TWI	Lightweight timber with mineral wool
TSI	Lightweight timber with straw
MOI	Massive wood with one-layer insulation
MTI	Massive wood with two-layer insulation

HS	Hybrid system with steel and wood elements
RC	In-situ reinforced concrete
PC	Precast concrete
LoE	Low emissivity
ACH	Air exchange hour [h^{-1}]
OI3	Austrian environmental indicator
GWP	Global warming potential [t]
PEC n.r.	Primary energy consumption from non-renewable energy sources [MJ]
AP	Acidification potential [kg]
$OI3_{KON}$	OI3 calculation for one square meter of a structure of building material [Points]
ΔOI3	OI3 calculation for one layer of a building material [Points]
$OI3_{BGX}$	OI3 calculation in terms of thermal building envelope [Points]
$OI3_{BGX,lc}$	OI3 calculation in terms of characteristic length [Points]
$OI3_{BGX,BGF}$	OI3 calculation in terms of gross floor area [Points]
$OI3_{STGH}$	OI3 calculation in terms of thermal retrofit [Points]
lc	Characteristic length of the building (Volume/Area)
A	Area [m2]
Fc	Frequency [-]
z	Normalized value
x	Analyzed value
μ	Mean value

7 LITERATURE

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8 APPENDIX

8.1 Thermal assessment

8.1.1 Assumptions and database

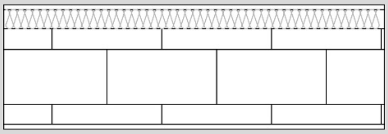
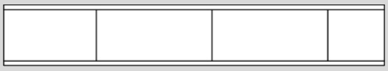
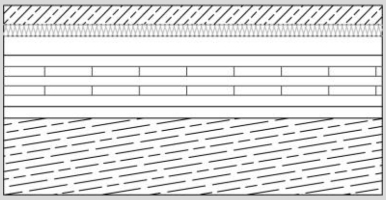
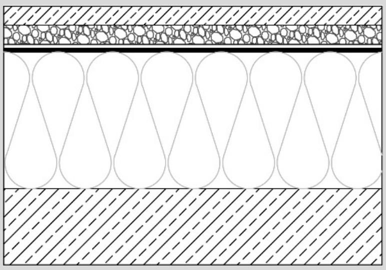
Dividing wall		13	mm	Gypsum fiberboard
		50	mm	Glass wool
		250	mm	Brick
		13	mm	Gypsum fiberboard
		376	**mm**	**Total thickness**
		0,294	$W.m^{-2}.K^{-1}$	U-Value
		87,90	$kJ.m^{-2}.K^{-1}$	Heat Storage
		325,2	$Kg.m^{-2}$	Weight
Interior wall		13	mm	Gypsum fiberboard
		135	mm	Brick
		13	mm	Gypsum fiberboard
		276	**mm**	**Total thickness**
		1,157	$W.m^{-2}.K^{-1}$	U-Value
		98,16	$kJ.m^{-2}.K^{-1}$	Heat Storage
		323,4	$Kg.m^{-2}$	Weight
Ceiling (*)		50	mm	Cement screed
		-	mm	Separation layer
		30	mm	Sound insulation MW-T
		50	mm	Filling of sand, gravel and grit
		-	mm	Vapor barrier
		134	mm	Cross laminated timber
		30	mm	Air gap
		200	mm	Existent slab
		50	mm	Glass wool between battens
		1,3	mm	Gypsum plaster
		563	**mm**	**Total thickness**
		0,19	$W.m^{-2}.K^{-1}$	U-Value
		40,09	$kJ.m^{-2}.K^{-1}$	Heat Storage
		316,2	$Kg.m^{-2}$	Weight
	(*) Values are calculated for the additional construction, excluding the existent slab (*) For the new ceiling, the same building elements apply (without the existent slab)			
Terrace		50	mm	Cement screed
		50	mm	Filling of sand, gravel and grit
		10	mm	Rubber mat
		7,8	mm	Polymer-bitumen membrane
		1,6	mm	Vapor barrier
		360	mm	EPS-W25 (23kg.m^{-3})
		1,4	mm	Aluminum membrane
		200	mm	Reinforced concrete
		3	mm	Gypsum plaster
		683	**mm**	**Total thickness**
		0,096	$W.m^{-2}.K^{-1}$	U-Value
		173,79	$kJ.m^{-2}.K^{-1}$	Heat Storage
		691,4	$Kg.m^{-2}$	Weight

Figure 49: Building elements

Table 16 : Inhomogeneous materials

Material	Percentage [%]	Conductivity [W.m^{-1}.K^{-1}]	Density [Kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]
Glass wool between battens 10 cm				
Wood	10	0,12	475	1.600
Glass wool	90	0,03	18	1.030
	100	**0,04**	**64**	**1.087**
Mineral wool between wood beams 20 cm				
Wood	10	0,12	475	1.600
Mineral wool	90	0,04	11	1.030
	100	**0,05**	**57**	**1.087**
Straw between wood beams 40 cm				
Wood	10	0,12	475	1.600
Straw	90	0,05	100	2.000
	100	**0,06**	**138**	**1.960**
Glass wool between battens 4 cm				
Wood	6	0,12	475	1.600
Glass wool	94	0,03	18	1.030
	100	**0,04**	**45**	**1.064**
Mineral wool between steel beams 20 cm				
Steel	10	12,00	700	1.610
Mineral wool	90	0,04	11	1.030
	100	**1,24**	**80**	**1.088**
Mineral wool between battens 28 cm				
Wood	2	0,12	475	1.600
Mineral wool	98	0,04	11	1.030
	100	**0,04**	**20**	**1.041**
Air between battens 3 cm				
Wood	15	0,12	475	1.600
Air gap	85	0,31	1	1.006
	100	**0,28**	**72**	**1.095**
Air between battens 5 cm				
Wood	10	0,12	475	1.600
Air gap	90	0,31	1	1.006
	100	**0,29**	**49**	**1.065**

Table 17: Building materials' properties (Dataholz 2018; baubook GmbH 2018; Stroh & Lehm 2017)

Material	Thickness [m]	Conductivity [W.m^{-1}.K^{-1}]	Density [Kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]
Brick	0,250	0,500	1.200	900
Cement screed	0,050	0,980	1.600	1.080
CLT 100 mm	0,100	0,130	470	1.600
CLT 134 mm	0,134	0,120	475	1.600
CLT 210 mm	0,210	0,130	470	1.600
Concrete	0,160	2,300	2.400	1.110
EPS-W	0,360	0,036	23	1.450
Filling material	0,050	0,700	1.800	1.000
Gypsum board	0,013	0,250	900	1.000
Fire protection plasterboard	0,015	0,210	900	1.050
MDF plate	0,020	0,130	650	1.700
Sound insulation MW/T	0,030	0,033	80	810
Tiles	0,025	1,000	2.000	800
Wood fiber	0,020	0,057	250	1.700
Wood slab	0,200	0,130	500	1.610

Table 18: Ventilation rates in summer and winter for each thermal zone

Thermal Zone	m^2	m^3	SUMMER			WINTER
			$m^3.m^{-2}.s^{-1}$			$m^3.m^{-2}.s^{-1}$
			19:00 - 9:00	9:00 - 15:00	15:00 - 19:00	8:00 - 8:10 17:00 - 17:10
1 (South)	168,31	900,48	0,0008	0,0002	0,0006	0,0089
2 (West)	58,06	212,64	0,0006	0,0001	0,0004	0,0061
3 (North)	87,93	272,57	0,0005	0,0001	0,0004	0,0052
5 (East)	58,06	212,64	0,0006	0,0001	0,0004	0,0061
6 (North)	129,71	441,03	0,0005	0,0001	0,0004	0,0057

8.1.2 Results

Table 19: Heating and cooling demand and variation from mean values for all assemblies

Details	Heating demand [kWh.m^{-2}]	Cooling demand [kWh.m^{-2}]	Variation [%]	Variation [%]
TWI	43,63	22,75	-2%	2%
TSI	43,52	22,70	-3%	2%
MOI	49,03	21,23	10%	-5%
MTI	44,99	22,31	1%	0%
HS	46,41	22,13	4%	-1%
RC	40,63	22,96	-9%	3%
Mean	44,7	22,3		

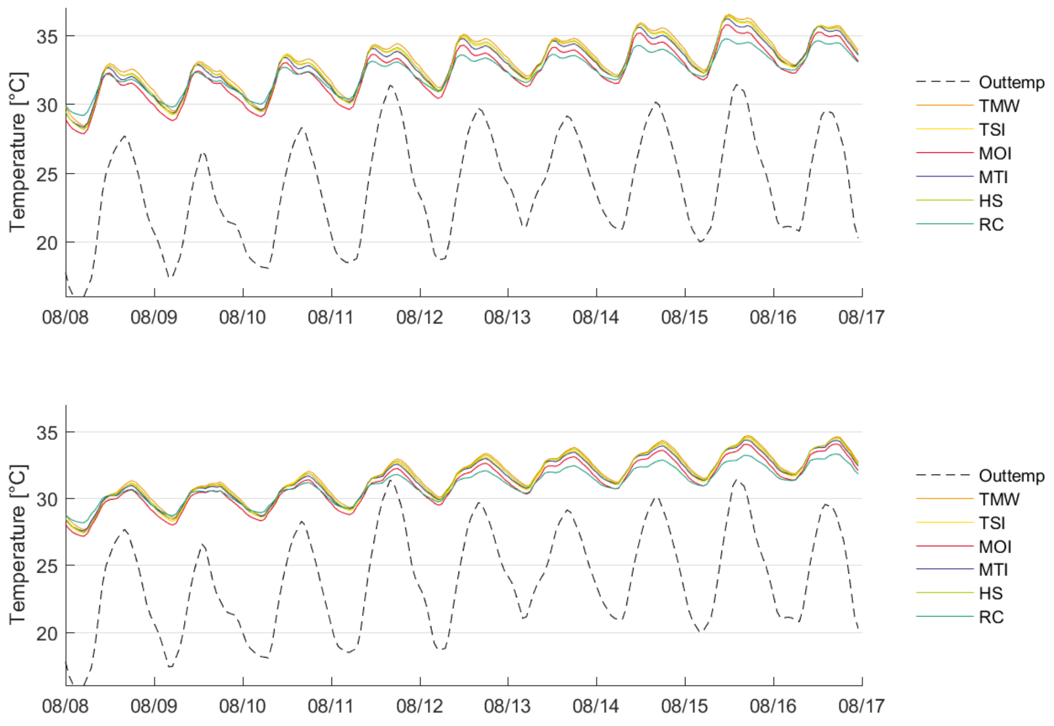


Figure 50: Temperature variation in hottest week for zones east (top) and north (bottom)

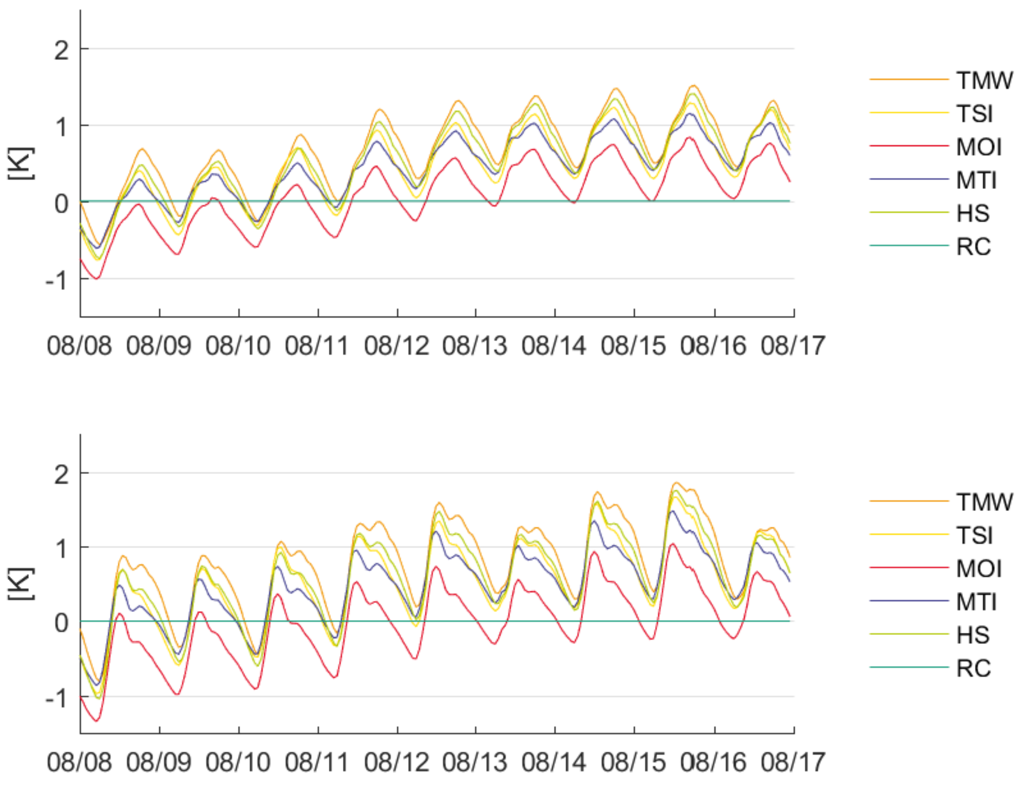


Figure 51: Temperature difference to RC (reference) in hottest week for north (top) and east (bottom) zones

8.2 Ecological assessment

8.2.1 Results

Table 20: Calculated values of primary energy content, global warming potential and acidification and its correspondent OI3 values for each assembly

OI3 Evaluation	PEC nr [MJ]	GWP [t]	AP [kg]	PEC nr [point]	GWP [point]	AP [point]
TWI	1,84E+06	-134,30	405,00	48,39	-10,87	2,53
TSI	1,81E+06	-196,47	417,00	46,79	-27,47	5,17
MOI	2,12E+06	-236,57	490,00	63,27	-38,18	20,68
MTI	1,98E+06	-184,43	455,00	55,80	-24,26	13,17
HS	2,08E+06	-137,21	467,00	61,03	-11,64	15,83
RC	2,01E+06	-125,63	473,00	57,55	-8,55	17,13

Table 21: Building components' ecological properties (IBO GmbH) and calculation of ΔOI3

Building component	PEC nr [MJ.m^{-2}]	GWP [kg.m^{-2}]	AP [kg.m^{-2}]	Delta OI3 [Point]
TWI				
Wood fiber insulation	82,42	-3,64	0,0204	2,17
Battens	0,00	0,00	0,0000	0,00
Glass wool	83,24	4,41	0,0275	3,55
Beams	0,00	0,00	0,0000	0,00
Mineral wool	85,57	5,02	0,0139	3,71
MDF plate	107,90	-17,60	0,0216	0,69
Vapor barrier PE	55,03	1,71	0,0066	2,13
Battens	0,00	0,00	0,0000	0,00
Mineral wool	21,39	1,25	0,0034	0,93
Fire protection plasterboard	63,18	2,59	0,0094	2,55
Sum	**498,73**	**-6,26**	**0,1028**	**15,72**
TSI				
MDF plate	107,90	-17,60	0,0017	0,67
Beams	478,02	-284,95	0,0009	-31,56
Straw bale	34,93	-54,31	0,0009	-7,89
MDF plate	107,90	-17,60	0,0017	0,67
Vapor barrier PE	55,03	1,71	0,0103	2,13
Battens	0,00	0,00	0,0009	0,00
Mineral wool	21,39	1,25	0,0054	0,93
Fire protection plasterboard	63,18	2,59	0,0007	2,54
Sum	**868,35**	**-368,91**	**0,0224**	**-32,51**
MOI				
Wood fiber insulation	82,42	-3,64	0,0041	2,15
Battens	119,50	-71,23	0,0009	-7,89
Glass wool	83,24	4,41	0,0153	3,53
Cross laminated timber	620,35	-168,15	0,0017	-7,34
Vapor barrier PE	55,03	1,71	0,0103	2,13

Battens	0,00	0,00	0,0009	0,00
Mineral wool	21,39	1,25	0,0054	0,93
Fire protection plasterboard	63,18	2,59	0,0007	2,54
Sum	**1.045,11**	**-233,06**	**0,0393**	**-3,95**
MTI				
Wood fiber insulation	82,42	-3,64	0,0204	2,17
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	83,24	4,41	0,0275	3,55
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	83,24	4,41	0,0275	3,55
Cross laminated timber	310,17	-84,07	0,0807	-3,57
Vapor barrier PE	55,03	1,71	0,0066	2,13
Battens	0,00	0,00	0,0000	0,00
Mineral wool	21,39	1,25	0,0034	0,93
Fire protection plasterboard	63,18	2,59	0,0094	2,55
Sum	**937,67**	**-215,80**	**0,0060**	**-4,36**
HS				
MDF plate	107,90	-17,60	0,0017	0,67
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	33,29	1,76	0,0110	1,42
Steel beams	3.039,40	190,40	0,7420	134,04
Mineral wool	85,57	5,02	0,0139	3,71
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	83,24	4,41	0,0275	3,55
MDF plate	107,90	-17,60	0,0017	0,67
Vapor barrier PE	55,03	1,71	0,0066	2,13
Battens	0,00	0,00	0,0000	0,00
Mineral wool	21,39	1,25	0,0034	0,93
Fire protection plasterboard	63,18	2,59	0,0094	2,55
Sum	**3.835,90**	**29,48**	**0,0060**	**133,99**
RC				
MDF plate	107,90	-17,60	0,0216	0,69
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	33,29	1,76	0,0110	1,42
Beams	334,61	-199,46	0,1255	-21,92
Mineral wool	119,81	7,03	0,0195	5,19
Battens	119,50	-71,23	0,0448	-7,83
Glass wool	33,29	1,76	0,0110	1,42
Reinforced concrete	372,48	51,45	0,1152	21,14
Vapor barrier PE	55,03	1,71	0,0066	2,13
Sum	**1.295,41**	**-295,81**	**0,0060**	**-5,59**

8.3 Cost analysis

Table 22: Description of each detail's layer and its correspondent costs

Detail	Layer	Code(*)	Work	Description	Unit	Time [h]	Labor [€]	Material [€]	Machinery [€]	Total [€]	Deviation [%]	from [€]	middle [€]	to [€]
1. TWI	1.1.Wood fiber insulation	016.0.19.910	1.1.1.Material and assembly	Porous, 12mm	m^2	0.2	7.38	4.5		11.88	+4.95	9.74	11.32	14.32
	1.2.Glas wool btw battens	016.0.12.080	1.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	1.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm (****)	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	1.3.Mineral wool btw beams	016.0.03.020	1.3.1.Wood delivery	Swan structural timber, S10, C24, until 20/20cm	m^3	0.00		323.00		323.00	-0.19	272.30	323.63	405.37
		016.0.05.010	1.3.2.Wood assembly	Beam colocation and assembly, not including connection elements and wood delivery, until 20/20cm	m	0.22	8.12			8.12	+6.17	4.81	7.61	8.82
		016.0.17.055	1.3.3.Insulation material and assembly	Between beams, 1 layer without cover layer, 200mm	m^2	0.20	7.38	10.10		17.48	+1.81	14.57	17.17	20.29
	1.4.MDF/OSB Plate	016.0.14.322	1.4.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	1.5.Vapor barrier	016.0.16.150	1.5.1.Material and assembly	PE Film	m^2	0.08	2.95	2.00		4.95	-8.16	4.77	5.39	6.74
	1.6.Inner sheathing	039.2.38.230	1.6.1.Material and assembly	Fire protection and gypsum board including profiles 60/27mm and mineral wool 180mm	m^2	0.75	28.58	26.52		55.10	-2.67	48.38	56.61	63.96
2. TSI	2.1.MDF/OSB Plate	016.0.14.322	2.1.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	2.2.Straw btw beams	016.0.04.215	2.2.1.Wood delivery	Double T beam, 300mm height	m	0.00		18.50		18.50	-3.9	16.49	19.25	20.32
		016.0.05.010	2.2.2.Wood assembly	Beam colocation and assembly, not including connection elements and wood delivery, until 20/20cm (**)	m	0.22	8.12			8.12	+6.17	4.81	7.61	8.82
		016.0.19.338	2.2.3.Insulation material and assembly	Cellulose (calculated for straw) 300mm between beams (***)	m^2	0.2	7.38	17.26	1.7	26.34	-0.94	21.61	26.59	31.58
	2.3.MDF/OSB Plate	016.0.14.322	2.3.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	2.4.Vapor barrier	016.0.16.150	2.4.1.Material and assembly	PE Film	m^2	0.08	2.95	2.00		4.95	-8.16	4.77	5.39	6.74
	2.5.Inner sheathing	039.2.38.230	2.5.1.Material and assembly	Fire protection and gypsum board including profiles 60/27mm and mineral wool 180mm	m^2	0.75	28.58	26.52		55.10	-2.67	48.38	56.61	63.96
3. MOI	3.1.Wood fiber insulation	016.0.19.910	3.1.1.Material and assembly	Porous, 12mm	m^2	0.2	7.38	4.5		11.88	+4.95	9.74	11.32	14.32
	3.2.Mineral wool btw battens	016.0.12.080	3.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	3.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	3.3.Massive wood structure	016.0.09.010	3.3.1.Wood delivery	Cross laminated timber slab structure	m^3	0.00		547.25		547.25	-4.03	523.57	570.23	645.91
		016.0.08.312	3.3.2.Wood assembly	Includes connection elements	m^2	0.6	22.14			22.14	-8.29	22.45	28.66	35.9
	3.4.Vapor barrier	016.0.16.150	3.4.1.Material and assembly	PE Film	m^2	0.08	2.95	2.00		4.95	-8.16	4.77	5.39	6.74
	3.5.Inner sheathing	039.2.38.230	3.5.1.Material and assembly	Fire protection and gypsum board including profiles 60/27mm and mineral wool 180mm	m^2	0.75	28.58	26.52		55.10	-2.67	48.38	56.61	63.96

4. MIT	4.1.Wood fiber insulation	016.0.19.910	4.1.1.Material and assembly	Porous, 12mm	m^2	0.2	7.38	4.5		11.88	+4.95	9.74	11.32	14.32
	4.2.Mineral wool btw battens	016.0.12.080	4.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	4.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	4.3.Mineral wool btw battens	016.0.12.080	4.3.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	4.3.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	4.4.Massive wood structure	016.0.09.025	4.4.1.Wood delivery	Cross laminated timber slab structure	m^3			532.32		532.32	-4.03	497.65	554.67	642.80
		016.0.08.312	4.4.2.Wood assembly	Includes connection elements	m^2	0.6	22.14			22.14	-8.29	22.45	28.66	35.9
	4.5.Vapor barrier	016.0.16.150	4.5.1.Material and assembly	PE Film	m^2	0.08	2.95	2.00		4.95	-8.16	4.77	5.39	6.74
	4.6.Inner sheathing	039.2.38.230	4.6.1.Material and assembly	Fire protection and gypsum board including profiles 60/27mm and mineral wool 180mm	m^2	0.75	28.58	26.52		55.10	-2.67	48.38	56.61	63.96
5.HS	5.1.MDF/OSB Plate	016.0.14.322	5.1.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	5.2.Mineral wool btw battens	016.0.12.080	5.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	5.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	5.3.Steel structure	017.1.20.007	5.3.1.Profil	HEA beam until 0,32kN/m	m	0.75	33.23	71.02		104.25	0.24	91.48	104	111.28
		016.0.17.055	5.3.7.Insulation material and assembly	Between beams, 1 layer without cover layer, 200mm	m^2	0.20	7.38	10.10		17.48	+1.81	14.57	17.17	20.29
	5.4.Mineral wool btw battens	016.0.12.080	5.4.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	5.4.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	5.5.MDF/OSB Plate	016.0.14.322	5.5.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	5.6.Vapor barrier	016.0.16.150	5.6.1.Material and assembly	PE Film	m^2	0.08	2.95	2.00		4.95	-8.16	4.77	5.39	6.74
	5.7.Inner sheathing	039.2.38.230	5.7.1.Material and assembly	Fire protection and gypsum board including profiles 60/27mm and mineral wool 180mm	m^2	0.75	28.58	26.52		55.10	-2.67	48.38	56.61	63.96
6. RC	6.1.MDF/OSB Plate	016.0.14.322	6.1.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	6.2.Glas wool between battens	016.0.12.080	6.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	6.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm (****)	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	6.3.Mineral wool between beams	016.0.03.020	6.3.1.Wood delivery	Swan structural timber, S10, C24, until 20/20cm	m^3	0.00		323.00		323.00	-0.19	272.30	323.63	405.37
		016.0.05.010	6.3.2.Wood assembly	Beam colocation and assembly, not including connection elements and wood delivery, until 20/20cm	m	0.22	8.12			8.12	+6.17	4.81	7.61	8.82
		016.0.17.055	6.3.3.Insulation material and assembly	Between beams, 1 layer without cover layer, 200mm	m^2	0.20	7.38	10.10		17.48	+1.81	14.57	17.17	20.29
		016.0.12.130	6.4.1.Battens	Battens 40/60mm, S10	m	0.08	2.95	3.10		6.05	-2.42	5.17	6.20	7.45

	6.4.Glas wool between battens	016.0.17.520	6.4.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm (****)	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	6.5.Reinforced concrete	013.0.11.410	6.5.1.Pitched roof slab	C 20/25 150mm (without insulation, formwork and reinforcement	m^2	0.16	6.22	17.10	1.48	24.80	+7.45	14.76	23.08	27.04
		013.0.18.010	1.5.2.Reinforcement	Steel bars/rods, B 500 A, 12-14 mm	t	21.60	840.24	712.62		1552.86	+3.76	1193.92	1496.56	1867.84
		013.0.24.010	6.5.3.Formwork	Not treated, for further covering, until 4 m height	m^2	0.90	35.01	8.24		43.25	+4.98	35.10	41.20	47.90
	6.6.Gypsum plaster	023.1.45.400	6.6.1.Material and assembly	Gypsum plaster 12mm	m^2	0.25	9.03	4.07	0.28	13.38	-8.04	12.03	14.55	18.08
7. PC	7.1.MDF/OSB Plate	016.0.14.322	7.1.1.Material and assembly	20mm	m^2	0.20	7.38	11.30		18.68	-2.25	17.56	19.11	21.07
	7.2.Glas wool between battens	016.0.12.080	7.2.1.Battens	Battens 50/100mm, S10	m	0.06	2.21	3.91		6.12	-5.99	5.17	6.51	7.14
		016.0.17.520	7.2.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm (****)	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	7.3.Mineral wool between beams	016.0.03.020	7.3.1.Wood delivery	Swan structural timber, S10, C24, until 20/20cm	m^3	0.00		323.00		323.00	-0.19	272.30	323.63	405.37
		016.0.05.010	7.3.2.Wood assembly	Beam colocation and assembly, not including connection elements and wood delivery, until 20/20cm	m	0.22	8.12			8.12	+6.17	4.81	7.61	8.82
		016.0.17.055	7.3.3.Insulation material and assembly	Between beams, 1 layer without cover layer, 200mm	m^2	0.20	7.38	10.10		17.48	+1.81	14.57	17.17	20.29
	7.4.Glas wool between battens	016.0.12.130	7.4.1.Battens	Battens 40/60mm, S10	m	0.08	2.95	3.10		6.05	-2.42	5.17	6.20	7.45
		016.0.17.520	7.4.2.Mineral wool	On site assembly under roofing and vapor barrier, 160mm (****)	m^2	0.17	6.27	31.8		38.07	-7.64	36.64	41.22	44.76
	7.5.Precast concrete	013.0.34.075	7.5.1.Pitched roof slab	Ribbed reinforced concrete slab, 220mm	m^2	0.81	31.51	36.69	5.89	74.09	+5.71	60.11	70.09	81.32
	7.6.Gypsum plaster	023.1.45.400	7.6.1.Material and assembly	Gypsum plaster 12mm	m^2	0.25	9.03	4.07	0.28	13.38	-8.04	12.03	14.55	18.08

(*) Code from "sirAdos Kalkulationsatlas"
(**) Values are not in the "sirAdos Kalkulationsatlas". Values were proportionally calculated according to the material dimensions.
(***) Values are not in the "sirAdos Kalkulationsatlas". Material cost for straw bales insulation was taken from *http://baubiologie.at* . Time and salary costs values were taken as cellulose insulation, as the mounting process and efforts are similar.
(****) Values are not in the "sirAdos Kalkulationsatlas". Time and salary costs values were taken as mineral wool insulation instead, as the mounting process and efforts are similar.

Table 23: Calculation of elements‘ amount per m²

Components/Work	Unit	Dimensions (h/w) [mm]		Separation [mm]	Length [mm]	Amount per m²	Unit per m²
1.2.1.Battens	m	100	60	500	1.000	2,00	2,00
1.2.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
1.3.1.Wood delivery	m3	200	100	500	1.000	2,00	0,04
1.3.2.Wood assembly	m	200	100	500	1.000	2,00	2,00
1.3.3.Insulation material and assembly	m2	200	1.000		1.000	0,80	0,80
2.2.1.Wood delivery	m	400	100	500	1.000	2,00	2,00
2.2.2.Wood assembly	m	400	100	500	1.000	4,00	4,00
2.2.3.Insulation material and assembly	m2	400	1.000		1.000	0,80	0,80
3.2.1.Battens	m	100	60	500	1.000	2,00	2,00
3.2.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
3.3.1.Wood delivery	m3	210	1.000		1.000	1,00	0,21
4.2.1.Battens	m	100	60	500	1.000	2,00	2,00
4.2.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
4.3.1.Battens	m	100	60	500	1.000	2,00	2,00
4.3.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
4.4.1.Wood delivery	m3	100	1.000		1.000	1,00	0,10
5.2.1.Battens	m	100	60	500	1.000	2,00	2,00
5.2.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
5.3.1.Profil	m	200	100		1.000	2,00	2,00
5.3.7.Insulation material and assembly	m2	200	1.000		1.000	0,80	0,80
5.4.1.Battens	m	100	60	500	1.000	2,00	2,00
5.4.2.Mineral wool	m2	100	1.000		1.000	0,88	0,88
6.2.1.Battens	m	40	40	500	1.000	2,00	2,00
6.2.2.Mineral wool	m2	40	1.000		1.000	0,92	0,92
6.3.1.Wood delivery	m3	280	100	500	1.000	2,00	0,06
6.3.2.Wood assembly	m	280	100	500	1.000	2,00	2,00
6.3.3.Insulation material and assembly	m2	280	1.000		1.000	0,80	0,80
6.4.1.Battens	m	40	40	500	1.000	2,00	2,00
6.4.2.Mineral wool	m2	40	1.000		1.000	0,92	0,92
7.2.1.Battens	m	40	40	500	1.000	2,00	2,00
7.2.2.Mineral wool	m2	40	1.000		1.000	0,92	0,92
7.3.1.Wood delivery	m3	280	100	500	1.000	2,00	0,06
7.3.2.Wood assembly	m	280	100	500	1.000	2,00	2,00
7.3.3.Insulation material and assembly	m2	280	1.000		1.000	0,80	0,80
7.4.1.Battens	m	40	40	500	1.000	2,00	2,00
7.4.2.Mineral wool	m2	40	1.000		1.000	0,92	0,92

9 GLOSSARY

Fire protection classes: R= load-bearing capacity; E= integrity; I= insulation; M= mechanical effort

Heating demand Gross Floor Area (HWB_{BGF}) [kWh.m^2.a^{-1}] is the heating demand per gross floor area [m^2].

Heating Energy Demand (HEB) [kWh.m^{-2}.a^{-1}] is calculated as the ratio between the heating demand (HWB) and the efficiency of the heating system (η) [%].

Characteristic length (ℓc) [m] of a building is the ratio between the heated gross volume and the heated gross area.

Specific heat capacity (c) [J.kg^{-1}.K^{-1}] is the amount of heat needed to raise the temperature by one Celsius degree of 1 kg of a substance.

Heat storage capacity C [J.m^{-2}.K^{-1}] denotes the same concept as the specific heat capacity but can be measured in terms of square meters of substance, and does not necessarily includes the unit of mass [kg]. In that sense, the latter is an extensive variable while the specific heat capacity is an intensive variable, referring to an attribute which belongs to a specific substance and not to any substance in general.

Thermal conductivity λ [W.m^{-1}.K^{-1}] is a measure of the rate of heat flow (or Btu h–1 ft–2) through a material subjected to unit temperature difference (K or °F) across unit thickness (m or in.).

Moisture content (MC) [%) is the ratio between the mass of water in a substance to the total mass of it.

Thermal diffusivity α [m^2.s^{-1}] is also known as absorptance and expresses how fast a substance can absorb heat from its surroundings. It is defined as the ratio of thermal conductivity to the product of density and heat capacity.

Temperature factor (fR_{si}) is difference between internal surface temperature and external temperature, divided by the difference between the internal temperature and the external temperature, calculated with a surface resistance R_{si} at the internal surface.

Airborne Sound Insulation (R_w) [dB] is defined as the difference between the sound pressure level in the emitting room and the sound pressure level in the receiving room plus a term depending on the equivalent absorption area in the receiving room.

Impact Sound Insulation (L_n). The impact sound is produced by the collision of two solid objects (typically footsteps or dropped objects on a building surface). The *Impact* *sound pressure level (L_i)* is the average sound pressure level in a specific frequency band in the receiving room when the tested floor is excited by a standardized impact sound source.

Sound Absorption coefficient (α) is the ratio of the absorbed sound intensity in a certain material to the incident sound intensity.

Global Warming Potential describes the contribution of a gas to the greenhouse effect in relation to that of an identical quantity of carbon dioxide. For each greenhouse gas, an equivalent amount of carbon dioxide is therefore calculated in kilograms.

Acidification potential is the unit of measurement for the tendency of a constituent to acidify; for each acid-forming gas, this is expressed in relation to the acidification potential of sulphur dioxide**.**

Non-renewable energy resource requirement is the overall consumption of energy resources required to manufacture a product or a service and is calculated from the highest calorific value of all the non-renewable energy resources (oil, natural gas, lignite and coal, and uranium).

Vapor barrier refers to the layer in a building component which reduces the diffusion of water vapor in the construction. It is defined by the vapor diffusion equivalent air layer thickness (Sd) greater than 1500m. The membranes which possess a diffusion equivalent air layer thickness depend on the relative humidity are called moisture adaptive vapor barriers.

Sd-Value defines the thickness of an air layer providing the same resistance to vapor diffusion as a layer of a material with the thickness d, and the vapor diffusion resistance μ as given by Sd = μ . d [m]. (Dataholz 2018)