Bachelor's thesis at the Lucerne School of Engineering and Architecture

Title **Converting a 19th century farmhouse in Valais into a low energy demand residential building.**

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Bachelor's degree program **Bachelor in Energy Systems Engineering**

Semester **spring semester 19**

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Abstract -English

In accordance with the objectives of the Swiss Energy Strategy 2050, energy efficiency in buildings is central to combat the threat posed by global warming and climate change. The state of the building stock in Switzerland is similar to that of European Union; 35% is over 50 years old. The building envelopes of these buildings are invariably not well adapted to current needs of energy demand and thermal comfort. Indeed, nearly 75% of these buildings are energy inefficient, and only 0.4-1.2% are renovated each year. By means of the building energy simulation software WUFI®PLUS, this paper demonstrates the effect that location, orientation, glazing, thermal insulation, night-time ventilation, initial temperature, window to wall ratio and shading factor has on the heating energy demand and the thermal comfort of a farmhouse built in 1895 in Valais. The results were evaluated according to the SIA 380/1 and EN 15251 standards. The results illustrate how, by improving the thermal insulation to 0.25 W/m^2K or less, installing windows with thermal transmittances inferior to 1.00 W/m^2K and window to wall ratios of 0.53, high levels of thermal comfort could be achieved with regards to the EN 15251 standard, while keeping the heating energy demand below the limits set by the SIA 380/1 standard. Furthermore this scenario shows how: the effect of orientation, night-time ventilation and shading factor had no significant effect on the thermal comfort level and the heating energy demand.

Abstract - German

Entsprechend den Zielen der Schweizer Energiestrategie 2050, spielt die Energieeffizienz von Gebäuden eine zentrale Rolle im Kampf gegen die Bedrohungen durch Erderwärmung und Klimawandel. Ähnlich wie in der EU, sind auch 35% der Schweizer Gebäude mindestens 50 Jahre alt. Die Gebäudehüllen dieser Häuser müssen saniert werden um den heutigen Standards mit Hinblick auf Energiebedarf und thermischem Komfort gerecht zu werden. Die Realität bestätigt dass 75% dieser Gebäude nicht energieeffizient sind. Die jährliche Renovationsrate dieser Gebäude liegt lediglich zwischen 0,4 und 1,2%. Mit der Gebäudeenergie Simulationssoftware WUFI®PLUS wurde ermittelt, welcher Einfluss die Faktoren Standort, Ausrichtung, Verglasung, Wärmedämmung, Nachtlüftung, Referenztemperatur, WWR und Verschattungsfaktor auf ein Walliser Bauernhaus aus dem 19. Jahrhundert haben. Dabei wurde besonderes Augenmerk auf den Heizenergiebedarf und den thermischen Komfort gelegt. Die Ergebnisse wurden gemäß den Normen SIA 380/1 und EN 15251 ausgewertet. Dabei wurde ein hohes Maß an Wärmekomfort bezüglich der Norm EN 15251 erzielt. Gleichzeitig konnte der Heizenergiebedarf unterhalb der SIA 380 Grenzwerten gehalten werden. Dies konnte einerseits dank einer verbesserten Wärmedämmung, mit einer geringen Wärmedurchlässigkeit von 0,25 W / m2K, erreicht werden. Andererseits wurden Fenster mit einer Wärmedurchlässigkeit von weniger als 1,00 W / m2K eingeplant. Zusätzlich wurde ein Verhältnis von Fensterfläche zu Wandfläche von 0,53 eingeführt. Die Messungen zeigten dass die horizontale Ausrichtung, die Nachlüftung und der Beschattungsfaktor keinen erheblichen Einfluss auf den thermischen Komfort und den Heizenergiebedarf haben.

Luzern, 7th June 2019

Horw, Lucerne University of Applied Sciences and Arts - School of Engineering and Architecture

Bachelor Thesis

Converting a 19th century farmhouse in Valais into a low energy demand residential building.

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Declaration of authorship

I hereby declare that I have written this thesis without any help from others and without the use of documents and aids other than those indicated. All text excerpts used, quotations and contents of the other authors are explicitly denoted as such in compliance with Article 25, Paragraph 2 of the Swiss Copyright Act.

Horw, 7th June 2019

Christophe Kurkdjian

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Abbreviations and Nomenclature

Abbreviations

ACH	Air Change Rate
AC	Air Condition
HED	Heating Energy Demand
HVAC	Heating, Ventilation, Air Conditioning
NDC	Nationally Determined Contribution
NZEB	Nearly-Zero Energy Buildings
OFAT	One-Factor-At-A-Time
SES50	Swiss Energy Strategy 2050
SU	SketchUp
SIA	Société Suisse des Ingénieurs et Architects
WP	WUFI®PLUS
WWR	Window to Wall Ratio

Nomenclature

α	Thermal diffusivity
A_E	Energy Reference Area
A_{th}	Thermal Envelope Area
f_{cor}	Temperature Correction Factor
g	Solar Energy Transmittance
$Q_{H,N}$	Heating Energy Demand
$\Delta Q_{H,N}$	Increase in Heating Energy Demand
$Q_{H,DD}$	Initial Heating Energy Demand
σ	Penetration de pth
τ	Shading factor
T	Time period
$T_{E,AVG}$	Running Mean Exterior Temperature
T_i	Indoor Temperature
T_O	Operative Temperature
ΔT	Temperature Oscillation Amplitude
T(t,x)	Temperature Oscillation

1 Introduction

This century, climate change, global warming, greenhouse gases and the effect of human activity have been declared an "existential threat" (Laville, Taylor, & Hurst, 2019). Since the industrial revolution and the increase in global use of fossil fuels, the emission of greenhouse gases, especially CO2 (or CO2 equivalents), drastically rose which ultimately affects global warming and the climate change rate (NASA, 2019). Furthermore, as populations and urbanisation continue to grow over time, the demand for energy grows with them (Madlener & Sunak, 2011). This affects the continuous need for more energy and is the main driver for the use of fossil fuels and nuclear power. These energy sources are problematic as the burning of fossil fuels generates greenhouse gases and nuclear power has considerable safety concerns e.g. Fukushima in 2011 (Bose, 2010).

Internationally, numerous action plans exist to combat this threat. The most significant is the Paris Agreement, an agreement within the United Nations Framework Convention on Climate Change (UNFCCC), which was negotiated by the Committee of Parties (CoP21) in December 2015, and has now been signed by over 190 parties. It aims to hold global warming below 2°C and "pursue efforts" to limit it to 1.5°C. To achieve this target, Nationally Determined Contributions (NDCs) outlining post-2020 climate actions have been submitted by countries globally (UNFCC, 2015).

Following the Fukushima incident in 2011, Switzerland decided to phase out its five nuclear power plants which produce over 30% of domestic power (UVEK, 2011). Switzerland also submitted an NDC which "commits to reduce its greenhouse gas emissions by 50 percent by 2030 compared to 1990 levels" (NDC Registry , n.d.). In addition to the NDC, in May 2017 the Swiss electorate accepted the revised Energy Act. This sets out the "Swiss Energy Strategy 2050" (SES50), which aims to increase energy efficiency, promote the use of renewable energy and forbids the construction of any new nuclear power plants (SFOE, 2018).

In accordance with the objectives of the SES50, the Swiss must reduce their energy demand. Improving energy efficiency is the prime objective of the Energy Act. Almost 25% of the Swiss energy demand comes from the real estate sector. 30% of which is for heating, air-conditioning and hot water. To address climate change, it is therefore key to investigate how to implement solutions to improve energy demand in households (SFOE, 2018).

One approach of the SES50 focuses on tax rates. Market-based regulations fix CO_2 emission prices and electricity is taxed to adapt environmental cost to correspond to the political targets (Böhringer & Müller, 2014). Another way this legislation tackles the problem is by strict energy regulations on new building constructions and more specifically on the building envelope. Nearly-Zero Energy Buildings (NZEBs), are constructions which are designed in such a way that all parameters favour low energy demand, which is usually serviced by renewable energies (Energy performance of buildings, s.d.).

Data for the European Union's building stock reveal that about 35% of it is over 50 years old and nearly 75% of these buildings are energy inefficient. However, only 0.4-1.2% of the building stock is renovated each year (Energy performance of buildings, n.d.). A similar portion of the Swiss building stock are buildings where the objective of the construction was not the building envelope, but long-term usability. Therefore, the building envelopes of these buildings are invariably not well adapted to current needs of energy demand and thermal comfort.

The building considered in this research is a farmhouse built in 1895 in the area of Sion, Switzerland, with indoor temperature ranging from -8.5°C to 29.5°C without any central heating or cooling. Currently heating is provided by decentralised 13kW electric heaters which maintain a minimum internal temperature of 20°C from January to May and from September to December. It should be noted that the thermal transmittance (U-value) of the external walls, roofs, floors (apartment 1 & 2) and windows are: 1.39 W/m^2K, 1.05 W/m^2K, 1.32 W/m^2K & 1.72 W/m^2K and 2.84 W/m^2K respectively. The climate of southern Switzerland comprises cold winters and mild summers and any attempt to achieve NZEB for the farmhouse would require considerable refurbishment and investment.

In Switzerland, the "Société Suisse des Ingénieurs et Architects" (SIA) set the standards, regulations and guidelines for the construction industry. This paper will consider the SIA 380/1 (SIA, 2016) with reference to the thermal insulation of building components following a renovation and the energy demand of a building; as well as assess the European Standard EN 15251 (CEN, 2007) to evaluate the thermal comfort of the building envelope.

The main objectives for this research are:

1. By means of the building energy simulation software WUFI®PLUS and 3D modelling software SketchUp, to create a 3D model of the house in order to study the impact of insulation, glazing, window to wall ratio, shading, orientation and location on thermal comfort (EN 15251) throughout the whole year, as well as the energy demand for heating during heating periods (SIA 380/1).
2. Demonstrate and analyse the impact of the different measures on the energy demand and thermal comfort and quantify the effect of each respective measure using a one-factor-at-a-time (OFAT) method.

Research on renovation of Swiss pre-war buildings' thermal envelope are scarce. However, research on similar buildings in other countries is available. Bojić et al. (2014) looked at small residential buildings in Serbia and how optimising the thickness of thermal insulation could improve energy efficiency. Research in Canada in a similar climate, reveals space heating accounts for 60% of residential energy usage. Here again, reducing energy consumption by minimising envelope heat losses is a common approach used (Dixon, Richman, & Pressnail, 2012). Also, Simona et al. (2017) demonstrated similar benefits by increasing in thermal insulation on the energy demand of households in Romania. Available research therefore strongly suggests that optimal insulation is key to improving the building envelope of and reducing energy demand in colder climates.

Additional research considers other approaches to improve the building envelope. For instance, Manz & Menti (2012) show the impact of glazing on energy gains and losses in different locations in Europe. Additionally, passive design approaches such as window-wall ratio (WWR), efficient shading and passive cooling by night-time ventilation have also shown positive results (Manz, et al., 2018). Several researchers from China considered multiple parameters in improving the building envelope and reducing the energy consumption. Huang et al. (2014) investigated the effect of WWR and types of window glazing on the optimisation process of the building envelope of houses in the city of Shenyang. Also, Yu et al. (2008) showed that shading combined with thermal insulation of the walls decreased air conditioning (AC) needs and electricity consumption by 11.31% and 11.55% respectively. Lastly, Yang et al. (2008) investigated how the building envelope of an office would behave in different climates in China and analysed the thermal transmittance of the building walls and the heating degree-days.

Whilst only limited Swiss research exists on solutions to improve the building envelope, Rinquet and Schwab (2017) have an approach named eRen. Their research aims to put together a well-balanced solution comprising energy savings, constructive and physical issues, architecture, cost and use value of buildings. Their research sampled 193 buildings with specific criteria built in the time frame of 1900-1990.

In light of the numerous studies on renovation solutions of buildings done overseas against the few available nationally (eRen), the aim of this thesis is to evaluate the different measures that can impact the heating demand and thermal comfort of a farmhouse built in 1895, in Valais while respecting the SIA 380/1 (SIA, 2016) and EN 15251 (CEN, 2007) standards. The industrial partners concern to preserve the climate and preserve the traditional character of the house will therefore require careful analysis and creative solutions.

2 Methodology

The scope of this thesis considers the building envelope a 19th century large farmhouse in Riddes, in Valais, Switzerland. This building was chosen because it is family owned and therefore the access to data for the research process was straightforward. The structure of this section follows the steps depicted in Figure 1 below. The first task was collecting the relevant data and information to set up an accurate current building envelope in the simulation software. Then came the parametric study to evaluate the effect of the input variables on the energy demand for heating and thermal comfort. The final step was to evaluate the different energy demand and thermal comfort results and comparing them to SIA 380/1 (SIA, 2016) and EN 15251 (CEN, 2007) standards as well as discussing the outcomes.

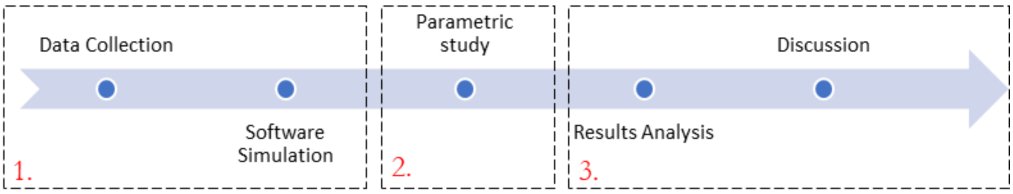

Figure 1: Approach used to reach results

2.1 Data Collection

The data collection process was split into three main parts:

- Collecting the architectural plans of the farmhouse – Building Geometry
- Determining all the surface compositions of the farmhouse – Building Assembly
- Collecting the weather data over the course of the year in the area of the farmhouse – Climate and Weather Data

Building Geometry

The first step was to get the architectural plans from the business partner and house owner. Figure 2 shows the architectural plan of the ground floor. The complete plans and measurements of the whole building can be found in Appendix A.

Building Assembly

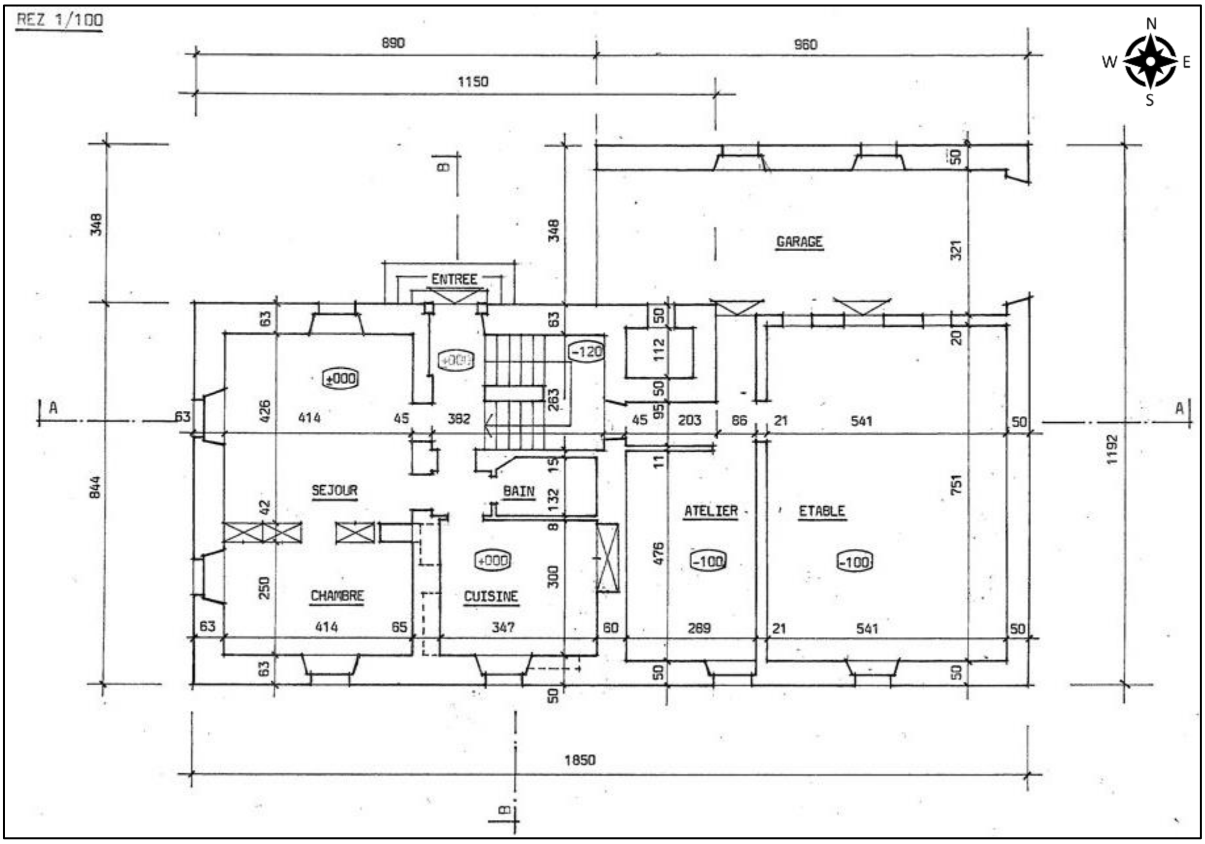

Figure 2: Architectural plans of the ground floor

Defining the assembly of each wall, ceiling, floor, window and roof was the second step. These were sought out by inspecting the building in real life, looking at old pictures and building architectures in the surrounding area. The main surface assembly is that of the exterior. These walls are all made of a mix of granite and mortar with a layer of plaster on both sides of the wall. Determining the exact ratio of granite to mortar was not possible from the collected data. As a result, a material composed of 70% of granite and 30% mortar was defined for the calculation. The weighted average properties of this material can be found in the Appendix B.

Climate and Weather Data

Riddes is a village in Valais in the southern part of Switzerland. This climate is temperate oceanic climate (Cfb) according to the Köppen-Geiger climate classification. The exterior climate conditions of a building are important in many aspects because they determine the energy required to heat or cool a thermal envelope. In addition, it determines the indoor environment, for unheated or uncooled building zones (Manz, 2016). The two climates considered in this research are the exterior air temperature and the ground temperature from 01.01.2019 to 01.01.2020.

The exterior air temperature was collected using Meteonorm. This software was used because it generates key data such as global radiation, daily temperature, precipitation, wind speed and diffused radiation. This data can be collected for approximatively 5000 sites including Riddes

(Remund, 2010). The file can be extracted as a "wufi ascii climate" (.wac) file and directly uploaded to the simulation software. Figure 3 below shows the exterior air temperature over the year with maximum temperature of 32.90°C, minimum temperature of -8.50°C and a mean temperature of 11.23°C. The data period used by Meteonorm for irradiation data is from 1996 to 2015, and 2000 to 2009 for other parameters (Meteonorm 7.3). Appendix C provides more details on the weather data in Riddes.

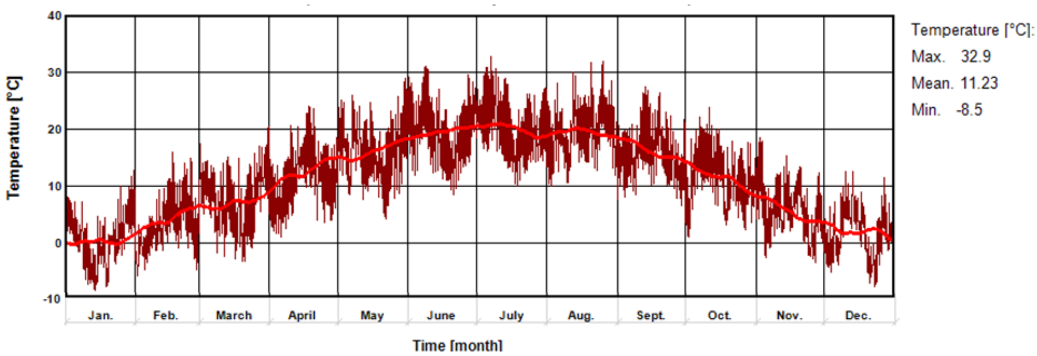

Figure 3: Year-round temperature graph for Riddes

The ground temperature over the year needs to be calculated from the exterior climate for the cellar and stable. Similarly to the exterior air temperature, the ground temperature follows a sine wave pattern that oscillates through the seasons. However, because of the variable physical properties and thermal diffusivity (α) of the ground, the amplitude of the sine wave is dampened. Therefore, the temperature oscillation in the semi-infinite layer (the ground) is given by the equations below (Manz, 2016):

Temperature oscillation (°C): $$T(t,x) = T_{E,avg} + \Delta T \times e^{-x/\sigma} \times cos\left[\frac{2\times\pi}{T} \times t - \frac{x}{\sigma}\right]$$

Penetration depth (m): $$\sigma = \sqrt{\frac{T}{\pi}} \times \sqrt{\alpha}$$

To use these equations, the temperature of the earth at 2.50 m (depth underground of the cellar) would be required. Furthermore, the ground around the farmhouse would have to be sampled and analysed to determine the thermal diffusivity of it. Instead, a general approach was considered. At a depth of 2.50 m the estimated amplitude of the ground temperature is set at 4.00 K. Combined with the mean temperature of 11.23°C (see Fig. 3) and the maximum temperature date, the ground temperature profile could be set for the simulation software (see Fig. 4).

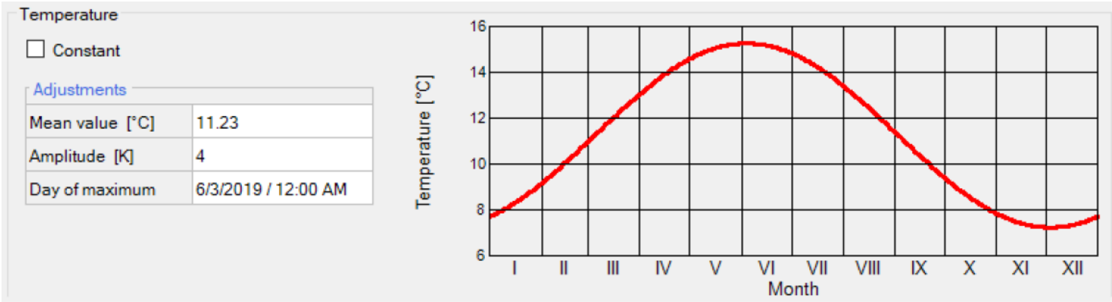

Figure 4: Ground temperature profile as seen in the energy simulation software WUFI®PLUS

2.2 Software Modelling & Reference Case

WUFI®PLUS

The main software used for this research was WUFI®PLUS v3.2.0.1 (WP). This software simulates the indoor environment, thermal comfort and energy consumption in buildings. Furthermore, it can be used to simulate hygrothermal conditions in building components, this refers to the movement of moisture and heat through walls (WUFI®, 2019).

The simulations in WP are based on user defined parameters. Therefore, the data collected in section 2.1 above will set up the reference case for this research. Starting with the weather data, although WP has an in-built database of climates across the globe, the closest available location to Riddes is Locarno in Tessin. Instead, the weather data for a year (01.01.2019 to 01.01.2020) for Riddes, was extracted from Meteonorm for more accurate climate data.

Then, the next step is to define the building geometry. One way is to use the building wizard tool available in WP. This allows the user to design a simple building geometry by defining width, length and height of floors, roofs and basements. However, the farmhouse modelled in this report has a complex geometry that WP does not handle properly.

SketchUp

Therefore, SketchUp (SU) was used as a 3D modelling software for the complex geometry of the building. This software is a general-purpose 3D polygon-modeler (it considers surfaces only, not volumes), which features dimension-controlled modelling, general editing tools and easy-to-use dimensioning (Schreyer & Simi, 2008). Using the architectural plans presented earlier, the building geometry of the farmhouse could be built. This software was used because the 3D model built in SU can directly be imported to WP through a built-in. Figure 5.A shows the farmhouse 3D model in SketchUp before being imported to WUFI®PLUS (Figure 5Figure 5.B). With the building geometry set, the surface assembly of each component of the reference case can be defined. Table 1 below summarizes the building geometry and use of the reference model exported to WP.

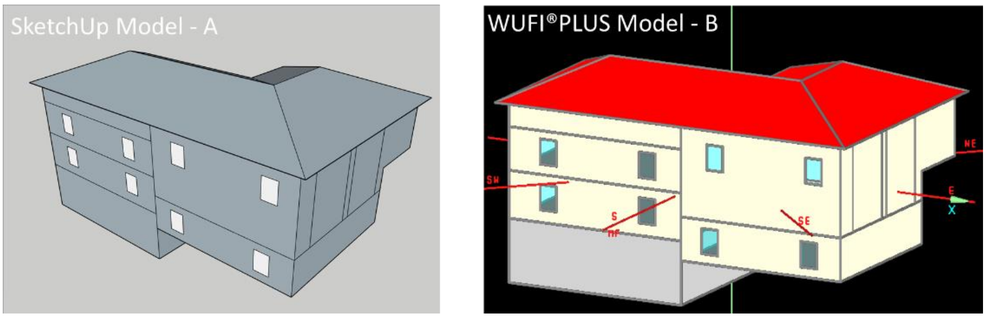

Figure 5: Farmhouse model in SketchUp (A) imported to WUFI®PLUS (B)

Table 1: Geometry and use of the building

Main Building - length x width x height (m)	18.50 x 8.44 x 6.89
Gross floor Area (m^2)	651.23
Gross Volume (m^3)	1610.37
Window to Wall Ratio S/W/N/E (-)	0.07/0.08/0.05/0
Area of internal walls (m^2)	139.68
Use (-)	Residential living

2.3 Reference Building Model

Gathering the information of the surface assembly can be challenging for old building as the documentation listing these features never existed or was lost over time. Estimations of the different assemblies were done from real time observations, existing pictures, information from similar local buildings and insights on some of the surface assemblies during minor renovation work.

The main surface assembly of the apartments is the exterior walls. These walls are made of a mixture of granite and mortar and is covered on the inside and outside with a layer of gypsum plaster. Table 2 below shows the materials used for the surface assembly, details of the thickness, thermal conductivity, density, specific heat and the thermal transmittance(U-value). U-values define how a material transmits heat in steady state (Manz, 2016). Figure 24 in the Appendix D displays the complete assembly of all of the surfaces (extracted from WP) of the reference case. Internal walls were defined because although they do not enclose the simulation volume, their properties affect the calculation (WUFI®, 2019). Other internal elements such as furniture, stairs and toilets were not modelled because the current scenario is already complex.

Similarly to the walls, windows also have U-values. The U-value, the total solar energy transmittance and the frame factor of the windows of the farmhouse are displayed in Table 3 below. Furthermore, Window-to-wall ratio (WWR) is an important variable affecting energy performance in a building. Window area compared to wall will have an impact on the building's heating, cooling, and lighting (Manz, 2016).The overall WWR of the farmhouse is 0.2.

Table 2: Layer sequence of floors, walls, roof and door

Assembly		Material	Thickness	Thermal Conductivity	Density	Specific heat	Thermal Transmittance (U-Value)
Units		(-)	(m)	(W/(mK))	(kg/m³)	(J/(kgK)	(W/(m²K))
Walls	Exterior	Plaster	0.05	0.8	1900	850	
		Granite (70%) + Mortar (30%)	0.6	1.402	2122	746.4	
		Plaster	0.05	0.8	1900	850	1.387
	Interior	Plaster	0.05	0.8	1900	850	
		Brick	0.65	0.28	765	850	
		Plaster	0.05	0.8	1900	850	0.373
Floors	Cellar + Stable	Soil Floor	0.5	1.5	1500	2000	1.987
	Barn & Apt1	Plaster	0.01	0.2	850	850	
		Softwood	0.024	0.09	400	1400	
		Concrete	0.065	1.373	2104	776	
		Hardwood	0.025	0.13	685	1400	1.322
	Apt 2 Unheated Attic	Plaster	0.01	0.2	850	850	
		Hardwood	0.025	0.13	685	1400	1.717
Roof	Roof	Tiles	0.07	0.27	1300	1000	
		Softwood	0.05	0.09	400	1400	1.047
Door		Wooden Door	0.5	0.13	650	1500	0.249

Table 3: Reference case window parameters

	Type	U_{window} – mounted	Solar energy transmittance - g	Frame factor
Unit	(-)	(W/(m²K)	(-)	(-)
Windows	old double glazing	2.84	0.67	0.7

Specific Building Envelope

Due to the complex nature of the building, the simulated zones were shared in four as shown in Figure 6 below. The focus of this work is the current living area, depicted as zone 4. The apartments were modelled as a single zone and considered as one building envelope. The heating energy demand (HED) and thermal comfort of this zone were evaluated.

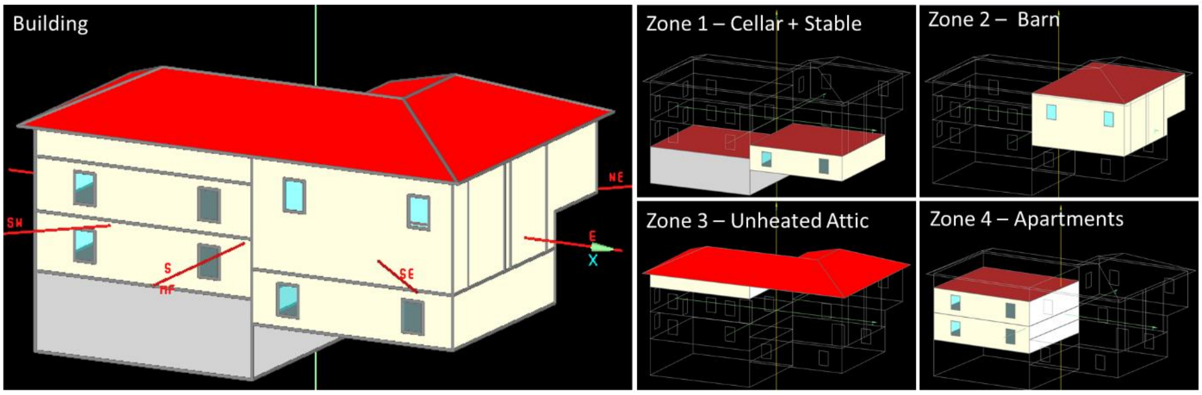

Figure 6: Reference case and the four zones

Prior to running the first simulations, additional metrics needed to be defined for the building envelope. First, the initial temperature in the zone was set to 20°C (SIA, 1999). This temperature was chosen based on the physical activity and clothing level worn in the apartments (See Appendix E). Then the internal loads were defined, WP has a set of existing profiles. The one chosen was: single household according to what was stated by the business partner. This corresponds to 1 Person, 12h/day; 5 Plants; 1 Bathroom; 1 Washing machine done in 4 days. This profile models the heat and carbon dioxide released from Monday to Friday and is based on the German standard DIN 18599-100.

Due to wind and/or temperature differences, pressure differences can occur between the interior and exterior that produce airflows through the air leakages in the building envelope. If the windows and doors are closed the air exchange will particularly occur through joints in the building envelope. This unintentional air exchange is called infiltration. The air exchange through open windows will be referred to as natural ventilation (Manz, 2016). An air change rate (ACH) of 0.5 is set for the natural ventilation, in combination to the infiltration ACH of 0.1 (through cracks in the door and window) a total ACH of 0.6 is set. Additionally, to prevent occasional overheating, blinds are manually adjusted. Thus shading factor is set to 0.1 according to the DIN 18599 standard.

2.4 Analysis

Energy demand through heating analysis

Heating is currently done through a combination of electric and oil heaters of a combined power of 13kW to maintain indoor temperature at 20°C from January 2019 to May 2019 and September 2019 to January 2020. From the months of May to September the heating is turned off and the free running temperature defines the T_O. The resulting energy heating demand for the year can be extracted from the WP reference case simulation in kWh per year. As mentioned in the introduction, the SIA 380 standard sets insulation limits for building components (walls, windows, doors, roofs etc.) but also defines an energy demand per m^2 (kWh/m^2) limit based on several parameters. The equations below were used to estimate the theoretical kWh/m^2 for zone 4. Furthermore, from the calculated limit value, a target value could be established by multiplying the limit value by 60%.

Heating energy demand limit (kWh/m^2) $Q_{H,N} = \left[Q_{H,DD} + \Delta Q_{H,N} \times (\frac{A_{th}}{A_E})\right] \times f_{cor}$

Temperature correction factor (-) $f_{cor} = 1 + \left[(9.4°C - T_{e,avg})\right] \times 0.06\ K^{-1}$

Thermal comfort analysis

Thermal comfort is determined by a combination of the building envelope and the heating, ventilation, air conditioning (HVAC) systems (Manz, 2016). In the present case, only heating is used. To assess the thermal comfort of the building envelope this report considers the European Standard EN 15251 (CEN, 2007). This standard is applied to buildings which do not use mechanical cooling systems and have openable windows. In this empirically derived adaptive thermal comfort, the acceptable operative room temperature range is defined as a function of an exponentially weighted running mean of the exterior temperature (Manz, et al., 2018). Four categories of thermal comfort are defined. The minimum-maximum operative temperature ranges for each category are calculated from the running exterior mean temperature of Riddes – 11.23°C. Table 4 shows the calculation for each category according to the EN 15251 standard. Additionally, category IV is defined as any temperature outside the range of categories I to III. These categories set ranges of temperatures corresponding to different levels of thermal comfort.

Table 4: Equations for the calculation of the categories I to III range

Category I	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 2$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 2$
Category II	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 3$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 3$
Category III	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 4$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 4$

T_i = limit value of indoor operative temperature (°C)
$T_{e,avg}$ = running mean exterior temperature (°C)

In the context of this research, the hourly operative temperatures of zone 4 were collected using WP. Every operative temperature was grouped in the category range it belonged to. From this data, percentages of time spent in each category could be evaluated. Therefore, the thermal comfort level of zone 4 could be evaluated from the percentage of time spent in categories I to IV.

2.5 Parametric Analysis

One-factor-at-a-time is a widely used method to investigate the impact of parameter change on the thermal comfort and the energy demand of the building envelope (Manz, et al., 2018). 8 parameters were varied. Table 2 summarises the reference and the 25 variation cases.

The general reasons behind the selected variable are explained here. Location: Zurich, Locarno and Davos were selected because they represent the three main climates in Switzerland. Orientation: north, west and east were taken to cover the four main orientations. Thermal insulation: values of 0.25 W/m^{2}K and 0.1 W/m^{2}K were chosen in accordance with the SIA 380/1 for limit and target values of walls, ceilings, floors and roofs (Figures 28 and 29 in Appendix F display the surface assemblies with the layer of insulation.). Glazing: values of 0.1 W/m^{2}K and 0.8 W/m^{2}K were chosen in accordance with the SIA 380/1 (SIA, 2016) for limit and target values. Additionally, a glazing of 5.05 W/m^{2}K was considered to see the effect of an inferior U-value. WWR: values of 0.35 and 0.53 were defined by doubling the window surface area of the existing windows and by adding windows to the eastern façade. Regarding the control temperature, ventilation and shading factor variations, the effect of an incremental increase in the respective parameter was done.

Table 5: Reference case parameter summary and variation of input data in the parametric study based on the principle one-factor-at-a-time

Parameter		Reference Case	Variation 1	Variation 2	Variation 3	Variation 4
Location		Riddes	Zurich	Locarno	Davos	
Orientation		South	North	East	West	
Glazing		Old Double	Modern Double	Modern Triple	Old Single	
		U ≈ 2.84 W/(m²K)	U = 1 W/(m²K)	U = 0.8 W/(m²K)	U = 5.05 W/(m²K)	
		g = 0.7	g = 0.65	g = 0.59	g = 0.75	
Exterior Surface Insulation	Walls	U ≈ 1.4 W/(m²K)	U = 0.25 W/(m²K)	U = 0.1 W/(m²K)		
	Floors	U ≈ 1.2 W/(m²K)	U = 0.25 W/(m²K)	U = 0.1 W/(m²K)		
	Ceilings	U ≈ 1.3 W/(m²K)	U = 0.25 W/(m²K)	U = 0.1 W/(m²K)		
	Roof	U ≈ 1.1 W/(m²K)	U = 0.25 W/(m²K)	U = 0.1 W/(m²K)		
Ventilation	Rest of Year	0.5 ACH	0 ACH	0.5 ACH	0.5 ACH	
	Additionally from 05.2019 to 09.2019 and from 9 pm to 5 am	0.5 ACH	0 ACH	2 ACH	6 ACH	
Internal Temperature		20°C	18°C	22°C	24°C	25°C
Window to Wall Ratio (S/W/N/E - Total)		0.07/0.08/0.05/0 Total = 0.2	0.14/0.17/0.05/0 Total = 0.36	0.18/0.17/0.05/0.13 Total = 0.53		
Shading factor		τ = 0.1	τ = 0.3	τ = 0.5	τ = 0.75	

3 Results

These results follow the steps presented in the methodology. First the results of the reference case are discussed with regards to the EN 15251 (CEN, 2007) and SIA 380/1 (SIA, 2016) standards. Then, the 8 parameters considered in the parametric analysis are individually presented.

3.1 Reference case results

The results from the software simulation of the reference case are presented here. The data focuses on the thermal comfort according to EN 15251 (CEN, 2007) and the energy demand per m^2 (kWh/m^2) according to SIA 380/1(SIA, 2016).

Thermal Comfort

Figure 7 below displays the operative temperature (T_O) as a function of time in months and against the yearly exterior temperature. As can be seen from the graph, when the heating is turned off from the month of May to the month of September the free running temperature drops below the desired 20.00°C internal temperature. T_O ranges from 15.00°C to 26.30°C during the summer period.

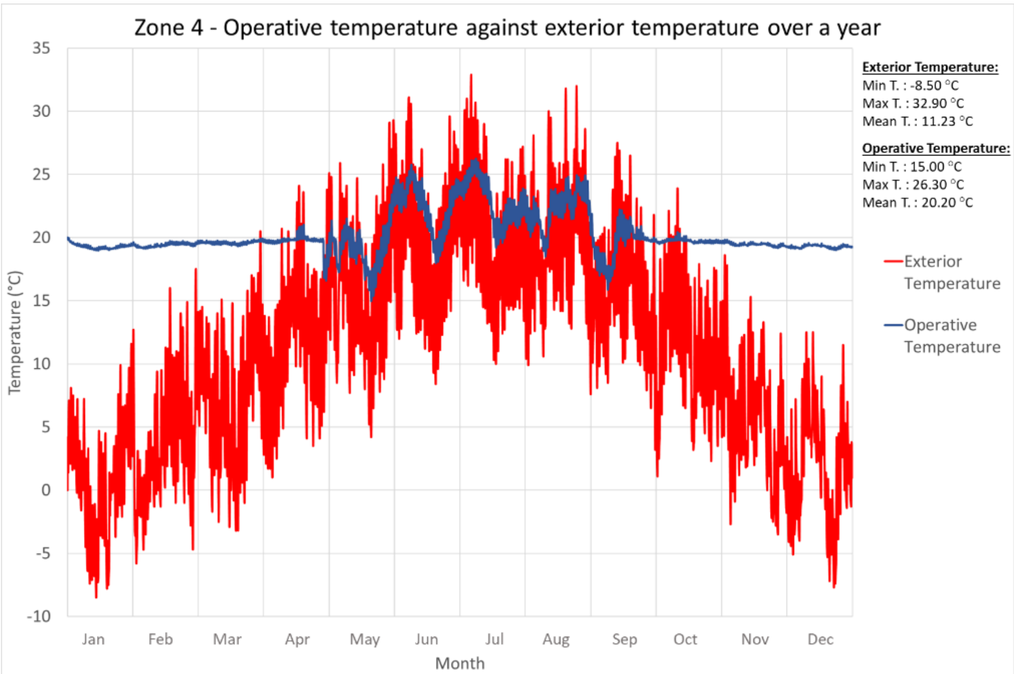

Figure 7: Zone 4 operative room temperature and exterior temperature as a function of time

As indicated in the methodology, to evaluate the thermal comfort level, categories I-IV need to be calculated and defined. These categories set ranges of temperatures corresponding to different levels of thermal comfort. The range of these categories is directly influenced by the mean exterior temperature ($T_{E,AVG}$) over a year. $T_{E,AVG}$ for the region of Riddes is 11.23°C. Table 6 below shows the results of the calculations, which will later be used as reference values in the parametric analysis. Further details on the calculations can be found in the Appendix F.

Table 6: Specific range of categories I-IV for the climate in Riddes

	Min (°C)	Max (°C)
Category I	20.50	24.50
Category II	19.50	25.50
Category III	18.50	26.50
Category IV	<18.50	>26.50

Figure 8 shows the cumulative T_O of the reference case and combines the results of the EN 15251 (CEN, 2007) standards in a 100% stacked bar chart. The results highlight that the reference case does not have an adequate thermal comfort level with only 21% of the year spent in category I. The current building envelope of zone 4 is not suited to the thermal comfort standards.

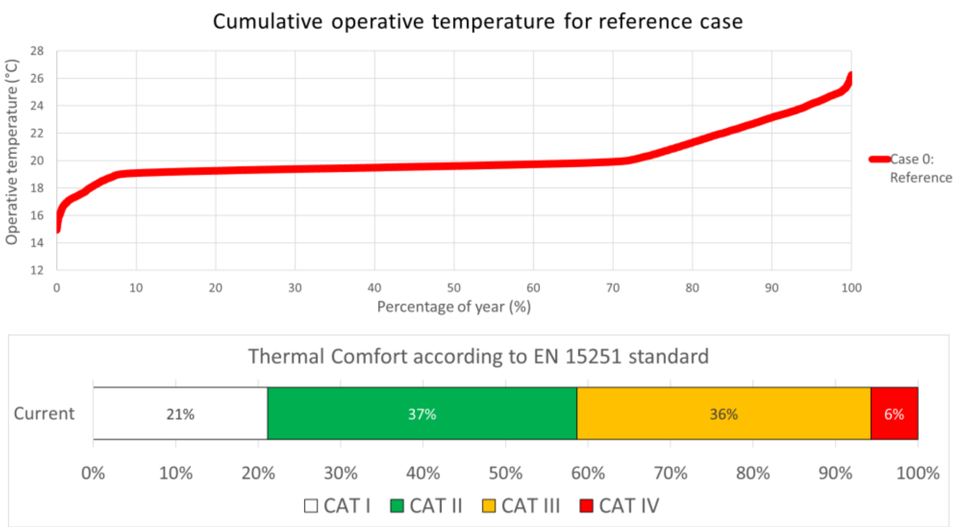

Figure 8: Cumulative T_O of the reference case and the performance against the EN 15251 standard

Heating Energy Demand

Maintaining the temperature at 20°C before the month of May and after the month of September is what contributes to the heating energy demand of the building envelope. As mentioned in the methodology, the SIA 380/1 (SIA, 2016) standard provides equations and reference values to estimate the heating demand a building envelope should have according to the energy reference area (A_E) and the thermal envelope area (A_{th}). The standard provides a formula for the limit HED value which is calculated using the A_E, the A_{th} and additional parameters, as well as a target value which corresponds to 60% of the limit value. The WP simulation calculated the actual energy demand of the building envelope which was then divided by A_E to give the heating energy demand for the reference case.

Figure 9 compares the heating energy demand of the current case as well as the limit and target value set by the SIA 380/1 (SIA, 2016). These values show that the current heating demand of zone 4 is extremely high and exceeds the calculated limit by over 150 kWh/m^2. The Appendix G shows the detailed calculations of these results.

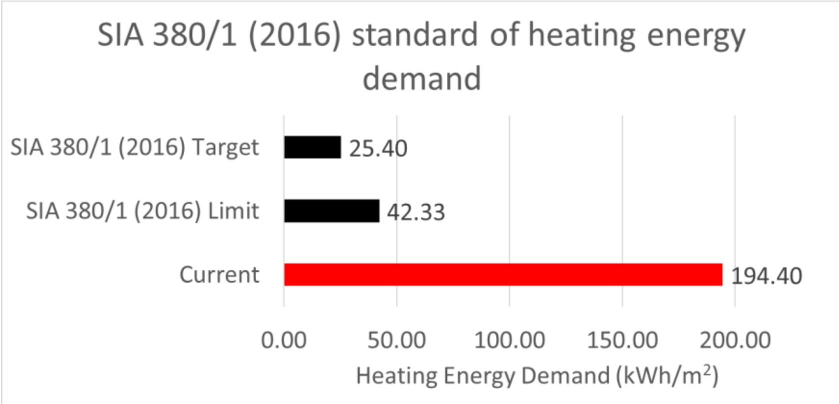

Figure 9: Heating energy demand of the reference case compared the SIA 380/1 standard (SIA, 2016)

The results of the reference case display how inadequate the building envelope of zone 4 is with regard to thermal comfort (EN 15251 (CEN, 2007)) and energy heating demand (SIA 380/1 (SIA, 2016)). In light of these results, the parametric analysis will show the effect of variable changes on the thermal comfort and energy heating demand using the OFAT method.

3.2 Parametric Analysis Results

Figure 10 gives an overview of the cumulative operative room temperature of the reference case (red bar) and the 25 other cases as a percentage of the year. Results show that close to 65% of the T_O is below 20°C in all simulations except the new thermal insulation and increased initial temperature. The effect of location, orientation, window and building thermal transmittance, ventilation, initial temperature, WWR and shading factor with regards to the SIA 380/1 (SIA, 2016) and EN 15251 (CEN, 2007) standards will be discussed individually next.

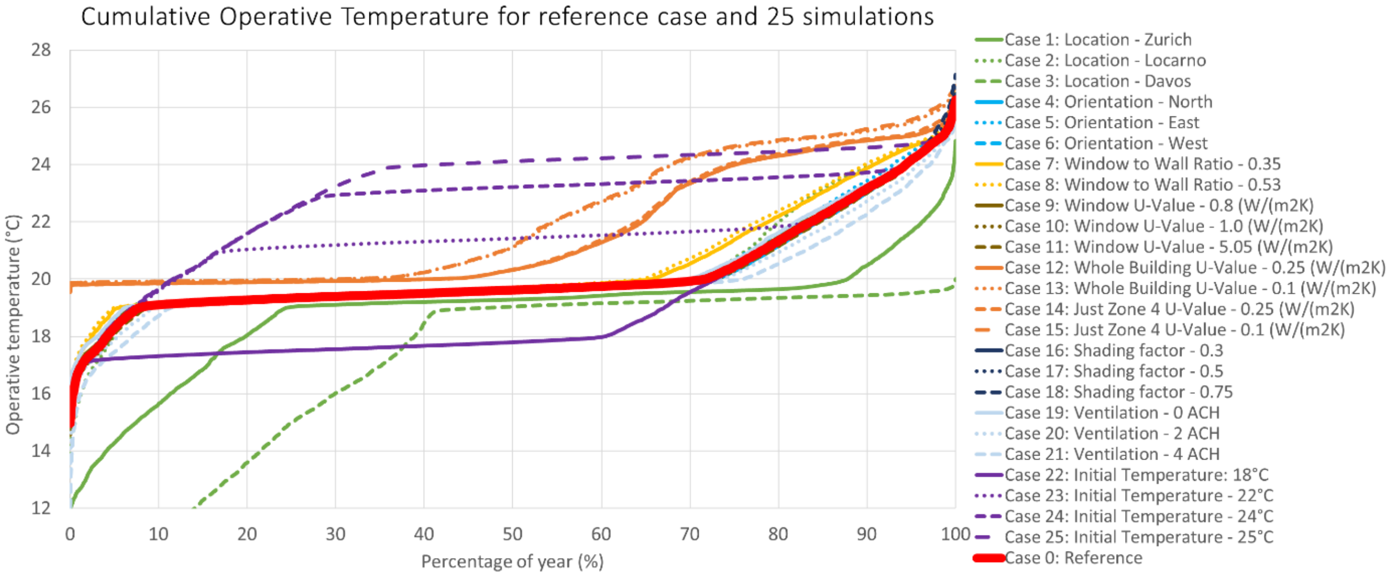

Figure 10: Cumulative frequency distributions of operative temperatures of the reference case and 25 other cases.

3.3 Results and Evaluation of the Parametric Analysis

The OFAT results of the 25 cases are grouped into 8 parameters. Each graph displays the heating energy demand in kWh/m² of the reference case (red bar) against that of the simulation of each variable in a clustered bar chart and the results of the EN 15251 (CEN, 2007) standard in a 100% stacked bar chart with the bottom bar being the result of the reference case (red outline). Appendix H and I show the compiled results of the 26 cases (with the reference case) for the heating energy demand and thermal comfort respectively.

Location

The location has a considerable effect on the heating demand (see Figure 11). Riddes and Locarno have similar heating energy demands of 194.40 kWh/m^2 and 203.91 kWh/m^2. However, the cities of Zurich and Davos require an additional 54.25 kWh/m^2 and 107.88 kWh/m^2 respectively. The thermal comfort results show that the best locations are those of Riddes and Locarno with 21% and 20% of T_O spent in category I. Yet, the T_O of these two locations is for 6% of the year outside Cat III. Davos and Zurich, on the other hand, have operative temperatures outside category III for 40% and 22% of the year respectively.

Looking at Davos, which is an alpine village at an altitude of 1560m with a mean temperature of 3°C and low temperatures reaching -20°C, the current building envelope is not suited to such climates. The climate in Locarno is similar to that of Riddes, both cities are at similar latitudes of 46.17° and elevation of 366m and 491m respectively. The city of Zurich is at a higher latitude of 47.38° but a similar elevation of 556m as Riddes. The colder climate is therefore the reason for the increase in energy demand. As can be seen, the year-round exterior temperature has a strong effect on the heating demand and the thermal comfort of a building.

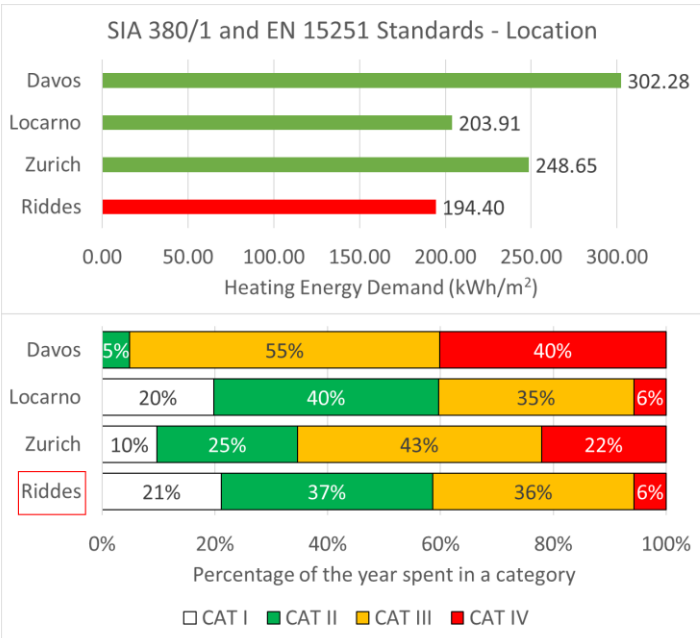

Figure 11: Heating energy demand and thermal comfort results of the effect of location

Orientation

Orientation does not show any sizeable changes in energy heating demand (see Figure 12). Eastern and southern orientations favour an optimal energy heating demand with 192.9 kWh/m^2 and 194.4 kWh/m^2 respectively. Whereas a northern and western orientation would increase the heating energy demand to 199.1 kWh/m^2 and 202.5 kWh/m^2 respectively. Changes in orientation only affect the percentage of thermal comfort in Category I by 1%. Although the general effect is negligible, the optimal orientation of the farmhouse as it is, is eastwards. The worst orientation is northwards.

The slight variation in heating demand and thermal comfort could be explained by the uneven window to wall ratio on the facades. Indeed, more accurate results could be generated if only one façade was glazed or if every façade has the same WWR.

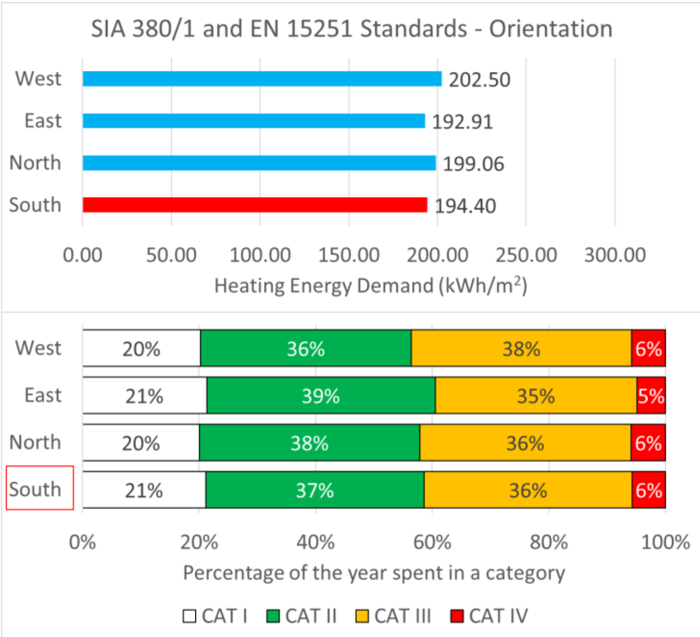

Figure 12: Heating energy demand and thermal comfort results of the effect of orientation

Ventilation

Passive cooling by night-time changes of 2 or 4 ACH have had no notable effect on the energy heating demand (see Figure 13). However, an ACH of 0 reduced the heating demand by 33.09 kWh/m^2. Greater ACH leads to lower levels of thermal comfort. Indeed, as the air exchange rate increases to 4 ACH, 10% of the recorded T_O is in category IV. The optimal level of ACH would be 0 ACH with 23% of the T_O of the year in category I.

The passive cooling by night-time did not have a satisfactory effect on the thermal comfort. The summer day temperatures were not sufficiently high, and the night-time temperatures were too low for night-time passive cooling to have a positive effect on thermal comfort. The results recommend an ACH of 0. However, this suggests that losses through infiltration do not happen and that no window or door are opened at any time which is not realistic. Furthermore, the indoor air quality would be extremely poor as CO_2 levels would build up quickly. However, this standard is not covered in this research.

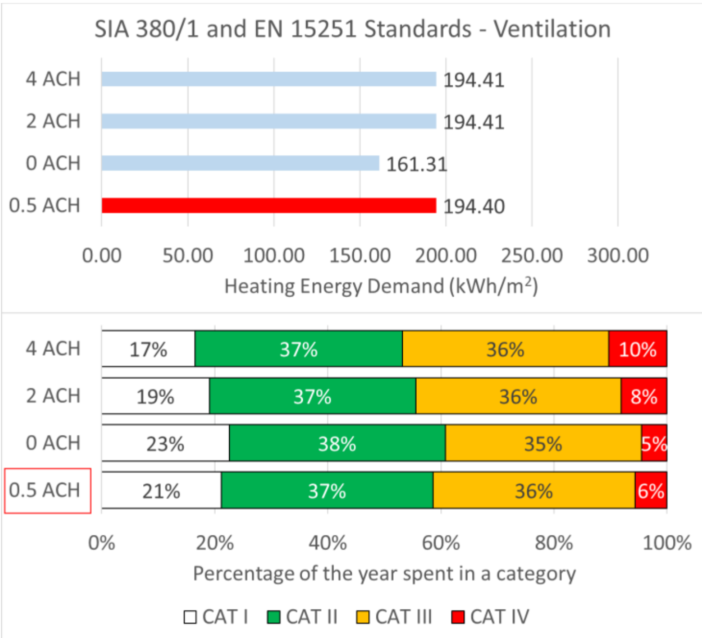

Figure 13: Heating energy demand and thermal comfort results of the effect of ventilation

Shading Factor

The shading factors have had no noticeable impact on the heating demand or the thermal comfort (see Figure 14). Because they were programmed to engage when internal temperatures exceeded 26°C, which occurred only for 15 hours of the year, the full benefits of shading could not be seen.

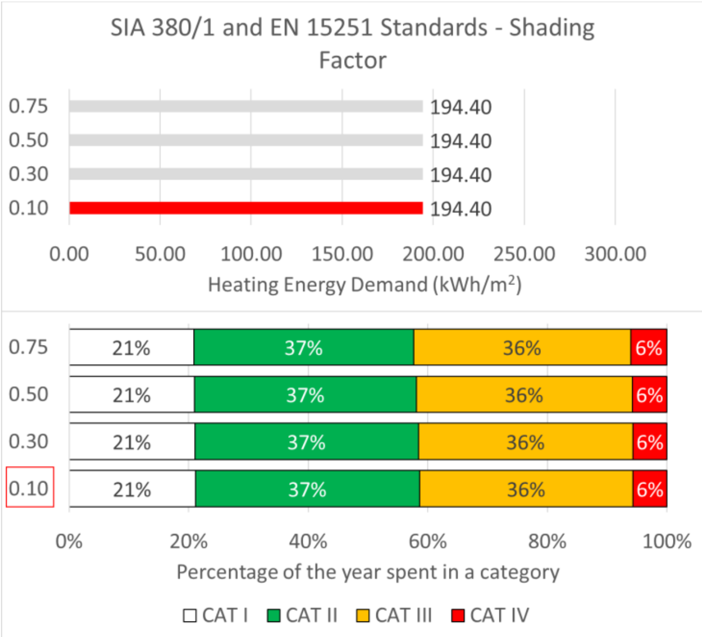

Figure 14: Heating energy demand and thermal comfort results of the effect of the shading factor

Thermal Insulation

Improving the thermal insulation generates significant reductions in HED (see Figure 15). However, only minor changes are observed because the insulation around the whole building is a fraction better than that of zone 4. When looking at the effect of insulating zone 4 only, an insulation of 0.25 W/m^{2}K would cut the HED to 45.81 kWh/m^2, and to 28.91 kWh/m^2 if the insulation is further increased to 0.1 W/m^{2}K. Changes to the insulation of the reference case considerably improve the thermal comfort. Over 94% of the recorded temperatures are then between category I and II against the original 58%. Similarly, the difference between insulating the whole building or just zone 4 only changes by 1% overall.

These results show that the most significant parameter is the thermal insulation of the building envelope. Indeed, the results approach the target and limit HED of 19.74 kWh/m^2 and 32.91 kWh/m^2 calculated from the SIA 380/1 standard. Furthermore, the thermal comfort is considerably improved.

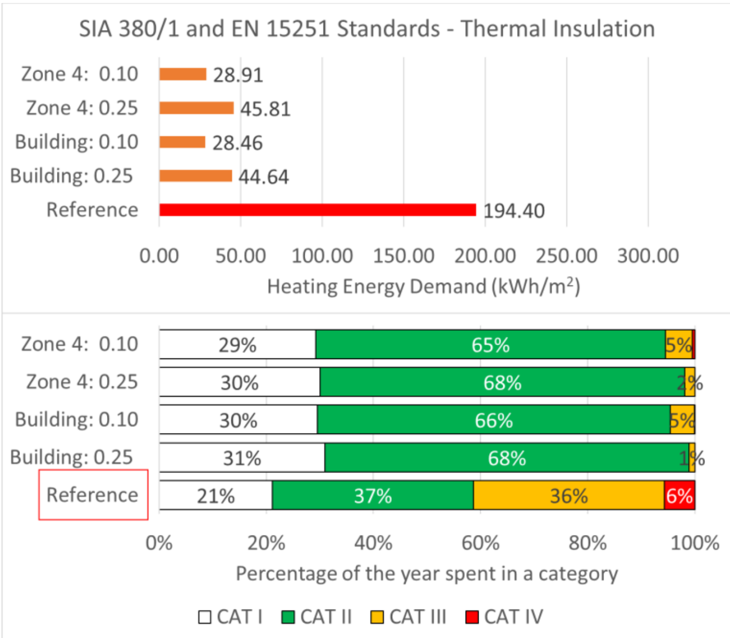

Figure 15: Heating energy demand and thermal comfort results of the effect of the building U-value

Glazing

Higher window thermal transmittance values result in increasing heating demand values (see Figure 16). The limit and target U-value of 0.8 W/m²K and 1.0 W/m²K (according to SIA 380/1) returned the lowest heating demands of 182.83 kWh/m² and 183.95 kWh/m². However, this still is not an acceptable heating demand for the thermal envelope of a building. The results also show that as the glazing is improved, with lower thermal transmittance values, the thermal comfort increases. However, the improvements are not significant as the percentage of time spent in category I and II only increase by 1% and 4% respectively. Furthermore, 5% of operative temperatures are still outside category III. Showing that changes to the glazing are not sufficient to significantly improve the building envelope.

The positive effect of glazing is dampened because of the huge thermal losses through poor insulation of the walls, ceilings and floors. Indeed, U-values of 0.80 W/m²K and 1.00 W/m²K resulted in a drop of 11.57 kWh/m² and 10.45 kWh/m². These drops in HED are crucial when compared to reasonable heating demands of 50 kWh/m² or less. The results of improving the thermal transmittance of the glazing are therefore slightly distorted.

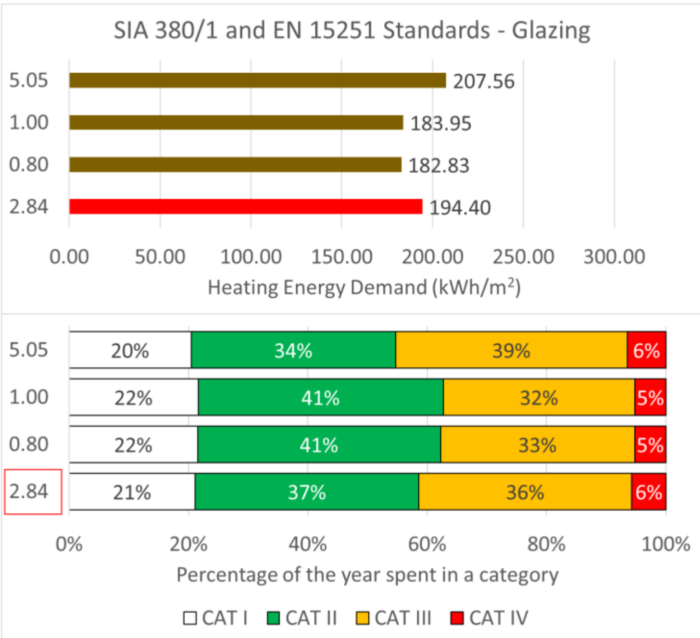

Figure 16: Heating energy demand and thermal comfort results of the effect of glazing

Window to Wall Ratio

The WWR have a significant effect on the kWh/m^2 (see Figure 17). Indeed, as the WWR increases, the heating demand decreases. Ratios of 0.35 and 0.53 resulted in HED drops of 7.65 kWh/m^2 and 9.96 kWh/m^2 respectively. Also, as the WWR increases, the thermal comfort also increases. At a WWR of 0.53, 25% of the operative temperatures are in category I. Additionally, only 3% is spent in cat. IV which amounts to less than 10 days over the year.

However, although the increased WWR improved the HED and thermal comfort the heating demand is still too high for a suitable energy efficient building envelope. Indeed, even if a larger WWR allows for greater solar gains, the thermal losses through the poor insulation of the walls, ceilings and floors are too great. As in the glazing evaluation, these drops in HED are crucial when compared to reasonable heating demands of 50 kWh/m^2 or less. The effect of improving, WWR cannot be fully appreciated because of the significant thermal losses through the walls, ceiling, floor and roofs.

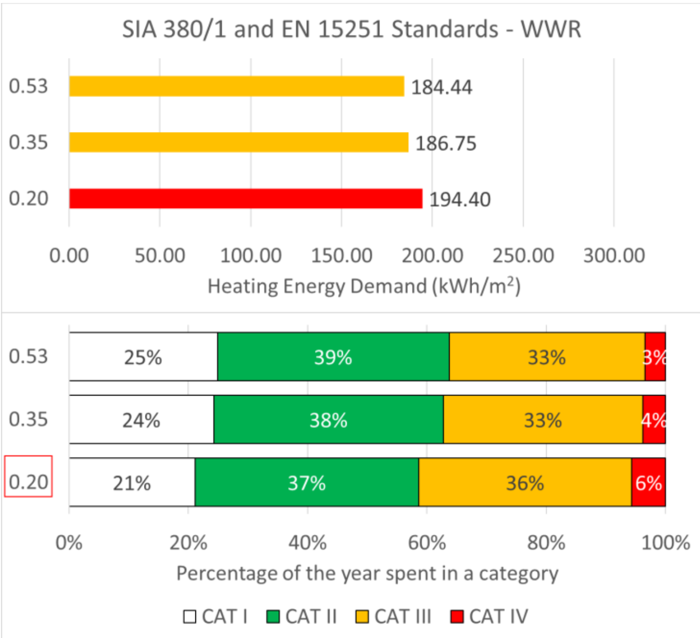

Figure 17: Heating energy demand and thermal comfort results of the effect of WWR

Control Temperature

The initial temperature has a crucial effect on the heating energy demand (see Figure 18). As initial temperature increases from 18°C to 25°C, the HED increases from 157.80 kWh/m^2 to 288.21 kWh/m^2. Changes to the control temperature of zone 4 also has a drastic effect on the thermal comfort of the building envelope. Maintaining an internal temperature between 22°C and 25°C sets over 79% of the operative temperatures over the year in category I. Whereas having the internal temperature at 18°C causes 64% of the recorded operative temperature hours to be in category IV.

These results are to be expected as keeping a higher level of thermal comfort requires a higher demand in energy for heating especially when exterior temperatures are low, as in Riddes.

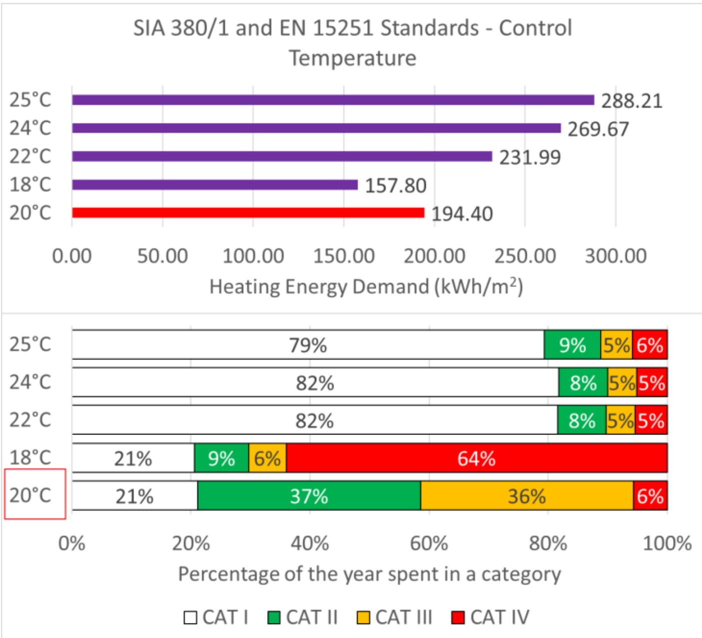

Figure 18: Heating energy demand and thermal comfort results of the effect of the initial temperature

The results of the parametric analysis highlight the importance of thermal insulation on the heating energy demand as well as the thermal comfort level. Indeed, improving the thermal insulation of the building envelope to 0.25 W/m^{2}K or 0.10 W/m^{2}K decreases the heating energy demand and improves the thermal comfort significantly. Furthermore, enhanced U-values of 1.00 W/m^{2}K and 0.80 W/m^{2}K as well as WWR ratios of 0.35 and 0.53 further improved the heating efficiency and thermal comfort of the building envelope. Lastly, increasing the initial room temperature level also improves the thermal comfort. However, the resulting heating energy demand naturally increases which is not a desired result.

4 Discussion

Because the reference case is a family owned building with easy access to plans, data and real time inspection, the collected information was reliable. However, due to the complex structure of the building and its age, some aspects could only be estimated such as the surface assembly and the exact building structure. Others such as the effect of moisture and thermal bridges were not considered in the calculations at all. Nevertheless, the reference model represented an accurate representation of the farmhouse. The results from the reference case showed how inadequate the building envelope of zone 4 was with regard to thermal comfort (EN 15251 (CEN, 2007)) and energy heating demand (SIA 380/1 (SIA, 2016)). Indeed, heating demands of 194.44 kWh/m^2 exceeded the calculated limit value by 152.07 kWh/m^2. Furthermore, only 21% of the recorded operative temperatures were in category I.

The results from changing the exterior climate and therefore the location, revealed that in colder regions like Davos and Zurich with lower $T_{E,AVG}$ values, less suitable levels of thermal comfort could be achieved. Similarly, the heating energy demand was significantly higher in the colder climates of Zurich and Davos. Locarno and Riddes have comparable climates and displayed a similar heating energy demand. Yang et al. (2008) had the same conclusion when evaluating the heating energy demand of an office building in different climates in China.

Because of the harsh winter conditions in Riddes, the addition of thermal insulation around the building showed a drastic improvement in the thermal comfort. The added layer of thermal insulation considerably increased the number of hours spent in category I and II (EN 15251 (CEN, 2007)) from 58% originally to 89%. Furthermore, the insulation values of 0.25 W/m^{2}K and 0.1 W/m^{2}K lowered the heating energy demand of the building - 194.40 kWh/m^2 - to 44.81 kWh/m^2 and 28.91 kWh/m^2 respectively. These U-values were in accordance with the SIA 380/1 standard. The research from Bojić et al. (2014), E. Dixon (2012) and Simona et al. (2017) showed similar findings when investigating the effect of thermal insulation on heating efficiency.

It was found that glazing and window to wall ratio had significant impacts on the heating energy demand. An increase in window to wall ratio led to a decrease of up to 10 kWh/m^2. Whereas a lower window U-value also reduced heating energy demand by up to 12 kWh/m^2. Huang et al. (2014) showed that improved glazing and window to wall ratio had a positive impact on thermal efficiency of the building envelope. The thermal comfort levels were not as significantly affected however, and only minor improvements could be seen. This does not entirely agree with the research Manz et al. (2018) completed. In their evaluation of the benefits of glazing and window to wall ratio (as well as other parameters) on thermal comfort, they concluded that these variables had significant improvements on the thermal comfort of the building. However, their research focused on an office building in Malta which has a Mediterranean climate. The impact of glazing and window to wall ratio in warmer climates appear to be more significant.

Furthermore, their research also assessed the effect of shading factors and passive cooling by night-time ventilation which also improved the thermal comfort. In the reference case, the shading device was used to reduce overheating (above 26°C) but this only occurred during 15 hours over the year and had negligible impact on thermal comfort and heating energy demand. Night-time ventilation was used for a more significant period from the May to September as passive cooling at night-time. The summer day temperatures were not sufficiently high, and the night-time temperatures were too low for night-time passive cooling to have a positive effect on thermal comfort.

The results of the control temperature variation of zone 4 indicated that as the temperature increased to 25°C the heating energy demand increased, and the thermal comfort improved. A control temperature of 18°C reduced the heating energy demand, but also lowered the thermal comfort levels. These results are to be expected as keeping a higher level of thermal comfort requires a higher demand in energy for heating.

The optimal results in the report were solely based on the direct effect on the heating energy demand and thermal comfort. These do not consider the cost factor in implementing any of the solutions. Therefore, a detailed cost-benefit analysis would assist decision making and finding an optimal solution. Additionally, more parameters that would expend the application of this research for the business partner could be evaluated such as the impact on CO_2 emissions and indoor air quality.

Furthermore, having carried out the parametric analysis with the one-factor-at-a-time method, clear results could be drawn regarding the effect of these parameters on thermal comfort and heating energy demand. With thermal insulation, glazing and window to wall ration generating the most significant benefits, further research could seek to combine these parameters in an optimal way to lower the heating energy demand as much as possible while maintaining a suitable thermal comfort level. This research could incorporate the NZEB standard and look into the renewable energy possibilities. With a roof area of 200 m^2 photovoltaic and/or thermal solar panels could be a solution for the reference case. Moreover, the heating system considered in this research comprised decentralised electric heaters. These are not optimal for low energy demand. Therefore, future research could also investigate different types of heating systems such as geothermal, heat pumps, pellet burners or combined heat and power systems.

The climate data used in this research was based on preceding years actual temperatures. However, current long-term forecasts suggest that because of global warming, climates will be changing faster (Santamouris, 2014); the accuracy of future weather data will decrease as year by year higher temperatures are recorded (UNFCC, 2018). This will have a direct impact on heating energy demand and some parameters such as insulation, glazing and window to wall ratio will have an even more significant impact on the building envelope.

The careful preparation of the building model provides an excellent basis for future testing of parameters. Indeed, any future changes to the building structure, internal load or exterior climate and or parameters discussed above can be readily presented simulated and thoroughly evaluated upstream.

5 Conclusion

The research focused on a farmhouse built in 1895 in Riddes, Valais which is in a temperate oceanic climate (Cfb). Through the use of the building energy software WUFI®PLUS, a reference model based on the architectural plans and surface assemblies could be designed. Next, a parametric analysis considering the following passive design strategies: location, orientation, glazing, thermal insulation, ventilation, initial temperature, window to wall ratio and shading factor, was carried out using the one-factor-at-a-time method. This research evaluated the effect of these passive design strategies on the thermal comfort and heating energy demand according to the EN 15251 (CEN, 2007) and SIA 380/1 (SIA, 2016)standards respectively.

The present study established that by improving the thermal insulation to 0.25 W/m^2K or less, installing windows with thermal transmittances inferior to 1.00 W/m^2K and window to wall ratios of 0.53, higher levels of thermal comfort could be achieved while keeping the heating energy demand below set limits by the SIA 380/1 (SIA, 2016) standard.

The author would like to acknowledge the contribution of the Fraunhofer Institute for Building Physics (IBP) to the project by making the software WUFI®PLUS available and thank the Hochschule Luzern and Prof. Heinrich Manz for supporting and advising on the project.

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Appendix

The following pages contain relevant information to further support and explain the mentioned methodology and results of the presented research. The detailed excel calculation is delivered separately.

Appendix A – House Plans

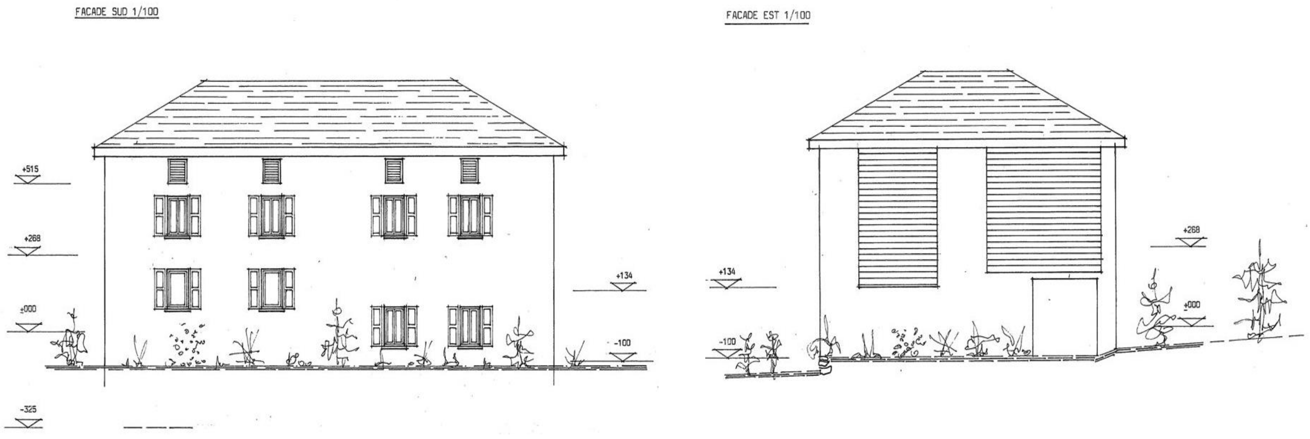


Figure 19: Appendix – South (left) and East (right) façades

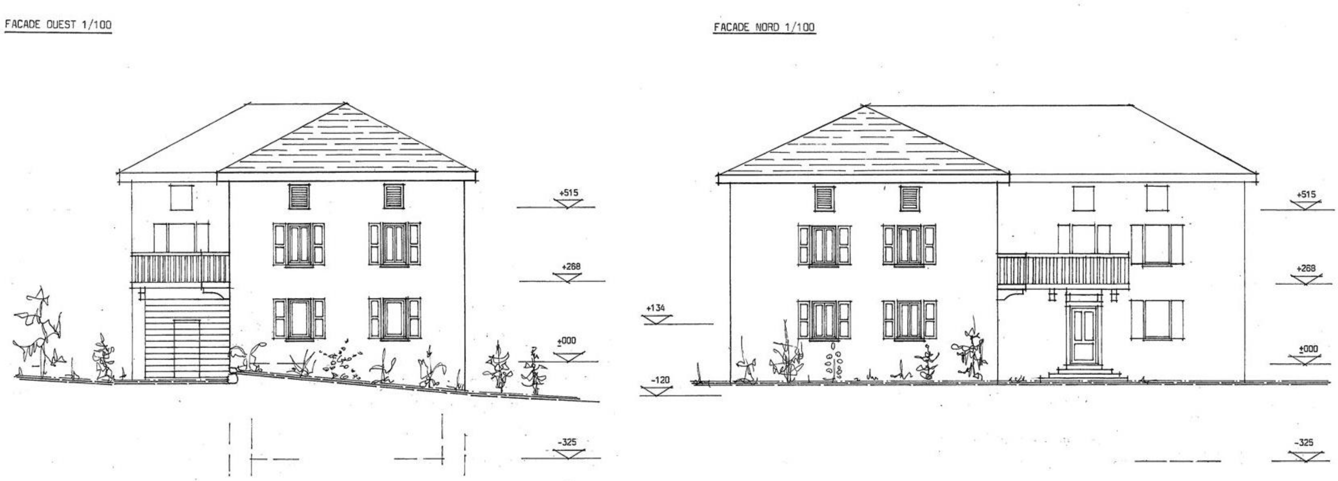


Figure 20: Appendix – West (left) and North (right) façades

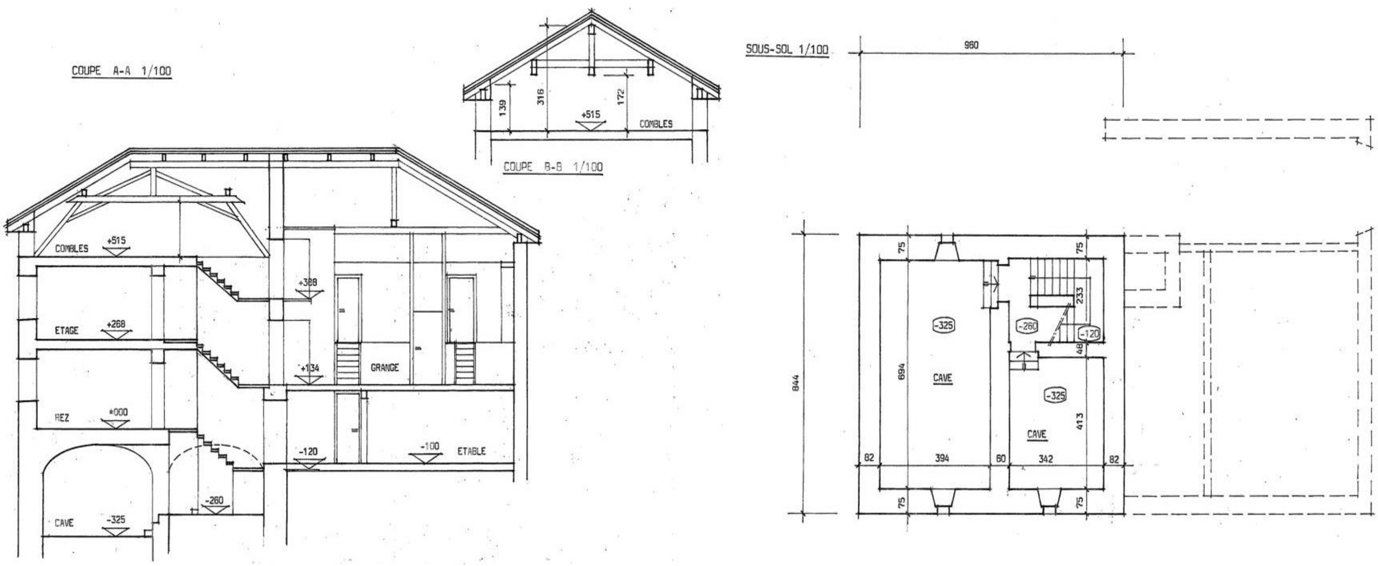


Figure 21: Appendix – Cross section views (left) and Architectural plans of Floor -1 (right)

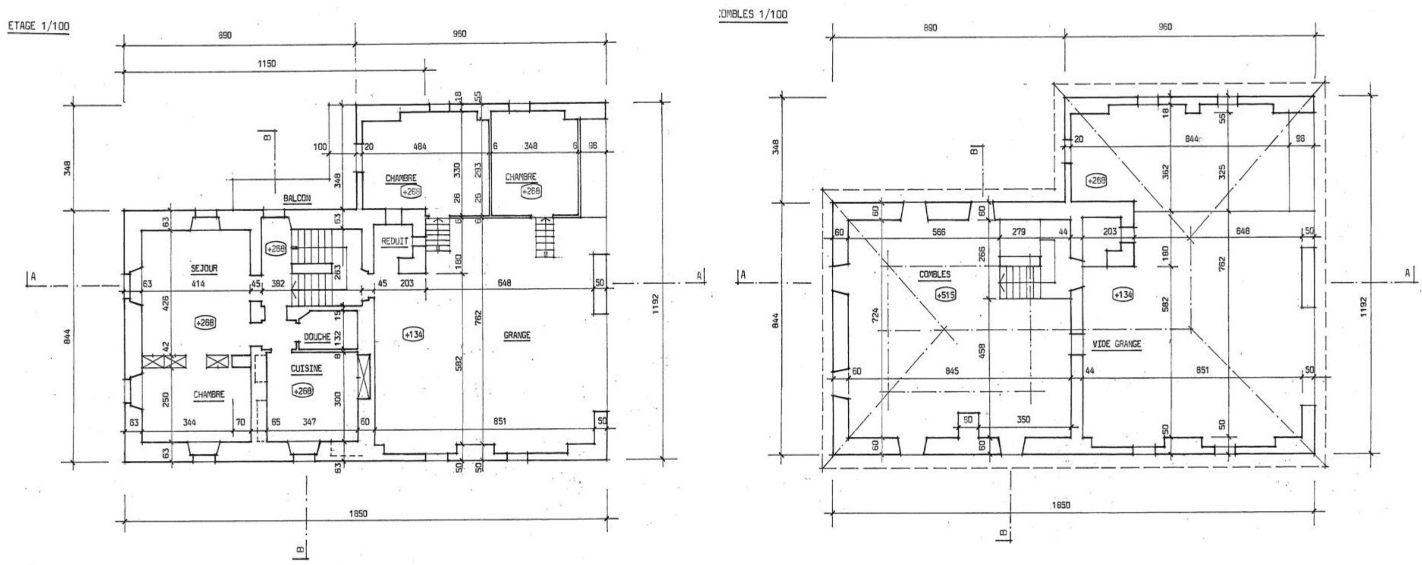


Figure 22: Appendix – Architectural plans of 1st Floor (left) and 2nd Floor (right)

Appendix B – Stone Wall Mixture Properties Calculation

Material	Bulk density	Porosity	Heat capacity	Heat transfer	Water vapour diffusion
Granite	2453	0.095	702	1.66	54
Bonding mortar	1350	0.44	850	0.8	16.12
Combined material - Formula (70% granite & 30% bonding mortar)	=2453*0.7+1350*0.3	=0.095*0.7+0.44*0.3	=702*0.7+850*0.3	=1.66*0.7+0.8*0.3	=54*0.7+16.12*0.3
Combined material - Result (70% granite & 30% bonding mortar)	2122.1	0.1985	746.4	1.402	42.636

Figure 23: Appendix – Stone Wall properties calculation table

Appendix C – Detailed Weather data sheets from MeteoNorm

Riddes
Location name

46.172
Latitude [°N]

7.222
Longitude [°E]

491
Altitude [m a.s.l.]

III, 3
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2000–2009
Temperature period

1991–2010
Radiation period

Additional information

Uncertainty of yearly values: Gh = 3%, Bn = 7%, Ta = 0.5 °C
Trend of Gh / decade: 2.3%
Variability of Gh / year: 4.0%
Radiation interpolation locations: Sion (1996-2015, 10 km), Aigle (29 km), Visp (50 km), Pully (57 km), Geneve-Cointrin (85 km), Changins (81 km) (Share of satellite data: 0%)
Temperature interpolation locations: Sion (10 km), Aigle (29 km), Pully (57 km), Visp (50 km), Geneve-Cointrin (85 km), Changins (81 km)
P90 and P10 of yearly Gh, referenced to average: 94.8%, 104.7%

Month	H_Gh	H_Dh	N	Ta	RH	FF
	[W/m2]	[W/m2]	[Octas]	[°C]	[%]	[m/s]
January	66	27	3.6	0.8	71	1.5
February	107	39	3.0	3.2	63	1.9
March	163	59	2.7	7.6	57	2.5
April	218	79	2.7	11.8	53	2.6
May	247	97	3.3	16.2	56	2.6
June	284	115	3.0	19.9	56	2.7
July	268	105	3.1	20.5	59	2.7
August	228	98	3.5	19.9	63	2.3
September	180	64	3.3	16.1	66	2.3
October	118	52	3.5	11.5	70	1.7
November	70	34	4.4	5.7	71	1.5
December	52	25	4.6	1.6	72	1.5
Year	167	66	3.4	11.2	63	2.2

Meteonorm

Meteonorm V7.2.4.31876 1/4

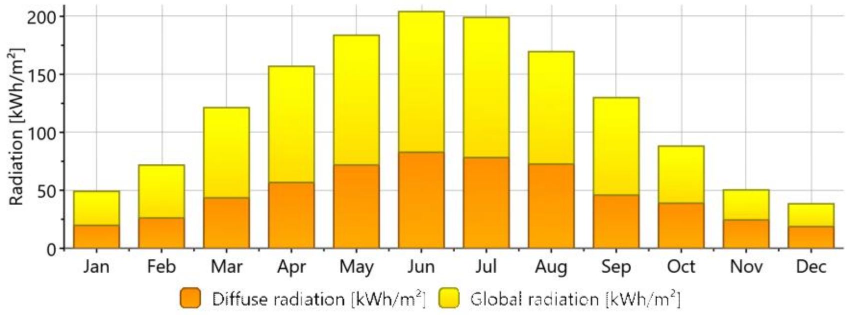
Month	DD	RR	G_Lin
	[grad]	[mm]	[W/m2]
January	132	58	255
February	215	32	260
March	249	52	275
April	249	35	292
May	251	43	320
June	254	60	338
July	254	65	345
August	253	69	347
September	250	31	328
October	171	41	308
November	128	45	281
December	104	46	262
Year	231	577	301

Ta:	Air temperature
H_Gh:	Mean irradiance of global radiation horizontal
H_Dh:	Mean irradiance of diffuse radiation horizontal
N:	Cloud cover fraction
RH:	Relative humidity
FF:	Wind speed
DD:	Wind direction
RR:	Precipitation

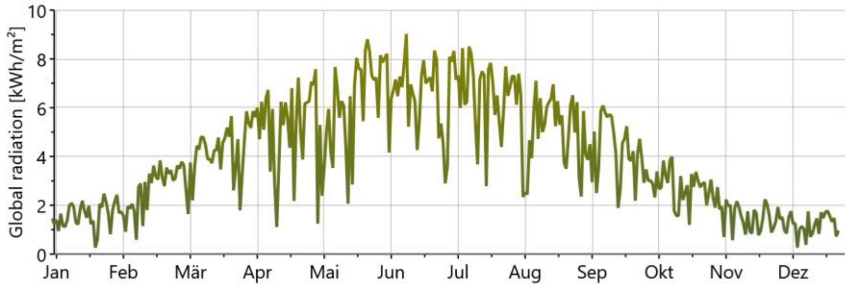
Meteonorm

Meteonorm V7.2.4.31876 2/4

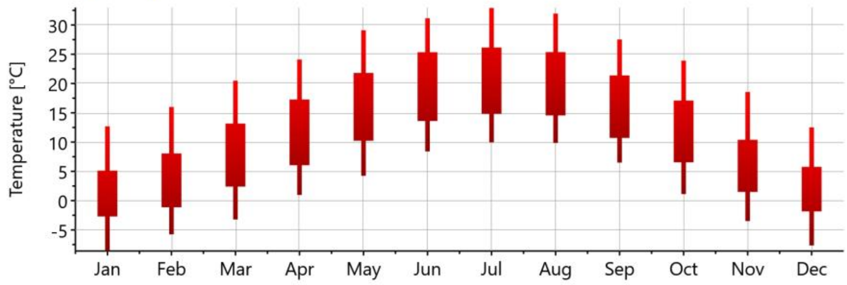
Monthly radiation



Daily global radiation



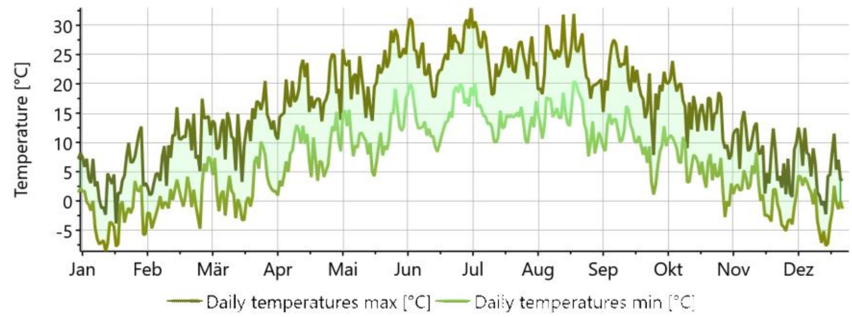
Monthly temperature



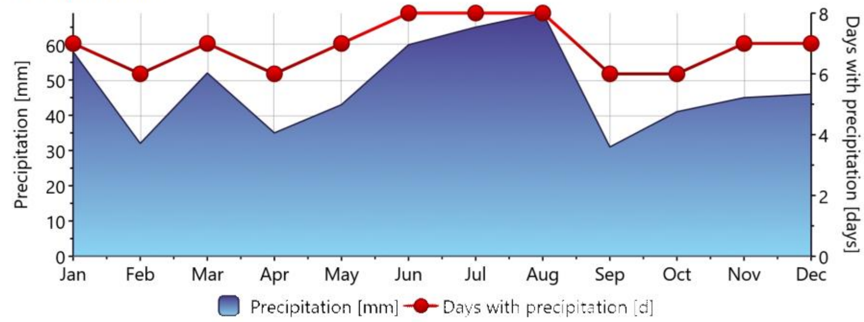
Meteonorm

Meteonorm V7.2.4.31876 3/4

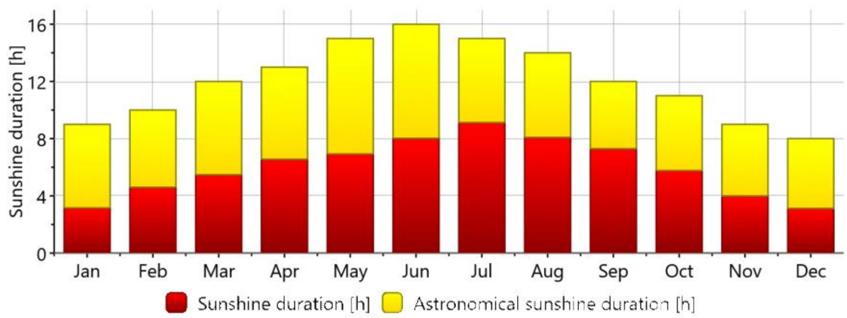
Daily temperature



Precipitation



Sunshine duration

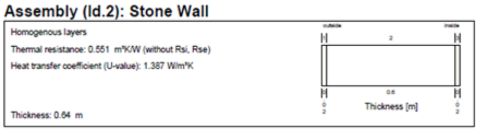


Meteonorm

Meteonorm V7.2.4.31876 4/4

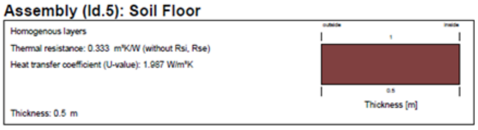
Appendix D – Reference Case Surfaces and Windows Assembly

Assembly (Id.2): Stone Wall



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Exterior Plaster A - layer 1 of 4 (exterior)	1310	850	0.87	0.02	
2	Granite (70%) + Mortar	2122.1	746.4	1.402	0.6	
3	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.02	

Assembly (Id.5): Soil Floor

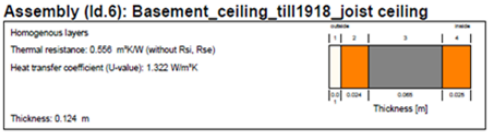


Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Soil 'Christian' DIN	1500	2000	1.5	0.5	

Assembly (Id.15): Door

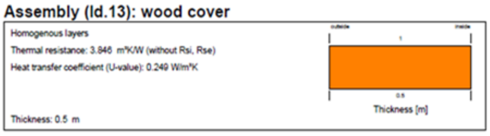
Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Wooden Door	650	1500	0.13	0.5	

Assembly (Id.6): Basement_ceiling_till1918_joist ceiling



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.01	
2	Softwood	400	1400	0.09	0.024	
3	Concrete	2104	776	1.373	0.065	
4	Oak, radial	685	1400	0.13	0.025	

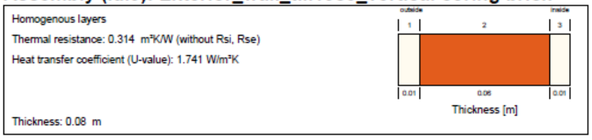
Assembly (Id.13): wood cover



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Hardwood	650	1400	0.13	0.5	

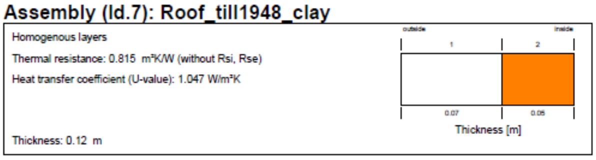
Figure 24: Appendix - Reference case surface assembly - 1

Assembly (Id.9): Exterior_wall_till1983_vertical coring brick



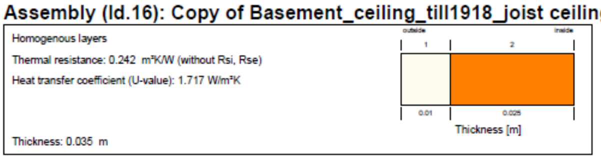
Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.01	
2	dena Brick 800 (heat cond.: 0.28 W/mK)	765	850	0.28	0.06	
3	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.01	

Assembly (Id.7): Roof_till1948_clay



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Tiles	1300	1000	0.27	0.07	
2	Softwood	400	1400	0.09	0.05	

Assembly (Id.16): Copy of Basement_ceiling_till1918_joist ceiling



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.01	
2	Oak, radial	685	1400	0.13	0.025	

Figure 25: Appendix - Reference case surface assembly - 2

Appendix E – Optimal room temperature according to SIA 180 standard

The initial room temperature of a room can be determined using Figure 26 below. The clothing level is displayed on the x-axis, and the physical activity on the y-axis. The red lines show the physical activity level evaluated at 1.7 met and clothing level at 0.75 clo. Thus giving an optimal room temperature of 20°C for the reference case (SIA, 1999).

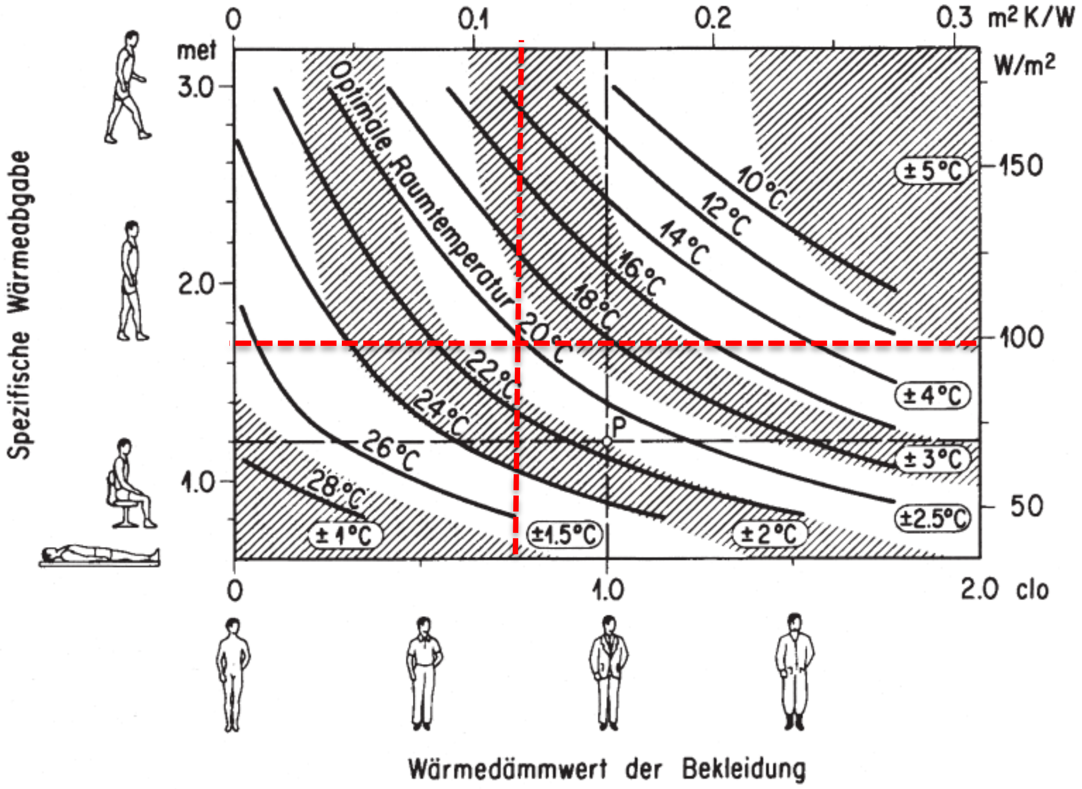


Figure 26: Appendix - Optimal room temperature as a function of physical activity and clothing according to SIA 180 standard

Appendix F – Thermal Transmittance Values for Windows and Walls According to SIA 380/1:2016

With the glazing and wall thermal insulation parameter analysis, the values of 0.25 W/m^{2}K (limit) and 0.10 W/m^{2}K (target) for the walls, roof and floor & 1.00 W/m^{2}K (limit) and 0.80 W/m^{2}K (target) for the windows were taken from the SIA 380/1 (SIA, 2016) standard tables shown in Figure 27 below.

Tableau 3 Valeurs limites des coefficients de transmission thermique pour les transformations et les changements d'affectation (température intérieure de 20 °C)

éléments d'enveloppe contre / éléments de construction	Valeurs limites $U_{K,re}$ en W/(m^2·K): l'extérieur ou enterré à moins de 2 m	locaux non chauffés ou enterrés à plus de 2 m
éléments opaques (toit, plafond, mur, sol)	0,25	0,28
fenêtres, portes-fenêtres	1,0	1,3
portes	1,2	1,5
portes supérieures à 6 m^2 (selon SIA 343)	1,7	2,0
caissons de store	0,50	0,50

Les valeurs limites pour les transformations ne s'appliquent que pour les éléments de construction touchés par une transformation ou le changement d'affectation.

Tableau 4 Valeurs cibles des coefficients de transmission thermique

élément de construction	Valeurs cibles U_{ta} en W/(m^2·K)
éléments opaques (toit, plafond, murs, sol)	0,10
fenêtres, portes-fenêtres, portes	0,80

Pour les valeurs cibles, il faut prendre en considération le rôle important joué par l'énergie grise.

2.2.2.5 Lorsque la température intérieure θ_{0} définie dans les conditions normales d'utilisation de la catégorie d'ouvrages à laquelle appartient le bâtiment ou la partie de bâtiment est inférieure resp. supérieure à 20 °C, les valeurs limites doivent être majorées resp. réduites de 5 % par Kelvin de différence (c'est-à-dire des valeurs limites plus basses pour des températures intérieures plus élevées). Les valeurs limites peuvent être corrigées au maximum jusqu'aux valeurs cibles établies selon 2.2.2.2. Les valeurs cibles ne sont pas corrigées.

Figure 2 Valeurs limites pour coefficients de transmission thermique d'éléments d'enveloppe plans pour les bâtiments à construire

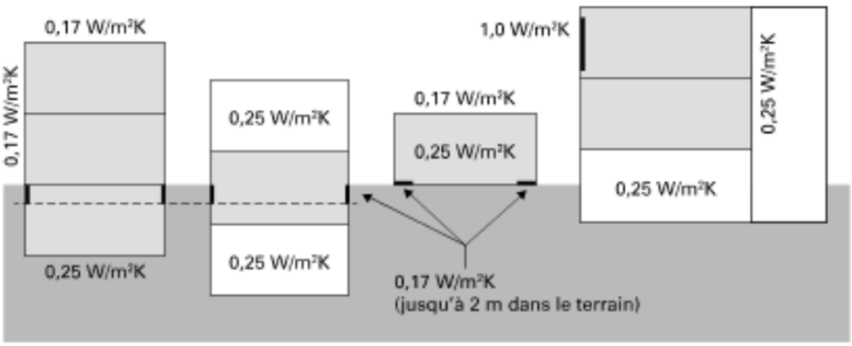
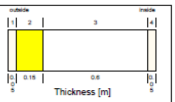


Figure 27: Appendix - Thermal transmittance values for windows and walls according to SIA 380/1 (SIA, 2016)

Assembly (Id.1): Stone Wall

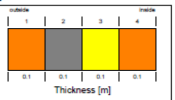
Homogenous layers
Thermal resistance: 4.303 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 0.224 W/m²K
Thickness: 0.85 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Cement Lime Plaster (stucco, A-value: 1.0 kg/m2h0.5)	1900	850	0.8	0.05	
2	Mineral Wool (heat cond.: 0,04 W/mK)	60	850	0.04	0.15	
3	Granite (70%) + Mortar	2122.1	746.4	1.402	0.6	
4	Cement Lime Plaster (stucco, A-value: 1.0 kg/m2h0.5)	1900	850	0.8	0.05	

Assembly (Id.39): Copy of Basement Floor

Homogenous layers
Thermal resistance: 4.101 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 0.233 W/m²K
Thickness: 0.4 m

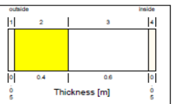


Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Hardwood	650	1400	0.13	0.1	
2	Concrete Screed, mid layer	1970	850	1.6	0.1	
3	Mineral Wool (heat cond.: 0,04 W/mK)	60	850	0.04	0.1	
4	Hardwood	650	1400	0.13	0.1	

Figure 28: New assembly of walls and ceilings for U-value = 0.25 W/m2K

Assembly (Id.22): Copy of Stone Wall

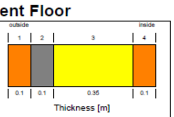
Homogenous layers
Thermal resistance: 10.553 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 0.093 W/m²K
Thickness: 1.1 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Cement Lime Plaster (stucco, A-value: 1.0 kg/m2h0.5)	1900	850	0.8	0.05	
2	Mineral Wool (heat cond.: 0,04 W/mK)	60	850	0.04	0.4	
3	Granite (70%) + Mortar	2122.1	746.4	1.402	0.6	
4	Cement Lime Plaster (stucco, A-value: 1.0 kg/m2h0.5)	1900	850	0.8	0.05	

Assembly (Id.40): Copy of Copy of Basement Floor

Homogenous layers
Thermal resistance: 10.351 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 0.095 W/m²K
Thickness: 0.65 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Hardwood	650	1400	0.13	0.1	
2	Concrete Screed, mid layer	1970	850	1.6	0.1	
3	Mineral Wool (heat cond.: 0,04 W/mK)	60	850	0.04	0.35	
4	Hardwood	650	1400	0.13	0.1	

Figure 29: Appendix - New assembly of walls and ceilings for U-value = 0.1 W/m2K

Appendix G – Thermal Comfort Categories EN 15251 Details

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Figure 30: Appendix - Thermal comfort level of categories I to IV explained

Table 7: Appendix - Categories I to III calculations and results

Category I	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 2$	$T_{i,max} = 0.33 \times 11.23 + 18.8 + 2$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 2$	$T_{i,min} = 0.33 \times 11.23 + 18.8 - 2$
Category II	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 3$	$T_{i,max} = 0.33 \times 11.23 + 18.8 + 3$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 3$	$T_{i,min} = 0.33 \times 11.23 + 18.8 - 3$
Category III	Upper Limit	$T_{i,max} = 0.33\ T_{e,avg} + 18.8 + 4$	$T_{i,max} = 0.33 \times 11.23 + 18.8 + 4$
	Lower Limit	$T_{i,min} = 0.33\ T_{e,avg} + 18.8 - 4$	$T_{i,min} = 0.33 \times 11.23 + 18.8 - 4$

T_i = limit value of indoor operative temperature (°C)

$T_{e,avg}$ = running mean exterior temperature (°C)

	$T_{i,min}$ (°C)	$T_{i,max}$ (°C)
Category I	20.50	24.50
Category II	19.50	25.50
Category III	18.50	26.50
Category IV	<18.50	>26.50

Appendix H – Heating Energy Demand SIA 380/1

The calculation of the limit heating energy demand is done using the following equations.

Heating energy demand limit (kWh/m^2) $Q_{H,N} = \left[Q_{H,DD} + \Delta Q_{H,N} \times (\frac{A_{th}}{A_E})\right] \times f_{cor}$

Temperature correction factor (-) $f_{cor} = 1 + [(9.4°C - T_{e,avg})] \times 0.06\ K^{-1}$

$Q_{H,DD}$ & $\Delta Q_{H,N}$: These values are directly taken from the table below from the SIA 380/1 report. The internal load defines the values – which in this case is single household. There the values are 16 kWh/m^2 and 15 kWh/m^2 respectively.

Table 8: Appendix - Limit values of heating energy demand of a building

Catégories d'ouvrages		Valeurs limites	
		Base $Q_{H,li0}$ kWh/m^2	Accroissement $\Delta Q_{H,li}$ kWh/m^2
I	habitat collectif	13	15
II	habitat individuel	16	15
III	administration	13	15

A_{th} & A_E : These areas represent the thermal envelope area (A_{th}) and the energy reference area (A_E) as pictured in Figure 23 below. The values of the areas are 326.5m^2 and 155.23m^2 respectively.

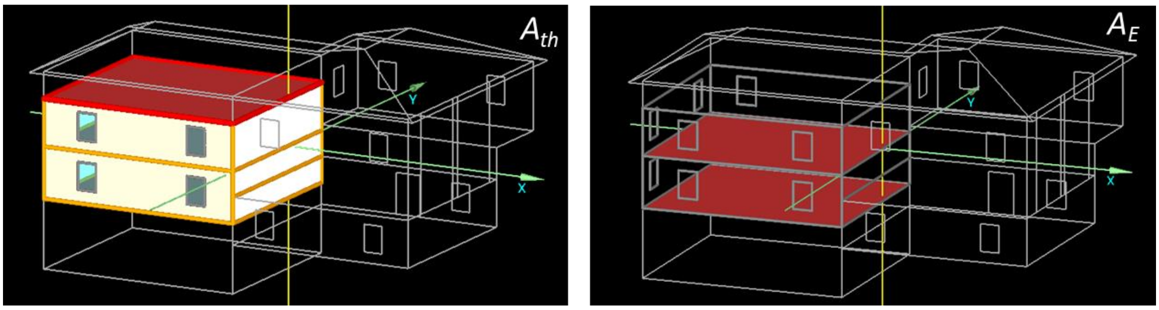


Figure 31: Appendix – Visual representation of A_{th} and A_E

f_{cor} & $T_{e,avg}$: Are the correction temperature factor and the annual mean temperature. f_{cor} is calculated from the mean annual temperature of 11.23°C as followed:

$$f_{cor} = 1 + [(9.4°C - 11.23°C)] \times 0.06\ K^{-1}$$

$$f_{cor} = 0.8902$$

$Q_{H,D}$: Can now be calculated as followed:

$$Q_{H,N} = \left[16 + 15 \times (\frac{325.5m^2}{155.23m^2})\right] \times 0.8902$$

$$Q_{H,N} = 42.33\ kWh/m^2$$

$Q_{H,target}$: Can be calculated as followed

$$Q_{H,target} = 0.6 \times Q_{H,N}$$

$$Q_{H,target} = 0.6 \times 42.33\ kWh/m^2$$

$$Q_{H,target} = 25.40\ kWh/m^2$$

Appendix I – Heating Energy Demand of Reference Case and 25 Simulation Cases

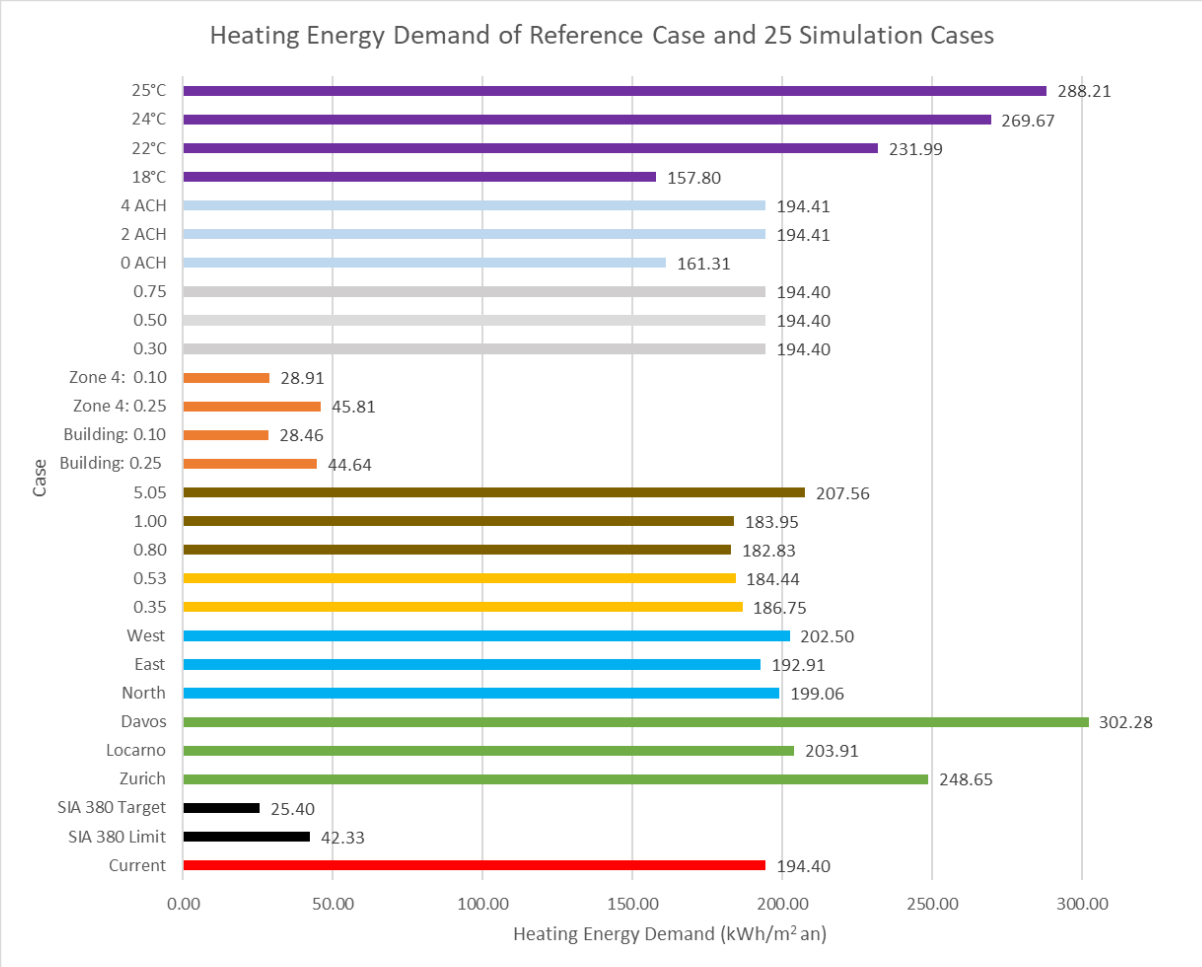


Figure 32: Appendix – Compiled results of the heating energy demand

Appendix J – Thermal Comfort of Reference Case and 25 Simulation Cases

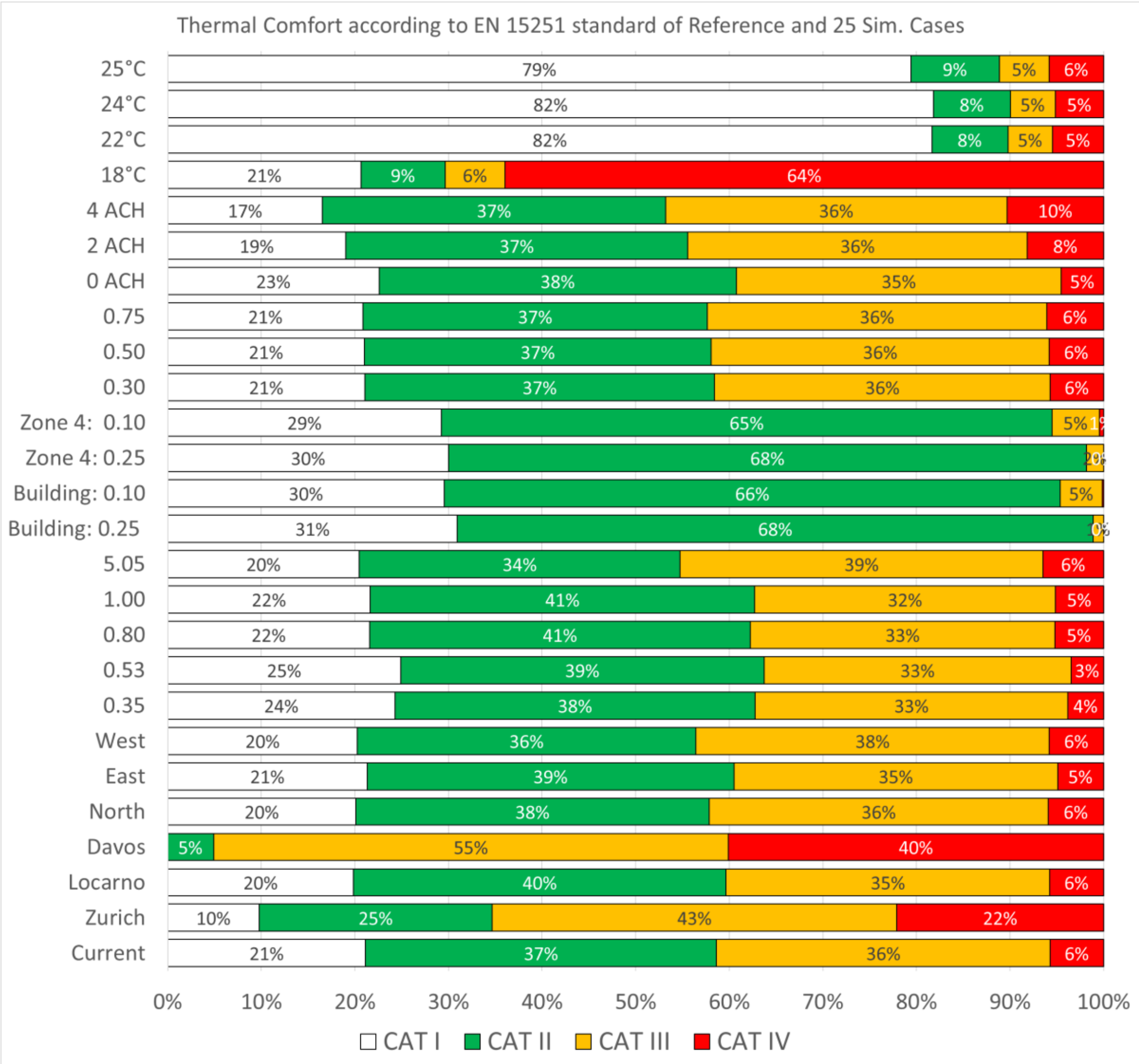


Figure 33: Appendix – Compiled results of the thermal comfort according to the EN 15251 standard