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The application potential of vacuum glazing in buildings' thermal retrofit: A case study

unter der Leitung von

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KURZFASSUNG

Der Bedarf an energieeffizienten Gebäuden ist in den letzten 20 Jahren stark gestiegen, um die ökologischen Einflüsse dieser zu minimieren, welche unter anderem durch die Treibhausgasemissionen verursacht werden, die der Hauptverursacher des Klimawandels sind. Der Wärmeschutz-Standard der Fenster ist ein wesentlicher Faktor in Bezug auf den Heizwärmebedarf. Dabei kommt einer Energieeffizienz-Strategie im Bauwesen, welche optimierte Materialien und Komponenten zur Minimierung der Wärmeverluste der Gebäudehülle zu einem Minimum und, in weiterer Folge, zur Reduktion des gesamten Heizwärme- und Kältebedafes verwendet, eine zentrale Rolle zu. Fenster haben in der Regel einen Anteil von 30 bis 50 Prozent an den gesamten Wärmeverlusten durch die Gebäudehülle, obwohl deren flächenmäßiger Anteil an der Gebäudehülle weitaus geringer ist als von anderen Bauteilen. Hoch wärmegedämmte Fenster können die wärmeschutztechnische Qualität des gesamten Gebäudes stark erhöhen.

Die Entwicklung von Vakuumverglasung gilt als großer Fortschritt im Bereich von Verglasungssystemen für energieeffiziente Gebäude. Sie besitzt ein hohes Potenzial zur Reduktion von Heizlasten. Diese Studie behandelt die Anwendung von Vakuumverglasung bei thermischer Sanierung von historischen Altbauten. Es wurde eine Reihe von typischen Fenster-Details ausgewählt, um den Einfluss von Vakuumverglasungen zu untersuchen. Es stellte sich heraus, dass der Einsatz von Vakuumverglasung in der thermischen Sanierung von Fenstern in Kombination mit Verbesserungen des Glasrandverbundes eine Reduktion des U-Wertes des Gesamtfensters von 50 bis 60 Prozent ermöglicht.

Weiters prüft diese Studie den Einfluss von Vakuumverglasung auf den Heizwärmebedarf des Gesamtgebäudes anhand von Fallstudien. In einem Gebäude mit 20 Prozent Glasflächenanteil ist es möglich, bis zu 15 Prozent des gesamten Heizwärmebedarfes einzusparen. Außerdem wird die Wirtschaftlichkeit von Vakuumverglasung in der Anwendung an bestehenden Gebäuden behandelt: Die Amortisationszeit für Investitionskosten und Betriebskosten wird anhand der Fallstudien untersucht.

Schlagwörter:
Vakuumverglasung, thermische Sanierung, Wärmebrückenberechnung, thermische Simulation, ökonomische Machbarkeit.

ABSTRACT

The demand of energy-efficient buildings is growing in last years in order to minimize the environmental impacts, including but not limited to greenhouse emissions which are the primary contributors to global warming. Thermal performance of windows is a crucial issue in total building heating demand. A key energy-efficient strategy in building sector is using optimum materials to minimize the thermal transmittance of building envelope to the lowest level, and as a result, decreasing the total building heating/cooling demands. Windows typically account for 30-50 percent of total heat losses through building envelope, although their area fraction of the envelope is far less than other building components. High thermal insulated windows can greatly improve the total building thermal performance.

The development of vacuum glazing is a significant advance in the area of glazing systems for low energy buildings. These developments show a high potential to reduce buildings' heating loads. This study addresses the possibility of using vacuum glazing in thermal retrofit of existing historical buildings' envelopes. A set of typical window details were selected to examine the impact of the application of vacuum glazing. It turned out that using vacuum glazing in window thermal retrofit combined with some improvements on the frame-glass junction, may reduce the total window U-value by 50-60%.

Furthermore, this study examined the effect of vacuum glazing on the total buildings' heating demand via use of case study buildings. It turned out that a building with 20% glazing surface, it is possible to achieve up to 15% savings of total building heating demands. Additionally, the economic feasibility of vacuum glazing application for existing buildings is addressed: The amortization time following the investment and operational cost are examined for the case study buildings.

Keywords

Vacuum glazing, Thermal retrofit, Thermal bridges evaluation, Thermal simulation, Economic feasibility.

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CONTENTS

NOTATIONS

Symbol	Definition	Unit
A	area	m^2
b	width, i.e. perpendicular to the direction of heat flow	m
d	depth, i.e. parallel to the direction of heat flow	m
h	surface heat transfer coefficient	$W.m^{-2}.K^{-1}$
L^{2D}	two-dimensional thermal conductance or thermal coupling coefficient	$W.m^{-1}.K^{-1}$
l	length	m
q	density of heat flow rate	$W.m^{-2}$
R	thermal resistance	$m^2.K.W^{-1}$
R_{se}	external surface resistance	$m^2.K.W^{-1}$
R_{si}	internal surface resistance	$m^2.K.W^{-1}$
T	thermodynamic temperature	K
T_i T_e	Temperature of internal and external environment	K
θ	Celsius temperture	^{o}C
U	thermal transmittance	$W.m^{-2}.K^{-1}$
RH	relative humidity	%
c_p	specific heat capacity	$J.kg^{-1}.K^{-1}$
d	thickness	m
m	Mass	kg
μ	vapor diffusion resistance factor	–
ε	emissivity	–
λ	thermal conductivity	$W.m^{-1}.K^{-1}$
f_{Rsi}	temperature factor at the internal surface	–
χ	point thermal transmittance	$W.K^{-1}$
Ψ	linear thermal transmittance	$W.m^{-1}.K^{-1}$

Subscripts	
e	external (outdoor)
g	glazing
eq	equivalent
f	frame
i	internal (indoor)
min	minimum
max	maximum
p	panel
r	radiative
vg	vacuum glazing
se	external surface
si	internal surface

1 INTRODUCTION

1.1 Overview

Today one of the main governments' challenges around the world is how to reduce greenhouse emissions. Knowing that buildings around the world due to its energy use are responsible for more than 24% of greenhouse emissions as it accounts for over 40% of primary energy use. In the newly constructed buildings, huge efforts are conducted to meet the maximum energy efficient requirements. A study carried out by the International Energy Agency shows that the existed buildings account for over one third of total final energy consumptions therefore for the greenhouse emissions. The existing buildings will use most of the energy consumed by all buildings in the future (Houssin 2013). This clearly points out the urgent need of enhancing the existed buildings in term of improving their energy performance and this can be achieved by using the new technologies in the energy retrofit for the existed buildings. Giving that the existing buildings may still functional, occupied and located in prime locations. And many of them as in Vienna city have historical value and being under heritage protection programs. Retrofitting such buildings is always address some extra challenges as these buildings should keep the external façades as in its original phase. In order to minimize building energy consumption of existing building, building envelope components should be thermally well insulated to reduce the heat transfer through the buildings' envelope.

An overview of thermal retrofitted buildings shows, in most cases, the designers focus on main building components such as walls and roofs, whereas less efforts are usually devoted to other components like windows and glazing areas in general. Although windows are considered critical components when designing energy efficient buildings in current good buildings' practices, they are considerably less well insulated than other parts of buildings' envelope. The need to reduce energy consumption leads to using smaller windows than may be architecturally or aesthetically desirable. Which, in turn, reduces the potential for solar gain in cold climates. The total amount of energy loss through windows is large. In absolute terms-over 3% of total energy consumption in the United States is lost through windows. In other countries like Sweden, This figure is even higher, at 7%. In general, windows are considerably less insulated than other components of building's envelope due to its function and desirable thickness as well as the limitation of advanced materials that can provide a light weight, small thickness while maintaining transparency to keep maximum solar gains during winter and at the same time minimum solar gains during summer. The heat transfer through the glazing system can be reduced to specified levels; however, the total glazing thickness, weight, and cost increase while the light transmittance decreases. A glazing that can achieve excellent thermal performance without recourse to more than two or at most three glass layers is highly desirable. More so, if it is suitable for retrofitting existing buildings in addition to new build applications. Insulation glass with a vacuum in the inter-pane cavity would be not only better insulation but also a thinner and lighter than conventional glazing systems.

1.2 Motivation

Knowing that buildings account for over 40% of primary energy use and for around 24% of greenhouse gas emissions. Up to 60% of total energy losses through building envelope may come from windows. Therefore, improved fenestration systems/materials have a huge potential to provide energy savings. Thermal insulation requirements in both building construction and building retrofit sectors will continue to be tightened. Nowadays, the challenge in building energy sector is: how to maximize energy efficiency and minimize energy consumption. In the present time, the existing buildings represent a burden for the energy sector as they are considered as non-efficient energy consumers. The buildings significantly contribute to the consumption of non-renewable energy sources due to employments such as building heating, lighting, among other utilities.

For exterior building components such as walls and roofs with heat insulation, there will be no problem. But for windows and glazing facades, it is conceivable that in a few years the thermal requirements will only be met by using triple-glazing conventional systems which considered impractical solution due to its massive weight and high cost. On the other side, vacuum-insulated glass can be the practical alternative solution. In this study, the use of vacuum glazing in the thermal retrofit buildings to be investigated. It is assumed there would be a great advantage of using such material in the retrofit process because in most cases the windows are responsible for the greatest heat loss in old buildings. The light weight of vacuum Glazing gives the advantage of preserving the window frames (those which still in a good condition) which consequently reflects on saving retrofit costs. By the end of this study, the decision maker in the retrofit process whether they are designers (thermal benefits) or owners (energy and cost savings) should be aware of what exactly would be the benefit of using vacuum glazing when they decide to carry out a thermal retrofit in the existing buildings.

1.3 Background

Windows are inseparable components of the building envelope and façade. From one side, windows are essential components as they are providing daylight and natural ventilation to the buildings as well as its significant role in architectural designs, on the other side windows are responsible for main heat loss in buildings' envelope. Therefore, window construction is considered critical in term of window energy performance. For most cases in thermal retrofit, window frame should not be replaced especially in historic buildings and that addresses the need of using revolutionary glazing methods in order to reduce heat losses that occurred due to thermal bridges while maintaining light window structure. In this thesis, the application potential of vacuum glazing to be addressed. The need of using such materials comes from the heavy structure of using traditional glazing methods to reach the required U-value in thermal retrofitted historic buildings. Usually, double or even triple thick glass pane with filler gasses in between used in windows thermal retrofit, this leads to additional loads to building structure which is not preferable for many historic buildings. As the vacuum glazing is highly insulating and has light weight comparing to the traditional double glazing, these properties make it an ideal alternative to conventional glazing materials.

The concept of vacuum glazing, i.e. a glazing using a vacuum to minimize conductive and convective heat transfer, is not new, initially being proposed by Zoller, with a patent granted to cover his ideas in 1924 (Zoller, 1913). The steady and continuing stream of patents in the area of vacuum glazing over the years indicates a high level of interest in the area of vacuum glazing and the considerable difficulty in fabricating a functional vacuum glazing system. In essence, vacuum glazing is similar to double glazing in which the gas-filled space is evacuated to low pressure, thus reducing the levels of convection and gaseous conduction to negligible values, the heat transfer remaining is predominantly due to radiation which can be reduced by the use of low e-coatings. Radiative heat transfer between two parallel sheets is not distance dependent, therefore, the spacing between the glass sheets can be reduced to provide a compact highly insulating glazing system. Comparing the vacuum glazing with filler gasses such as argon, krypton and xenon that are usually used where thermal conductance "due to convection and conduction,, cannot be reduced significantly whereas there are no heat losses in case of vacuum glazing due to conduction or convection. In previous time the vacuum glazing was encountering some practical problems regarding edge sealing but recently, a promising approach was found for the edge-sealing which poses the main obstacle to practical realization. This technology is currently being patented and has a great market potential in the vacuum glazing field. The advantage of vacuum glazing thermal insulation with high thermal performance combined to additional benefit of sustainable solar gains due to its transparency. Considering some disadvantages as there will be heat losses namely leakage through the edge seals as thermal bridges and this to be addressed and discussed in this study with some suggested improvements in the frame-glazing joints. Another issue should be taken into account is the need for spacers between two double-glazed assemblies in the vacuum glazing, this need is resulted from the high atmospheric pressure on evacuated flat glazing. The material and the size of the spacers is raising the heat flow through the vacuum glazing panels. In this study, the heat flow through the spacers and the frame-glazing joint area are investigated in order to evaluate the vacuum glazing performance in historic buildings and its impact on the total thermal performance of these buildings.

1.4 Understanding Windows

One may address the question: Why there is a big concern over windows in first place, and why it is considered a critical element of building envelope when aiming energy efficient design?

Frome architectural viewpoint, windows are important aspect of building architectural character. Windows bring light, warmth, and beauty into buildings and give a feeling of openness and space to living areas. “When making decisions about windows in historic buildings, it is important to understand what makes windows significant. Windows should be considered significant to building if they: 1) are original, 2) reflect the original design intent for the building, 3) reflect period of regional styles or building practices, 4) reflect changes to the building resulting from major periods or events, or 5) are examples of exceptional craftsmanship or design” (Wasielewski, 2004). In most historic buildings, the wooden windows are the most used windows either in a single or double pane (casement windows). These windows are constructed of old-growth wood, which is more durable than new wood. As these windows have served for more than fifty years and in some cases for hundred years which proves its high durability. Furthermore, these windows exist in old historic buildings that had been designed to be naturally energy efficient as these buildings were not heated or cooled centrally. Additionally, the massive wall thickness and the window size as well as many other aspects were strategically chosen to minimize energy losses and increase thermal building performance. Windows typically account for 30-50% of heat losses through the building envelope. To illustrate that, a comparison between the U-values of the windows with U-values of opaque building components such as walls, roofs and floors showed that the best windows have U-value at least 3 times more than the opaque components (around 0.7-1.0 [$W.m^{-2}.K^{-1}$] for windows and 0.2 -0.3 [$W.m^{-2}.K^{-1}$] for opaque components). The windows in existed buildings are responsible for about 40% of the heat loss through typical building envelopes. Much significant push has been given for thermal performance upgrades of existed windows by lowering window frame and glazing units’ U-values. Poor window thermal performance has negative impact on the overall thermal resistance of buildings' envelope. In the Figure 1, a simple analysis has been made by the U.S Department of Energy shows the impact of window U-value on effective thermal R-value of wall assemblies.

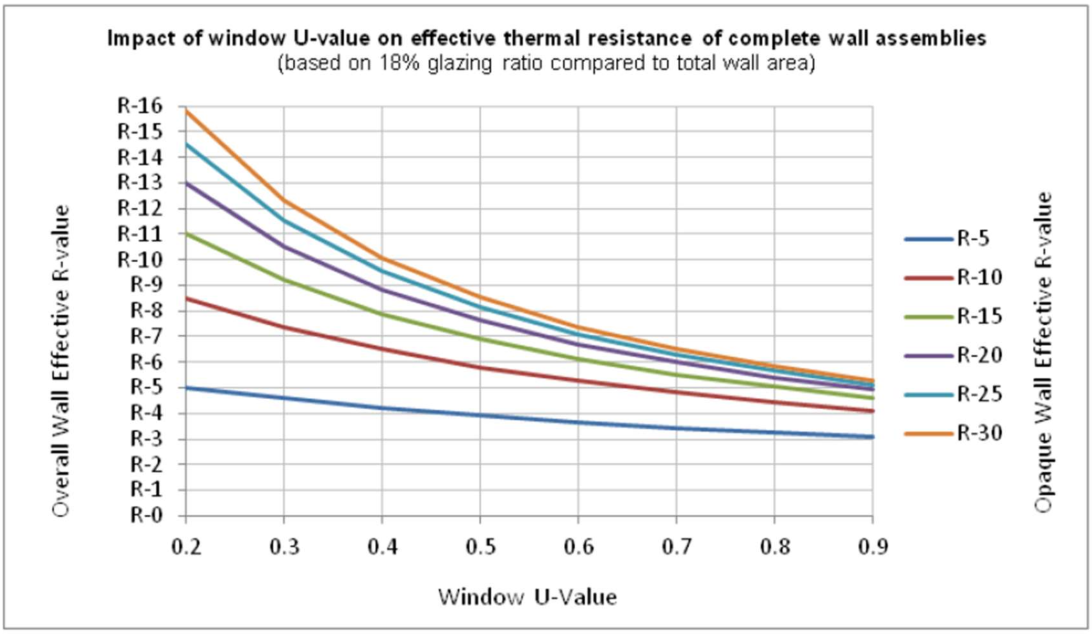


Figure 1. Impact of window U-value on the thermal resistance of the whole wall (WWRRR 2012)

1.5 Material for window manufacturing

A window can be defined as an opening constructed in a wall or roof that allows light and air at an enclosure and is often framed and spanned with glass mounted to permit opening and closing. At the beginning, windows were simple holes in walls, then they were covered with different materials such as cloth or wood. Over time, windows were constructed in a way to provide light and used as natural ventilation source, the glass in windows were the main choice among Europe through history whereas paper window were used in ancient Chinese and Eastern lands. Modern style floor-to-ceiling windows became possible only after the industrial glass making process was perfected. In the mid-1970s, USA comes to the fact the energy is limited and not free. The US Department of Energy calculated that 25% of heating costs in a house were used to countervail the heat loss through the window. In most old historic buildings, a single pane window with wooden frames either in a single or double wings were used. This research investigates these window types as it is the most used type in historic buildings. Multi-pane windows started to appear only after the 1970s. Then a filler gasses were used between double or triple glass windows such as Krypton or argon in order to improve window thermal performance. Because the Aluminium frames are poor in term of thermal insulation, windows industry where going toward using alternatives such as vinyl and wood-vinyl composite frames with foam used instead of metal spacers in order to reduce the heat loss through frames. Recently, new technologies have appeared like electrochromic windows, a new genre of windows is composed of special materials that have coatings, which can darken the glazing by running electricity through the unit. Some manufacturers already have prototypes of these high technology windows in operation. At night and on sunny, summer days, an electric switch can be turned on to render the windows virtually opaque.

In this chapter, the used materials for windows in Austria are presented. The most common materials used for frames and glazing, as well as the best techniques for installation of the window, are also described.

1.5.1 Window frames

Wooden frames

They have higher R-values, and low thermal conductivity $\boldsymbol{\lambda}$ = 0.13 – 0.18 [W.m^{-1}.K^{-1}] (EN ISO 10077-2:200).They are not affected by temperature extremes, and do not generally promote condensation. Wooden frames do require considerable maintenance in the form of periodic painting or staining. If not properly protected, wooden frames can swell, which leads to rot, warping, and sticking. A good approach could be wooden clad windows on top of vinyl or aluminium as it gives the wooden exterior appearance and requires less maintenance.

Figure 2. Window wooden frame (Seamlesschoice 2016)

Aluminium frames

It is one of the most durable and rigid window frames comparing to other traditional window frames. It is highly resistant to moisture, fading, distortion and does not require too much maintenance. For the previous characteristics, it is widely used in buildings industry. The main problematic issue in aluminum frames its high conductivity $\boldsymbol{\lambda}$ =160 [W.m^{-1}.K^{-1}]. Because of its poor thermal insulation prosperity, it is less competitive with other frame materials in energy efficient applications. With thermal spacer, it can help to reduce thermal conductivity between interior and exterior glass layer. In addition, accelerated wear tests have shown that, in the long run, aluminium windows are more durable and more water- and airtight than any other frame materials.

Figure 3. Aluminium window frame (Seamlesschoice 2016)

PVC frames

PVC (polyvinyl chloride) windows are known for their energy efficiency and their excellent quality/price ratio. They are durable, easy to maintain and highly resistant to deformation, discoloration and shocks. Due to its low conductivity $\boldsymbol{\lambda}$ =0.17 [W.m^{-1}.K^{-1}] it is considered very energy efficient as well as its low sound conductivity. Its disadvantage that it is affected by high temperatures which cause window frame expansions.

Figure 4. PVC window frame (Seamlesschoice 2016)

Hybrid (PVC and aluminum)

Hybrid casement, sliding or sash windows consist of a PVC frame covered with extruded aluminum cladding. On the inside, PVC maximizes the window energy efficiency while its aluminum exterior affords robustness to its structure. The aluminum exterior shell allows the application of paint in the color according to designer choice.

Figure 5. Hybrid window frame (Seamlesschoice 2016)

Hybrid (PVC and aluminum)

The hybrid PVC and aluminum window combines the performance and robustness of a hybrid window with the elegance and antique feel of wood, which offers a range of finishes and an unlimited choice of colors, making it a highly versatile product that blends easily with the rest of other home components.

FIBERGLASS FRAMES

Like aluminium-framed windows, fiberglass frames are lower in maintenance. However, fiberglass is much stronger than aluminum and more energy-efficient too, making this a good choice if those two factors matter most to designer.

Although fiberglass can be a little more expensive, it is possible to get fiberglass replacement windows in a variety of colors, and it won’t corrode or crack over time.

Figure 6. Fiberglass window frame (Seamlesschoice 2016)

1.5.2 Glazing

The most common used materials for window glazing are Soda lime glass, polymethylmethacrylate, and polycarbonate.

Soda-lime glass

It is the most prevalent type of glass. It is made of 70% silica, 15% soda (sodium oxide, 9% lime (calcium dioxide) and some other different components in small percentages. Soda-lime glass accounts for 90% of the manufactured glass. It is relatively cheap, chemically stable, reasonable hard and extremely workable. The density of the soda-lime glass is 2500 [kg. m^{-3}] while it is thermal conductivity is 1 [W.m^{-1}.K^{-1}].

Polymethacrylate (PMMA)

It is a polymer with a high light transmission with composition $C_5H_8O_2$. What makes it good as glazing choice its extremely long life time as well as its high resistance to weathering and unlimited color options. Above all, it has the highest surface hardness comparing to thermoplastics and it is 100% recyclable. It has a density of 1180 [kg.m^{-3}] and thermal conductivity of 0.18 [W.m^{-1}.K^{-1}].

Polycarbonates

A special type of polyester usually used as an engineering plastic. The type used in engineering applications are strong and some of its types are optically transparent. It has a density of 1200 [kg. m^{-3}] and thermal conductivity of 0.2 [W.m^{-1}.K^{-1}].

State of the art of window glazing products

Glazing is the most important part of fenestration assemblies as it has the largest area of window thus it has the largest impact on window thermal performance. Therefore using the proper glazing materials and method provide a significant insulating efficiency. When the glazing has low U-value it can greatly reduce the overall window U-value. Generally, there are three common glazing configurations. Single, Double and Triple Glazing. As the names indicate, Single glazing consists of one layer of glass, Double Glazing consists of two layers and the triple glazing consists of three layers. For the double and triple glazing usually a filler gas such as argon or Krypton in the space between the panes because the gasses transfer less heat than air does. However, multi-pane glazing are considerably more expensive than single-pane glazing and limits framing option due its bigger thickness and their increased weight.

Multilayer glazing:

Commonly known as a double or triple pane. As its name, double glazed windows consist of two layers of glass with a layer of inert gas sealed between them. This technique creates nearly twice insulation as single glazed units. For more thermal insulation and to lower U-value of the glazing a third layer of glass is usually to be added to the two panes to form a glazing called triple glazing in order to get the advantage of one more inert gas layer. Typically the fill gas used is argon or krypton. Using krypton as filler gas can reduce the U-value and the cavity thickness as a result reducing frame thickness. Looking at the commonly used filler gasses figures shows that nowadays the most used gas as filler inert gas is krypton but its price is much higher than the argons' price. Using argon as filler gas in triple pane glazing can produce relatively low U-vales glazing but in this case, the total glazing thickness will increase as the gas filler layer thickness can reach 18 [mm].

Suspended films

The use of dual glass pane instead of single glass pane gives an advantage to the window thermal performance. In the same way, the use of multiple glass pane with two or three insulating chambers using lightweight suspended film layers provides significant improvements over triple pane windows. The big advantage of using suspended films occurs due to its light weight comparing to a glass pane and also it allows for larger gas cavity thickness in the same window cavity as it is much thinner than a glass pane. A glazing with suspended film may have a competitive U-value comparing to ordinary multilayer glazing. This glazing type is preferable when a glazing with low solar factor is required to avoid overheating in the summer time.

Vacuum glazing

Vacuum glazing was first conceived in 1931 by Zoller. But it is first successful product was in 1989. When vacuum is used instead of filler gas in a double-glazed insulating glass we get vacuum glazing. Knowing that the conductivity of the vacuum is 0.0001 [$W.m^{-1}.K^{-1}$]. Its very low conductivity makes it the best insulating material that can be used in between two glass sheets. Vacuum glazing consists of two sheets of glass, hermetically sealed together around the edges and surrounding a narrow highly evacuated space. The separation of the glass sheets under the influence of atmospheric pressure is maintained with an array of small, high strength support pillars. In more advanced applications in order to reduce thermal radiative transmittance between internal glass surfaces, a low emissivity coating on the surfaces can be used. However, the main challenge in vacuum glazing is always addressed in the edge seal. In practical use of vacuum glazing, thermals bridges are always through edge seals causing more heat transfer from heated side to colder side. The support pillars are usually made of metal, typically 0.25 to 0.5 [mm] in diameter and separated by 20 to 25 [mm]. Using double-glazed assemblies with evacuated space, vacuum glazing system can achieve heat transfer coefficient of 0.8 [W.m^{-2}.K^{-1}] for the entire window and 0.58 [W.m^{-2}.K^{-1}] for the glazed area. With system assemblies projected to be less than 10 [mm] thick with 4 [mm] glass layer. The goal of this research is to investigate the thermal performance of vacuum glazing when using such type of glazing in the thermal retrofit application. Using vacuum glazing provides an advantage when the window architectural view has to remain as in its original state. That is typically required when retrofitting historic buildings which are under heritage protection. The vacuum glazing provides a thinner, lighter glazing and more thermally insulating comparing to traditional used glazing systems.

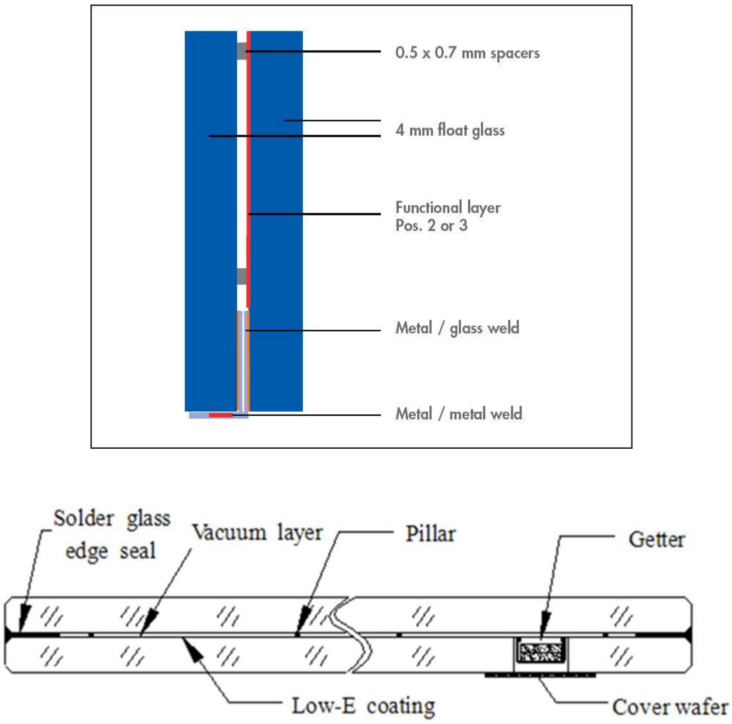


Figure 7. Vacuum glazing detail to be used in thermal bridge calculation (ZAE n.d.)

Vacuum glazing components

1. Two sheets of lime glass, typically 4 [mm] thick each.
2. Vacuum layer in between two glass sheets. Typically 0.15 [mm] thick.
3. Pillars: the aim is always to use pillars which are hardly visible but mechanically durable. Whereas small pillars with compact surface areas are better for the glass appearance and thermal performance of the vacuum glazing, the opposite is

preferable in terms of mechanical performance. It should be taken into account the size of the pillars and the spaces between them as well as their thermal conductivity in general, pillars with size less than 0.35 [mm] in diameter cannot be seen from a distance 1 m far whereas pillars with diameter 3.5 [mm] can be seen easily. In this research, a vacuum glazing with pillar size of 0.3 [mm] in outer diameter to be investigated. The spaces between the pillars would be 40 [mm]. The material of the pillars is also a concern in terms of durability, therefore scientists examined the mechanical durability of the pillars by inserting them between two floating glass panes and testing them in a universal testing machine with regard to their compressive strength. The conclusion after the test was that the metal supports were the safest in terms of overloading, hail impact. In conflicting area between appearance and durability and thermal performance, scientists suggested that metal cylinders are the most suitable supporting materials to be used in between glass sheets.

4. Edge seal: knowing that the heat transfer through the vacuum glazing occurs by radiation across the vacuum gap, conduction through the support pillars, and the conduction through the edge seal that makes the materials used as an edge seal in vacuum glazing a critical issue. The edge seal should be vacuum-tight for the duration of the windows' service life under all influences and loads. The evaluated vacuum glazing type of this research assessed the edge seal of solder glass as it is shown in Figure 7.

1.6 Windows' thermal performance

Energy transfer across a window assembly by several mechanisms. Conduction, convection (air movement such as air leakage), and radiation are all components of performance. With so many materials (wood, polymers, glass, metal) being combined to create a window system, the interactions between all these elements are not necessarily simple or straightforward. Figure 8 is a simplification of the energy transfer through a window and its surrounding enclosure elements. The actual energy transfer mechanisms are three dimensional, with all of the mechanisms interacting and impacting the actual performance. To more closely quantify window performance, extensive laboratory testing (or at minimum two-dimensional heat flow computer simulation modeling) is generally required.

Knowing the general heating transfer mechanisms helps to understand how a certain measure will modify the performance. Elements such as interior and exterior storm windows will impact mechanisms such as the conductance through the glass and sashes, air leakage between the frame and sashes or between the sashes and glass, and the radiation, absorption, and emittance from the vision glazing elements.

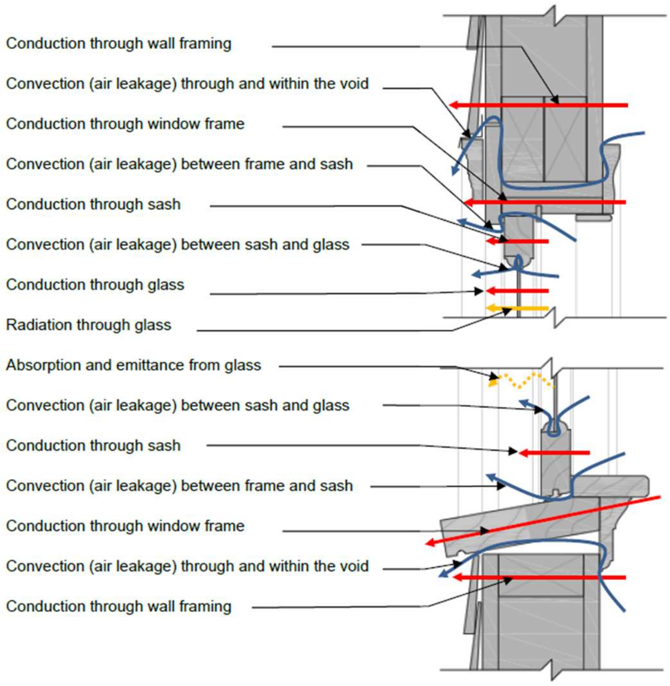


Figure 8. Illustration of the heat transmittance occurred through window (WWRRR 2012)

2 METHOD

2.1 Overview

- In thermal retrofit of buildings, the goal is to lower the U-value of building components as much as possible using different techniques such as high insulated materials with optimized construction structures, the main challenge in the historic buildings ,which are under heritage protection, is the limitation of changes and the need to maintain the same original façade, as this thesis investigates one of the best available materials in window thermal retrofit which is vacuum glazing, the following steps will be conducted in this study:
- As this research investigate the application potential in vacuum glazing in building retrofit, it is necessary to assessed this types of glazing in the historic buildings because thermal retrofit of these buildings is considered a difficult challenge due to its specific requirements that have to be met therefore two window details were selected as a study cases. These two window details are the most common used windows in Vienna Austria before 1960s.
- In order to assess the vacuum glazing performance when applied to windows, the total building thermal performance has to be evaluated when using such materials in window thermal retrofit therefore, two typical historic buildings in Vienna were selected as case study. These buildings were selected based on their age, their status concerning heritage protection, the availability of plan documents, and their percentage of glazing in the facade. Buildings with a larger glazing are have to show presumably a higher impact following an exchange of glazing/a retrofit of windows. However, the representatively of the selected buildings and the existence of all or some of the previously selected buildings is considered as selection criteria for the use case buildings.
- Determination, collection, and structuring of necessary data: This includes the collection and structuring of all necessary input data parameters that would be necessary for performing thermal bridge simulation and overall building performance evaluation. Such parameters include – besides others - the thickness of layers, the conductivity, vapor diffusion resistance, density and specific heat of used components, the U-Values/Layered components of opaque building parts, the heated gross area and volume of the case study building.
- Status Quo evaluation on thermal bridges and overall building performance. In this step, the status quo of thermal building performance on the levels of glazing

details/window junctions and of the heating demand of the overall case study buildings is derived. This includes the setup of the details following normative requirements for system borders and adiabatic plans and the performance evaluation of the historical state of the details. The heating demand of the status quo will also be calculated via normative approach. The tools intended for this and the next steps are AnTherm (Thermal Bridges) and ArchiPHYSIK (Heating demand calculation/energy certification).

- Based on the previous steps, different scenarios for application of the vacuum glazing were developed. These scenarios addressed different potential constructive measures to improve the U-Value of the windows and the thermal bridge evaluation parameters such as Ψ, f_{Rsi}, and thermal coupling coefficients. From this and the previous step, a matrix of results of the different scenarios was generated.
- Based on the results of the prior steps, refurbishment strategies for the overall building will was defined and calculated.
- Based on the previous steps, the different scenarios was evaluated from economic view via an amortization calculation.

2.2 Research question

The main question of this thesis is as follows:

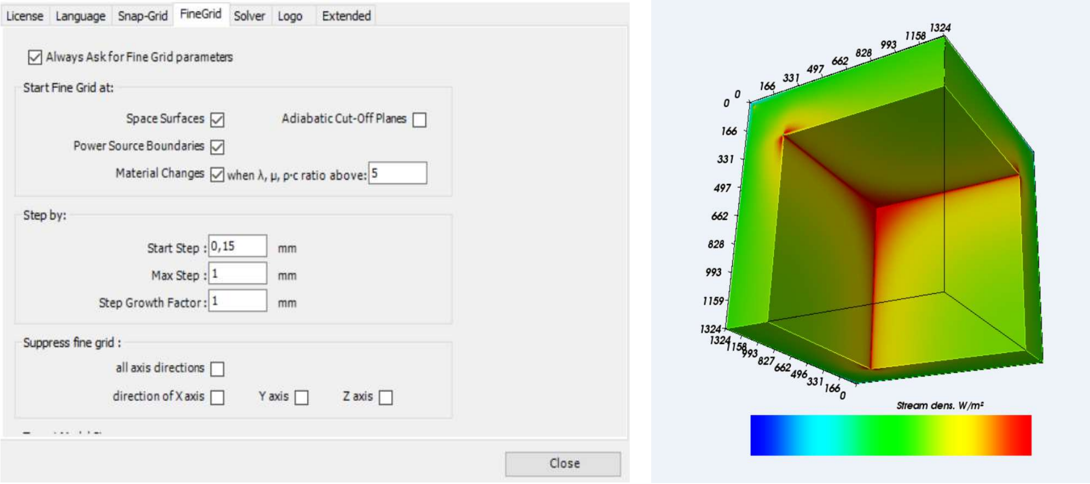
Can vacuum glazing be a potential future alternative to currently used glazing materials in thermal building retrofit due to its high thermal quality and near future availability?

2.3 Simulation and calculation engines:

Thermal bridge evaluation software and simulation settings:

In this study, the software AnTherm were used to evaluate thermal behavior of window components with heat bridges. As this software calculates temperature distribution and heat flows in building structures of arbitrary form and complex material composition particularly such as thermal bridges. The program package AnTherm fulfills all requirements raised in (EN ISO 10211:2007) and (EN ISO 10077-1&2:2003).

AnTherm is a rectangular-modelling software. In other words, in contrast to CAD-software, it is not capable of modelling sloping lines and curve-shaped details. Thus, sloping lines have to be approximated with steps of precise number and size according to the rules, each rectangular element is characterized with 4 coordinates of X1, X2 and Y1, Y2. Visually visible layers are taken into account for the simulation. Moreover, exterior and interior space should also be identified and its surface thermal resistance R_S [m²·K·W⁻¹], depending on the direction of a heat flow. AnTherm subdivides the model into small cells which are then used to solve the thermal equations during simulation, providing that vacuum layer thickness in the evaluated vacuum glazing is 0.15 [mm], which can greatly affects the simulation results if the smallest cell dimension is set to more than 0.15 [mm], so the cell size where given 0.15 [mm] during the simulation when deriving thermal bridges calculation elements for both selected window details. It is also to be defined before conducting thermal bridge simulation, the boundary conditions as illustrated in Table 1



☑ Always Ask for Fine Grid parameters

Start Fine Grid at:

Space Surfaces ☑ Adiabatic Cut-Off Planes ☐

Power Source Boundaries ☑

Material Changes ☑ when λ, μ, ρ·c ratio above: 5

Step by:

Start Step : 0,15 mm

Max Step : 1 mm

Step Growth Factor : 1 mm

Suppress fine grid :

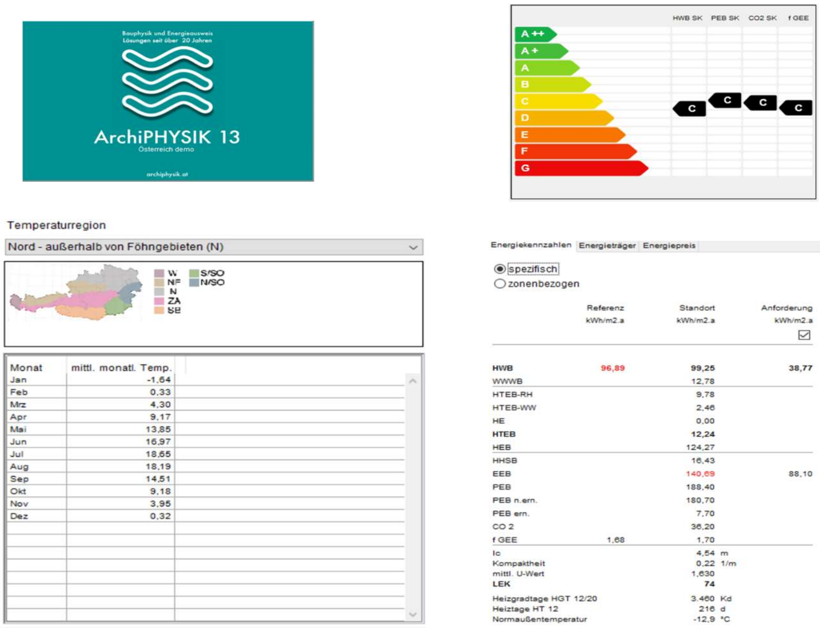
all axis directions ☐

direction of X axis ☐ Y axis ☐ Z axis ☐

Figure 9. Simulation settings in AnTherm for thermal bridges calculations

Heating demand calculation software

There are many programs for calculating building heating and total buildings’ energy demand in varies methods, In this study, the program called ArchiPHYSIK 13.0 produced by A-Null Development GmbH, Vienna-Austria was used to scale up the results that have been determined of window U-values and address the impact of reduced window U-value on a building scale, specifically the impact on building heating demand as this study evaluate the vacuum glazing in building thermal retrofit. The reason behind using ArchiPHYSIK software that it complies with Austrian standards. It calculates the heating demand in accordance with Austrian standards requirements and specs. ArchiPHYSIK is also able to assess thermal, acoustic and steam diffusion performance and provides energy and ecology certificate for single and multi-zone residential and non-residential buildings. It also provides information about summer overheating and it takes into account the codes of all Austrian federal states. Additionally, it has weather database of Austria, therefore its results are very reliable as it takes into account building local climate and Topography.



Temperaturregion

Nord - außerhalb von Föhngebieten (N)

Monat	mittl. monatl. Temp.
Jan	-1,64
Feb	0,33
Mrz	4,30
Apr	9,17
Mai	13,85
Jun	16,97
Jul	18,65
Aug	18,19
Sep	14,51
Okt	9,18
Nov	3,95
Dez	0,32

Energiekennzahlen | Energieträger | Energiepreis

● spezifisch
○ zonenbezogen

	Referenz kWh/m2.a	Standort kWh/m2.a	Anforderung kWh/m2.a ☑
HWB	96,89	99,25	38,77
WWWB		12,78	
HTEB-RH		9,78	
HTEB-WW		2,46	
HE		0,00	
HTEB		12,24	
HEB		124,27	
HHSB		16,43	
EEB		140,69	88,10
PEB		188,40	
PEB n.ern.		180,70	
PEB ern.		7,70	
CO 2		36,20	
f GEE	1,68	1,70	
lc		4,54 m	
Kompaktheit		0,22 1/m	
mittl. U-Wert		1,630	
LEK		74	
Heizgradtage HGT 12/20		3.460 Kd	
Heiztage HT 12		216 d	
Normaußentemperatur		-12,9 °C	

Figure 10. ArchiPHYSIK energy certificate software

2.4 Window study cases

After investigating the common window types and details that are used in historic buildings in Vienna-Austria which were constructed before 1970s, two window details were selected as study cases in this research, as these two window types were the most commonly used in in that period.

Window study case detail.1

Casement window consists of two window panes (outside W1 and inside W2) as illustrated in Figure 11 with single glazing layer in each external and internal panel, this window type is the typical historical window that was used in Austria until the year 1955.

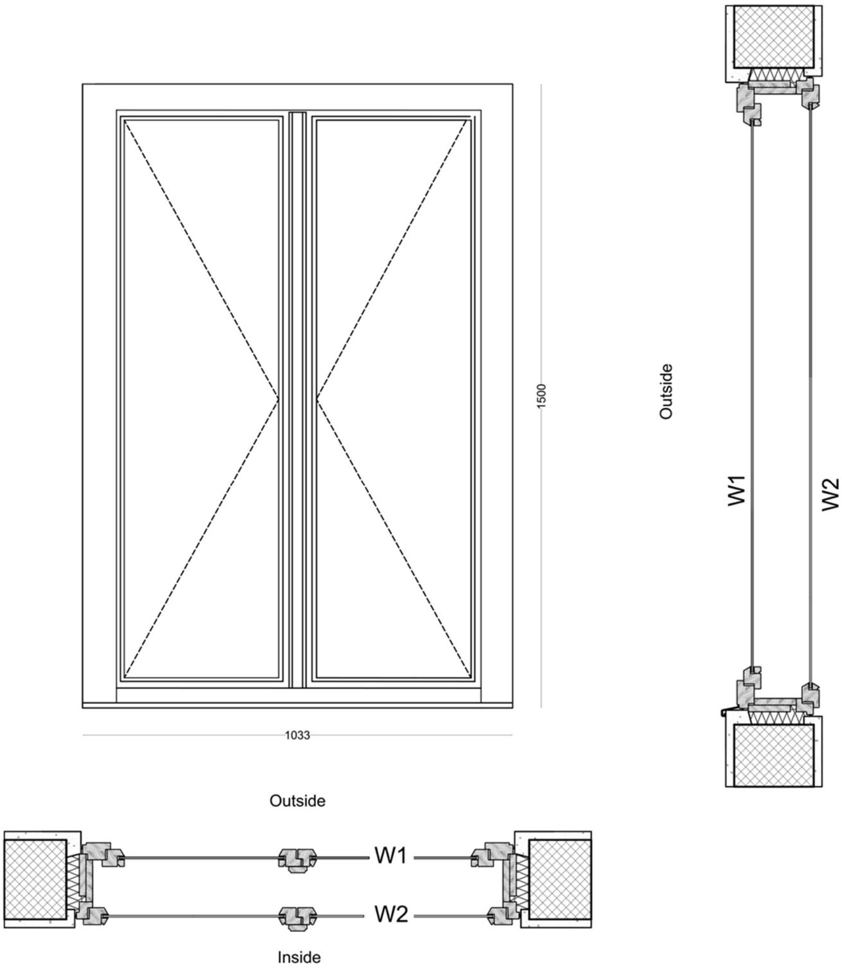


Figure 11. Casement window detail

Window study case detail.2

This window type was further development of casement windows, it was widely used in Austria until 1967 and it was a step before the modern insulated double or triple glass windows. The composite window consists of two wings (outside W1 and inside W2) as illustrated in Figure 12 with single glazing layer of 4 [mm] thick in each external and internal wing.

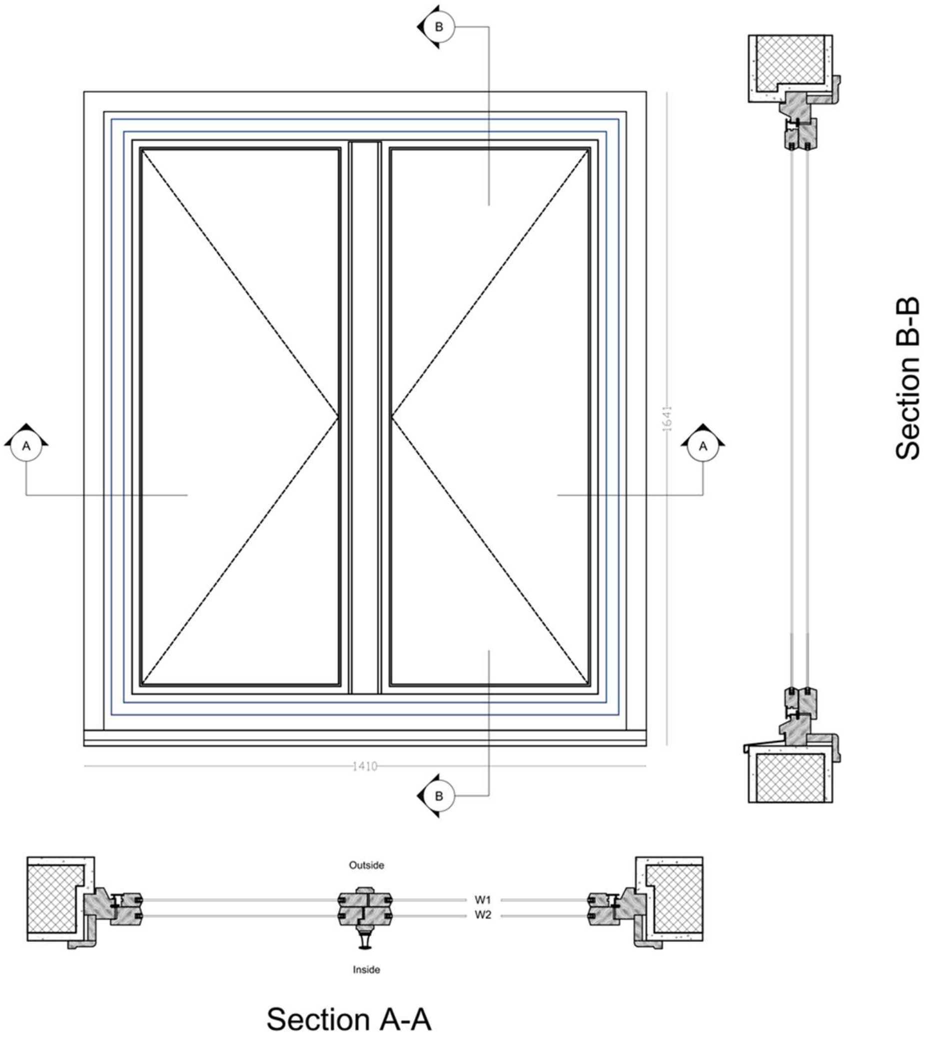


Figure 12. Composite window detail

2.5 Building study cases

Building study case .1

Historical building located in the first district in Vienna, the building is under heritage protection as the whole first district in Vienna classified as heritage protected. The building constructed between 1946 and 1976 and consists of 5 stories including the roof floor.

- Ground floor area 742 m²
- Transparent area 275 m²
- Total building envelope area exposed to air 2516 m²
- Transparent element area / total envelope area exposed to air 10.9%

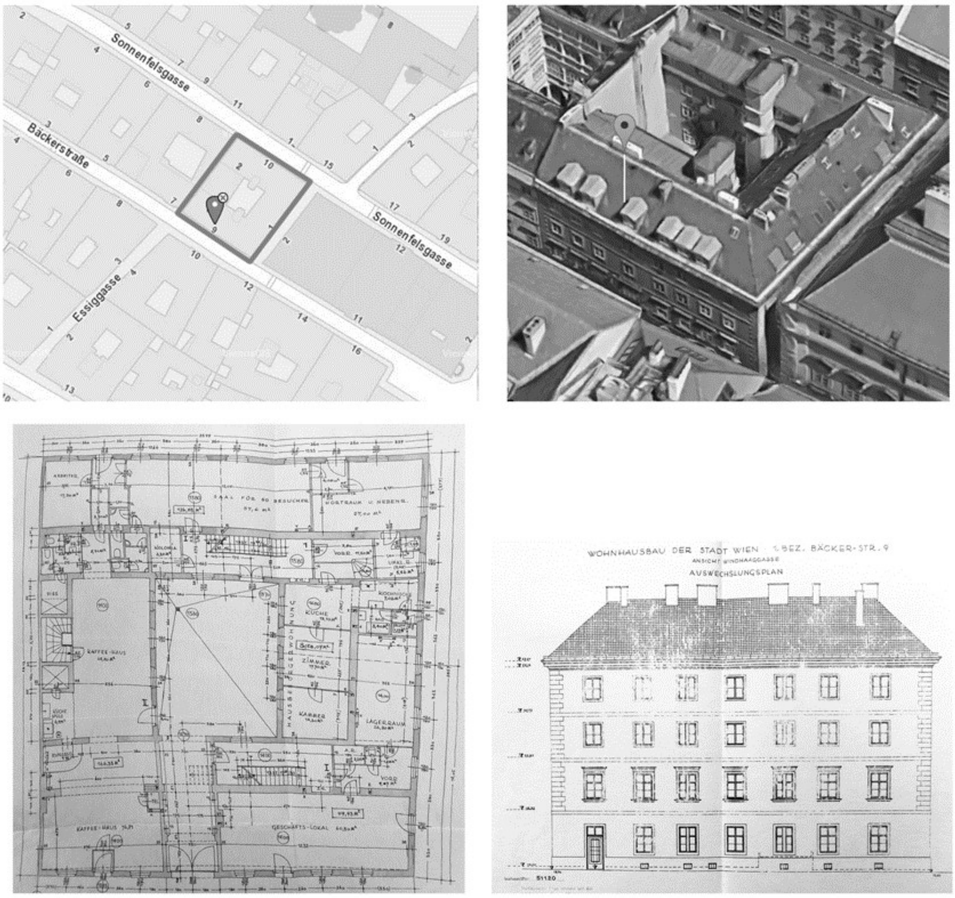


Figure 13. Building case 1 - Bäckerstraße 9, 1010 Vienna-Austria

Building study case .2

Historical building located in the first district in Vienna, the building is under heritage protection as well. It was constructed between 1946 and 1976 and consists of 8 stories including the roof floor.

- Ground floor area 603 m²
- Transparent area 536 m²
- Total building envelope area exposed to air 2703 m²
- Transparent element area / total envelope area exposed to air 19.8%

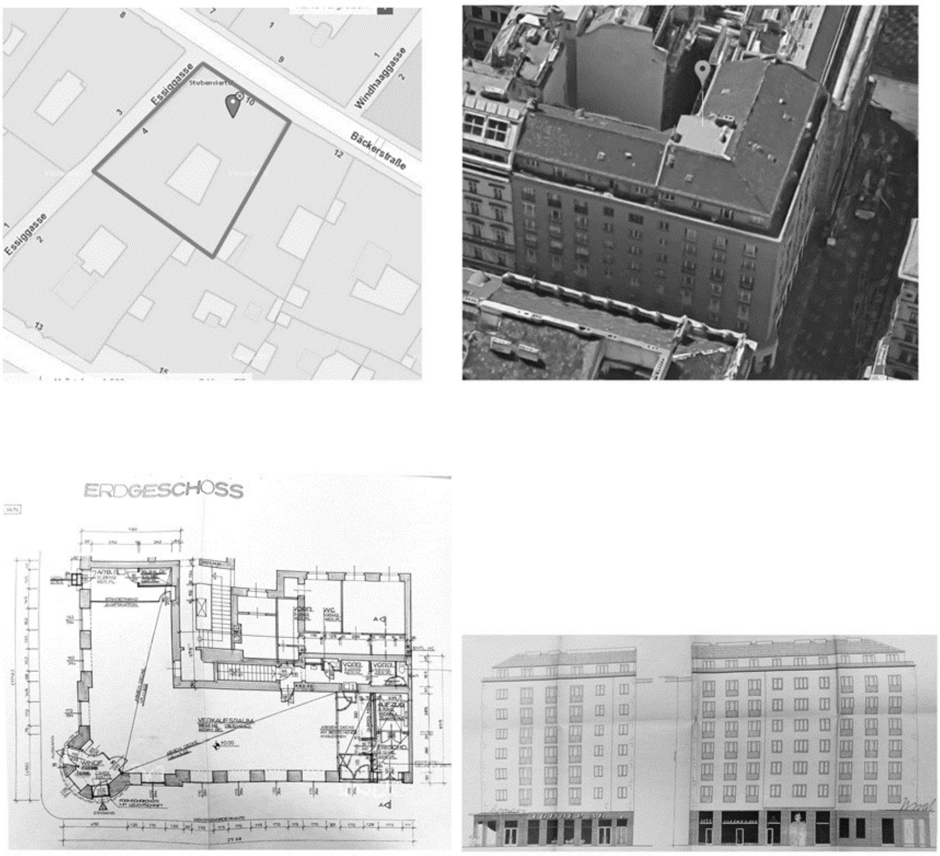


Figure 14. Building case 2 - Walfischgasse 10, 1010 Vienna-Austria

2.6 Boundary conditions and typical U-values of building components:

The boundary conditions that were considered in the simulation and calculations of both window details 1 and 2 are shown in the Table 1. In this study, Temperature of boundary conditions were set according to Appendix 2 of DIN4108 with +20 [^{o}C] for interior and -5 [^{o}C] for exterior environment. The thermal resistance of ventilated and unventilated air layers also were set, due to air layer thickness, according to table 10 in (DIN ISO 6946:2015-06) see Table 1.

Table 1. Boundary conditions of modeled detail

Ambient temperature [°C]	Outdoor	-5.0
	Indoor	20
Surface heat transfer coefficient [$m^2.K.W^{-1}$]	External	0.04
	Internal (ventilated)	0.13
	Interstitial (non-ventilated)	For detail.1=0.163 For detail.2=0.17

In order to assess the direct impact of vacuum glazing in window thermal retrofit on the total building heating demand, the U-value of building components other than windows, were set as shown in Table 2 according to Austrian norm (lt6-301211:2011)

Table 2. Typical U-values of historical building components for year between the 1945 and 1960 in Vienna, Austria

Building component	U-value [W/m^2 .K]
Ground slab	1.10
Typical floor slab	1.35
External wall	1.30
Roof slab	1.30
Outdoor gates and doors	2.50

2.7 Calculation models for windows:

Knowing that every year millions of euros are spent on heating our homes and businesses. This fact makes understanding the role of the windows in heat losses comes first when the goal is to reduce the building heat losses and improving building thermal performance. One of the best methods to measure the effect of windows on building thermal performance is windows' U-value. This value measures the heat transmittance through the window between inside and outside space due to difference temperatures between internal and external spaces. But U-value accounts only for heat losses not for incoming solar radiations.

The U-value of the whole window is calculated in the first term for the frame and in the second term for the window glazing and at third term, the frame glazing edge psi value is taken into account. After that, they have been combined so that the U-value of entire window structure has been obtained. In this study, two window details were selected due to their common use in Austria in the period before the 1960s as this study address the potential use of vacuum glazing in thermal building retrofit of historic buildings.

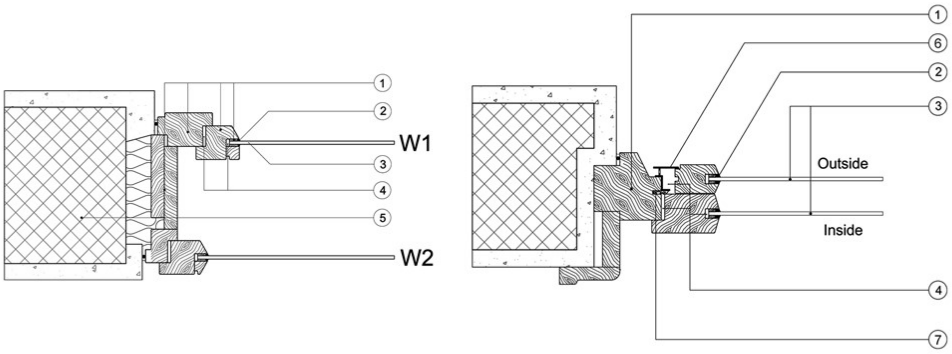


Figure 15. Typical used windows in Austria before 1960s

Table 3. Materials of the selected wooden window details

Number	Material name	λ [W.m^{-1}.K^{-1}]
1	Wooden frame	0.14
2	Window putty	0.50
3	Lime glass	1.00
4	Air cavity	0.05
5	Reinforced concrete	2.30
6	Aluminum	200
7	Silicon rubber	0.30

To do the calculations, the software called AnTherm where used, which provides analysis of thermal behavior of building constructions with heat bridges. This is powerful software is used for heat flow calculation in building construction elements, the thermal heat bridges and vapor bridges.

2.7.1 Heat transfer theory:

Heat is defined as energy transferred by virtue of temperature difference. It flows from regions of higher temperature to a region of lower temperature. It is customary to different types of heat transfer mechanisms as a method. The basic modes of heat transfer are conduction, radiation, and convection.

Heat transmittance through transparent building components is a complicated process. It is determined by the conduction of the different solid materials and convection between materials on surfaces and in encapsulated air compartments used to manufacture window. However, the emissivity is the ability of bodies' surfaces to emit energy by radiation. Thermal conductivity is represented by $\boldsymbol{\lambda}$, it is the material ability to conduct heat which is measured by the unit [$Wm^{-1}.K^{-1}$]. In Table 4 there are thermal conductivity of the most common materials in different kinds of windows

Table 4. Materials of different typical kinds of historical windows

Material name	**$\boldsymbol{\lambda}$ [$W.m^{-1}.K^{-1}$]**
Soft Wood	0.13
Hard wood	0.14
Steel	50
PVC (rigid)	0.17
EPDM	0.25
Glass (Soda lime)	1.00
Silicon rubber	0.30
Air	0.025
Argon	0.0168
Krypton	0.009
Polymid	0.25

Regarding constructions with encapsulated gas layers, not only conduction and radiation but also convection have to be considered. This identified as a separate mode of heat transfer, relates to the transfer of heat from bounding surface to the fluid in motion or to the heat transfer across a flow plane within the interior of the flowing fluid. This occurred due to the movement of molecules in the fluids. What means that convection doesn't happen in solids unless there are pores in the material for this reason, convection has a great influence on heat transmittance and therefore it should be avoided or minimized to the lowest level when the approach is high thermal insulated windows. One used technique is by reducing the cavities where the gas is contained because if the cavity is small enough the convection doesn't occur. Or by using some types of gasses with considerably low thermal conductance such as argon and krypton as insulation materials in double or tribble glazing materials.

A combination of these three factors has to be considered when the heat transmittance of the whole window is to be calculated. Both parts of the structure; the frame and the glazing would be affected by them. In Figure 16 the thermal transmittance through the window is observed due to conduction, convection, and radiation.

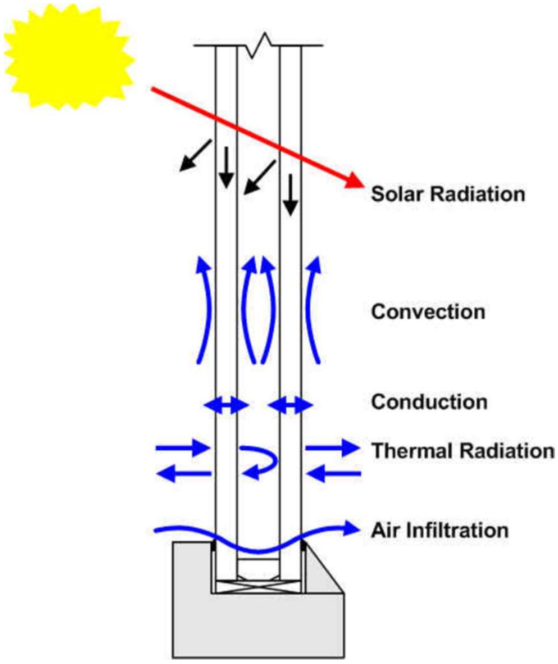


Figure 16. Thermal transmittance through window (Kent 1999)

2.7.2 Conduction:

It is defined as a transfer of heat from one part of a solid component at a high temperature to another part of the same component at a lower temperature, or from one body at higher temperature to another which stays in physical contact with it at a lower temperature. Conduction takes place always when there is a temperature difference between two sides of the material, or two or more different solids in contact. This intervenes also when heat transferred in gasses and liquids and in the contacts between a solid at one side and liquid or gas at another side. Single glazed fenestration products which were used widely in most historic buildings has a very low insulating quality that can be considered as a thermal hole in wall and typically has a heat loss rate ten to twenty times of the walls' heat losses. Conductive heat flow in a homogeneous isotropic material is given by Fourier law as follows:

$$Q = -\boldsymbol{\lambda}.\,\boldsymbol{\nabla}T = -\left(\frac{\partial T}{\partial X}, \frac{\partial T}{\partial Y}, \frac{\partial T}{\partial Z}\right), \text{ [W.m}^{-2}\text{]} \qquad (1)$$

Where:

$\boldsymbol{\lambda}$: is thermal conductivity (function of moisture and temperature) in [W.m^{-1}.K^{-1}]

$\boldsymbol{\nabla}$T: is temperature gradient in [K.m^{-1}]

2.7.3 Convection:

Convection is identified sometimes as a separate mode of heat transfer, relates to the transfer of heat from a bounding surface to a fluid in motion, or to the heat transfer across a flow plane within the interior of the flowing fluid. If the fluid motion is induced by a pump, a blower, a fan, or some similar device, the process is called *forced convection*. If the fluid motion occurs as a result of the density difference produced by the temperature difference, the process is called free of natural convection. Convection affects the heat transfer in many places in the window assembly. The inside glazing surface, the outside glazing surface, inside frame cavities, and inside any air spaces between glazing. In double and tribble glazing, the air layers in between glazing panes, convection currents in the air space can facilitate heat transfer from higher temperature space to lower temperature space causing heat losses through window, to avoid this heat loss or at least minimize it, an insulation gases are recommended to fill the space instead of air like Krypton or Argon and to get even better insulation value, the air should be evacuated from the space leaving vacuum layer in between glazing and that gives high potential of reducing the heat loss through glazing to the minimum level when it is applied properly.

The equation used to calculate the convective heat transfer is:

$$Q_{convection} = \boldsymbol{\alpha} \ . \ (T_s - T_e), \text{ [W]} \qquad (2)$$

Where

$\boldsymbol{\alpha}$: is the convection surface heat transfer coefficient and $(T_s - T_e)$ is the temperature difference between the surface and the ambient air [K]

2.7.4 Radiation:

Radiation, or more correctly *thermal radiation*, is electromagnetic radiation emitted by the body by virtue of its temperature and at the expense of its internal energy. Thus thermal radiation is the same nature as visible light, x rays, and radio waves. The difference between them being in their wavelengths and source of generation. All heated solids and liquids, as well as some gases, emit thermal radiation. The transfer of energy by conduction requires the presence of material medium, while radiation does not. In fact, radiation transfer occurs most efficiently in a vacuum. Knowing that all surfaces above absolute zero emit electromagnetic waves, and when these waves strike another surface, part of the energy is reflected, part is absorbed and sometimes part can be transmitted, depending on surface properties. All these emissions result in heat exchange between surfaces at different temperatures.

In buildings, the glass from window transmits a great part of the energy from the sun (because it is in shortwave length portion of infrared range). When the energy enters through the glass, the objects warm up and start to radiate heat in long wavelength range as a consequence of their low temperature. Then, this heat is blocked by the glass from the window (because these waves are in the long wavelength range), and as a consequence, the temperature inside increases rapidly as illustrated in Figure 17.

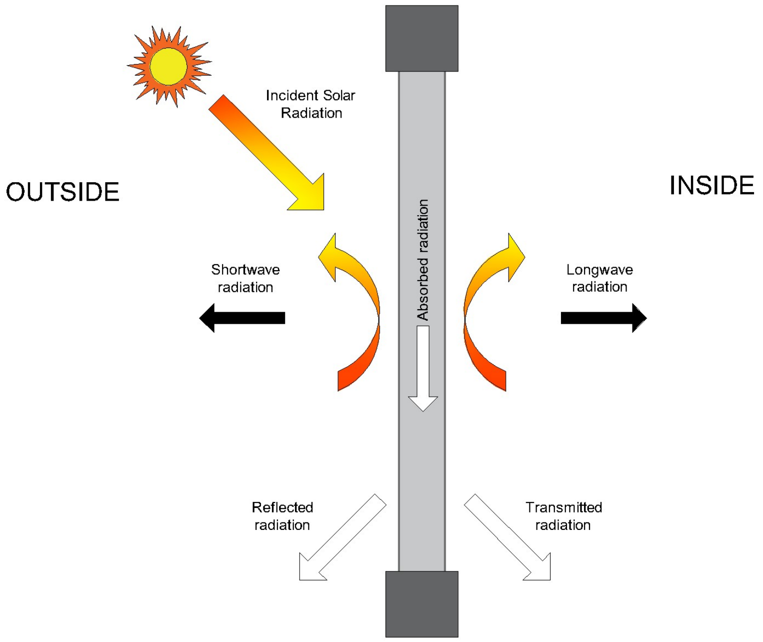


Figure 17. Heat flux over a single glass window

2.7.5 Thermal transmittance U-value:

The U-value is the standard way to quantify insulating value. In fenestration products, the U-value is used as an indicator of heat flow through the fenestration. The less window U-value the better-insulated window. The total window U-value is calculated according to international Standard (ISO 10077-1 and ISO 10077-2).

To calculate window U-value it is necessary at first to calculate the U-value of frame area U_f and this has to be calculated with reference to Figure 18, in the calculation model, the glazing is replaced by insulation panel with thermal conductivity $\boldsymbol{\lambda}$ = 0.035 [W.m^{-1}.K^{-1}] inserted into the frame. The values for the external surface resistance R_{se} and internal surface resistance R_{si} were considered 0.04 [m^2.K.W^{-1}] and 0.13 [m^2.K.W^{-1}] respectively. Whereas the surface resistance of the buffer space between two window wings were considered 0.16 [m^2.K.W^{-1}] in the first detail of casement window and 0.17 [m^2.K.W^{-1}] in the second window detail according to the buffer space thickness between two window wings.

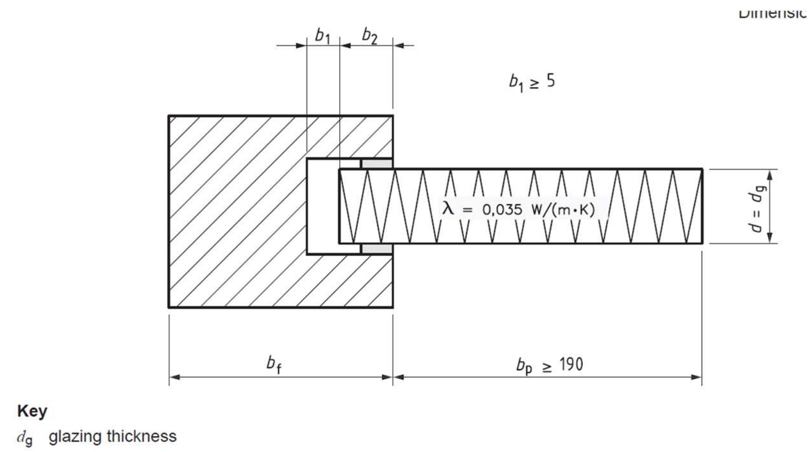


Figure 18. Schematic of profile section with insulation panel installed (ISO 10077-2 2012)

The two-dimensional thermal conductance L_f^{2D} , of the section is shown in Figure 18 consisting of frame and insulation panel and it is obtained from the simulation of the section using AnTherm software. The value of thermal transmittance of the frame, U_f is defined by the following equation:

$$\boldsymbol{U_f} = \frac{\boldsymbol{L_f^{2D} - U_p - b_p}}{\boldsymbol{b_f}} \tag{3}$$

Where:

$$\boldsymbol{U_p} = \frac{\boldsymbol{1}}{\boldsymbol{R_{se} + R_{si} + \frac{d_g}{\lambda_p}}} \tag{4}$$

$\boldsymbol{U_f}$ is thermal transmittance of the frame section, expressed in [W.m^{-2}.K^{-1}]

$\boldsymbol{L_f^{2D}}$ is the thermal coupling coefficient of the section when the glass panel is replaced by insulation panel with thermal conductivity $\boldsymbol{\lambda}$ = 0.035 [W.m^{-1}.K^{-1}] inserted into the frame with same glazing panel thickness.

U_p	is the thermal transmittance of the central area of the panel, expressed in [W.m⁻².K⁻¹]
b_p	is the visible width of the panel, expressed in [m], the larger of the projected widths as seen from both sides b_p is measured on the same side as b_f
R_{se}	is the external surface resistance for horizontal heat flow in [m².K.W⁻¹]
R_{si}	is the internal surface resistance for horizontal heat flow in [m².K.W⁻¹]
d_g	is the thickness of insulation panel in [m]
λ_p	is the thermal conductivity of the insulation panel, = 0.035 [W.m⁻¹.K⁻¹]

Next Step is to calculate the U-value of the glazing part of the window. This is either to be calculated by the following equation:

$$U_g = \frac{q_g}{\Delta T \,.\, d_g} \tag{5}$$

Where

U_g	is the thermal transmittance of the glass in [W.m⁻².K⁻¹];
q_g	is the heat transfer through the glass in [W.m⁻¹];
d_g	is the thickness of the glass in [m];

Or it can be also calculated using the following equation:

$$U = \frac{1}{R_{si}+R_T+R_{se}} \tag{6}$$

To calculate linear thermal transmittance between the glass and the frame the equation (10) has been used

Then, the U-value of the total single window pane shall be calculated using the following equation:

$$U_{\text{window}} = \frac{\sum A_g \, U_g + \sum A_f * U_f + \sum l_g * \Psi_g}{\sum A_g + \sum A_f} \tag{7}$$

Where:

$\sum A_{g(w1,w2)}$	is the glazing area of the external and internal window respectively in [m²];
$U_{g(w1,w2)}$	is the thermal transmittance of the glazing of the external and internal window respectively in [W.m⁻².K⁻¹];
$\sum A_{g(w1,w2)}$	is the frame area of the external and internal window respectively in [m²];
$U_{f(w1,w2)}$	is the thermal resistance of the external and internal frame respectively in [W.m⁻².K⁻¹];
$l_{g(w1,w2)}$	is the length of glazing –frame edge as illustrated in [m];

$\boldsymbol{\Psi}_{g(w1,w2)}$ is the linear thermal transmittance due to combined effect of Glazing, Spacer and, frame in [W.m^{-1}.K^{-1}];

2.7.6 The legal framework for building renovation:

Building renovation in Austria is regulated by Federal Heritage Office. Its guidelines cover the principles of energy-efficient retrofit of historical buildings. The main goal is the maintenance of historical buildings with minimum or no altering of original facades.

Window constructions are an integral part of the architecture and architectural surfaces. They are responsible for the appearance of the architectural monuments. Windows have to deal with a variety of tasks such as exposure, outlook, solar input, operability, maintenance, sound insulation, sun protection, ventilation, and heat protection. All these demands of the component have led to the development of sophisticated window systems over the centuries. As a rule, these are wooden constructions, but sometimes also metal constructions. The historic goal is the preservation of historic window and window shutter constructions, including window glass and fittings. Preservation is to be assessed in the context of the existing materials, the relevant time position in the appearance of the structure and the attainable conservation perspective. The technical necessities are thus to be reconciled. Material continuity is an essential prerequisite. Historical window constructions should not be regarded as wearing parts.

As in this study, the so called Box windows are investigated especially in historic buildings that were constructed around 1940s from the modernism of the interwar period. The characteristic element of these buildings is the so-called Wiener window - a window box with two window layers, which can be opened separately.

A general retrofit practice of this type of windows. The outer window wing should be preserved its original shape and improvements on this window part should not affect the original external window view and this also the case of internal window wing if the internal architectural view is needed to be preserved. Replacement of historical window box may occur only in case of extremely bad condition, or previously altered window box, or if dimensioning and detailing of a new element resembles an original design as much as possible.

Historical window constructions, including glazing, are to be obtained in principle. The existing historical stock should be repaired by a monumental repair. In individual cases, improvements can be made to the construction (e.g. for water management, energy improvement) by means of additions (e.g. weather limbs, prefabricated structures). In order to assess completeness, detail-specific work drawings must be prepared in individual cases or, if necessary, a window sample should be created. Historical fittings (tapes, Accessories, etc.) should be kept as far as possible in their operation. The wood surface like the paintings are part of the windows' biography and should, therefore, be preserved as far as possible.

Thermal performance improvements of window constructions are to be measured by the use of the room c as well as building physics aspects. In order to increase the heat transfer resistance, retrofitting seals, the change to coated single glazing or the installation of a second fenestration level on the inside or outside can be justified (composite or box construction, preliminary window). The solution should be developed according to the situation. Insulating glazing can be executed only in the second window level in specially defined exceptional cases, provided that the existing historical construction permits a solution comparable in size and detail to the original, and when it has demonstrable relevance for the overall energy balance of the object. Exceptions are buildings of the twentieth century which are characterized by insulating glass construction, or special constructions (e.g. in the case of completely new glazing of openings).

3 WINDOW THERMAL TRANSMITTANCE CALCULATIONS

3.1 Window study case detail.1

Calculation of total window thermal transmittance

According to ISO standard (ISO 10077-1), the thermal transmittance $\boldsymbol{U_w}$, of a system consisting of two separate windows shall be calculated using Equation 8

$$\boldsymbol{U}_{\mathrm{w}} = \frac{\mathbf{1}}{\mathbf{1}/\boldsymbol{U}_{\boldsymbol{w}\mathbf{1}} - \boldsymbol{R}_{\boldsymbol{si}} + \boldsymbol{R}_{\boldsymbol{s}} - \boldsymbol{R}_{\boldsymbol{se}} + \mathbf{1}/\boldsymbol{U}_{\boldsymbol{w}\mathbf{2}}} \tag{8}$$

Where:

$\boldsymbol{U_{w1}}, \boldsymbol{U_{w2}}$	are the thermal transmittance of the external and internal window shells respectively);
$\boldsymbol{R_{si}}$	is the internal surface resistance for horizontal heat flow;
$\boldsymbol{R_{se}}$	is the external surface resistance for horizontal heat flow;
$\boldsymbol{R_s}$	is the thermal resistance of the space between the glazing of external and internal window pane;

The thermal transmittance of the external and internal window $\boldsymbol{U_{w1}}$ and $\boldsymbol{U_{w2}}$ respectively is calculated using the following Equation:

$$\boldsymbol{U}_{\mathrm{w}(\mathbf{1},\mathbf{2})} = \frac{\sum \boldsymbol{A}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}\, \boldsymbol{U}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})} + \sum \boldsymbol{A}_{\boldsymbol{f}(\boldsymbol{w1},\boldsymbol{w2})} * \boldsymbol{U}_{\boldsymbol{f}(\boldsymbol{w1},\boldsymbol{w2})} + \sum \boldsymbol{l}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})} * \boldsymbol{\Psi}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}}{\sum \boldsymbol{A}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})} + \sum \boldsymbol{A}_{\boldsymbol{f}(\boldsymbol{w1},\boldsymbol{w2})}} \tag{9}$$

Where:

$\sum \boldsymbol{A}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}$	is the glazing area of the external and internal window respectively;
$\boldsymbol{U}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}$	is the thermal transmittance of the glazing of the external and internal window respectively;
$\sum \boldsymbol{A}_{\boldsymbol{f}(\boldsymbol{w1},\boldsymbol{w2})}$	is the frame area of the external and internal window respectively;
$\boldsymbol{U}_{\boldsymbol{f}(\boldsymbol{w1},\boldsymbol{w2})}$	is the thermal resistance of the external and internal frame respectively;
$\boldsymbol{l}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}$	is the length of glazing –frame edge as illustrated in Figure 26
$\boldsymbol{\Psi}_{\boldsymbol{g}(\boldsymbol{w1},\boldsymbol{w2})}$	is the linear thermal transmittance due to combined effect of Glazing, Spacer and frame;

NOTE: In the case of single glazing the last term of the numerator in the Equation (9) shall be taken as zero (no spacer effect) because any correction is negligible [ISO 1007-1 / 5.1.1]

$\boldsymbol{\Psi}$ -Value of external and internal part of casement window:

Is calculated using the following equation:

$$\boldsymbol{\Psi_{w(1,2)} = L_{\Psi}^{2D} - U_f * b_f - U_g * b_g} \qquad (10)$$

Where:

$\boldsymbol{L_{\Psi}^{2D}}$ is the thermal coupling coefficient obtained from a 2-D calculation of the Component separating the two environments being considered;
$L_{\Psi(buffer-ext)}^{2D}$ when calculating $\Psi_{w(1)}$
$L_{\Psi(int-buffer)}^{2D}$ when calculating $\Psi_{w(2)}$

$\boldsymbol{U_f}$ Heat transfer coefficient of the framing;
$U_{f(w1)}$ when calculating $\Psi_{w(1)}$
$U_{f(w2)}$ when calculating $\Psi_{w(2)}$

$\boldsymbol{U_g}$ Heat transfer coefficient of the glazing;
$U_{g(w1)}$ when calculating $\Psi_{w(1)}$
$U_{g(w2)}$ when calculating $\Psi_{w(2)}$

$\boldsymbol{b_f}$ Projected width of framing profile;
$b_{f(w1)}$ when calculating $\Psi_{w(1)}$
$b_{f(w2)}$ when calculating $\Psi_{w(2)}$

In order to get accurate results of the internal, buffer space and external surface temperatures of the casement window, the buffer space temperature $\Theta_{\boldsymbol{b}}$ is calculated using the following Equation:

$$\boldsymbol{L^{2D(1)}} * (\Theta_{\boldsymbol{i}} - \Theta_{\boldsymbol{b}}) = \boldsymbol{L^{2D(2)}} * (\Theta_{\boldsymbol{b}} - \Theta_{\boldsymbol{e}}) \qquad (11)$$

Where:

$\boldsymbol{L^{2D(1)}}$ is the thermal coupling coefficient (int-buffer) obtained from AnTherm Simulation Of the 2D-detail as illustrated in Figure 19;

$\Theta_{\boldsymbol{i}}$ is the internal temperature as illustrated in boundary conditions in Table 1;

$\Theta_{\boldsymbol{b}}$ is the buffer space temperature;

$\boldsymbol{L^{2D(2)}}$ is the thermal coupling coefficient (ext-buffer) obtained from the AnTherm Simulation Of the 2D-detail as illustrated in Figure 19;

$\Theta_{\boldsymbol{i}}$ is the external temperature as illustrated in boundary conditions in Table 1;

Calculation of the buffer space temperature for the original case (Scenario 1)

Using the Equation 11 and considering $\Theta_{\boldsymbol{i}}$ and $\Theta_{\boldsymbol{e}}$ from boundary conditions as illustrated in Table 1

$\Theta_{\boldsymbol{i}}$ = 20 in [C°] = 273 + 20 = 293 [K]
Θ_e = -5 in [C°] = 273 - 5 = 268 [K]

$L_{2D(1)}$ and $L_{2D(2)}$ are obtained from the simulated detail in Figure 19

Whereas $\boldsymbol{L^{2D(1)}}$ and $\boldsymbol{L^{2D(2)}}$ are obtained from the simulation in AnTherm considering $\boldsymbol{R}_{\mathrm{si}}$= 0.13, and $\boldsymbol{R}_{\mathrm{se}}$= 0.04 [m².K.W⁻¹]

$L^{2D(1)} * (\Theta_i - \Theta_b) = L^{2D(2)} * (\Theta_b - \Theta_e)$
2.24 * (293 - Θ_b)= 3.18 * (Θ_b – 2 68)
Θ_b = 278.34 [K]
Θ_b = 5.34 [C°]

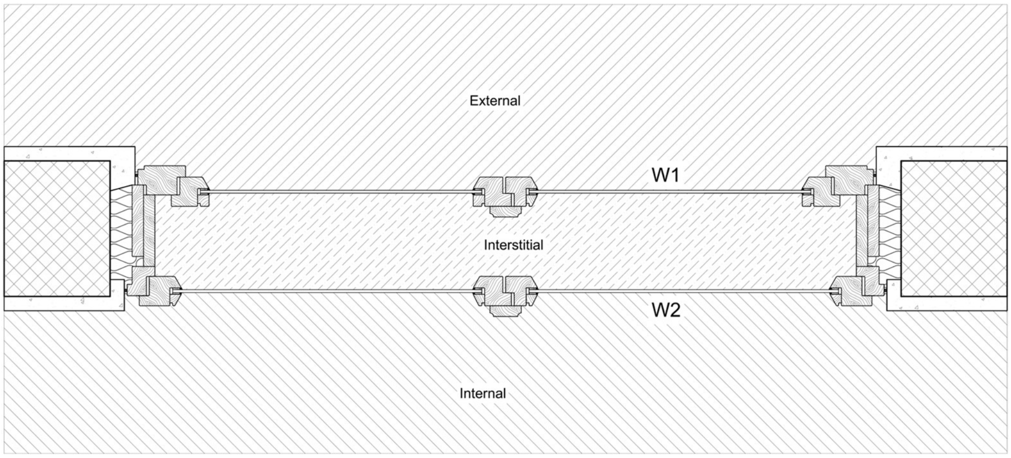


Figure 19. Casement window detail for obtaining buffer space temperature from AnTherm simulation

Calculation of linear thermal transmittance $\boldsymbol{\Psi_{w1}}$-Value of the external part of casement window

The thermal transmittance of the glazing,U_g is applicable to the central area of the glazing and does not include the effect of the spacer at edge of glazing. The thermal transmittance of the frame U_f, is applicable in the absence of glazing. The linear thermal transmittance Ψ, describes the additional heat flow caused by the interaction of the frame and the glass edge, including the effect of the spacer.

According to Standard (ISO 1077-1/E.1) for the single glazing, the linear thermal transmittance is neglected.

Due to Equation (10), the following elements are needed to be calculated in order to calculate Ψ_{w1}-Value as follows

$$\boldsymbol{\Psi_{w(1)}} = \boldsymbol{L_{\Psi}^{2D}}(\mathrm{w1}) - \boldsymbol{U_{f(w1)}} * \boldsymbol{b_{f(w1)}} - \boldsymbol{U_{g(w1)}} * \boldsymbol{b_{g(w1)}}$$

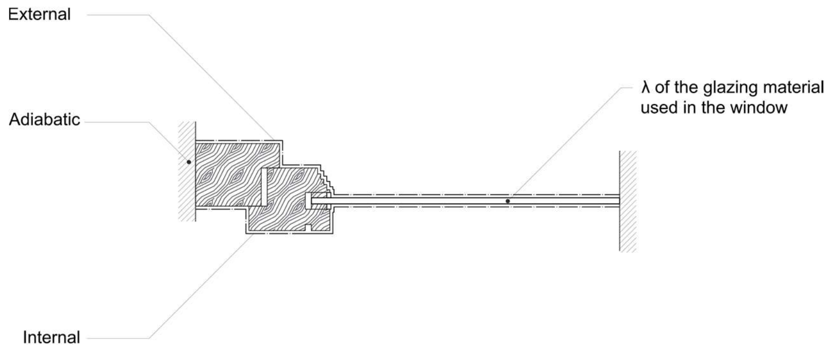


Figure 20. Section to calculate Ψ-value

Calculation of $L_{\Psi}^{2D}(w1)$ and $L_{\Psi}^{2D}(w2)$

L_{Ψ}^{2D} the thermal coupling coefficient obtained from a 2-D simulation as it is illustrated in Figure 21 by using the cropped section W1 when deriving $L_{\Psi}^{2D}(w1)$ and W2-section when deriving $L_{\Psi}^{2D}(w2)$

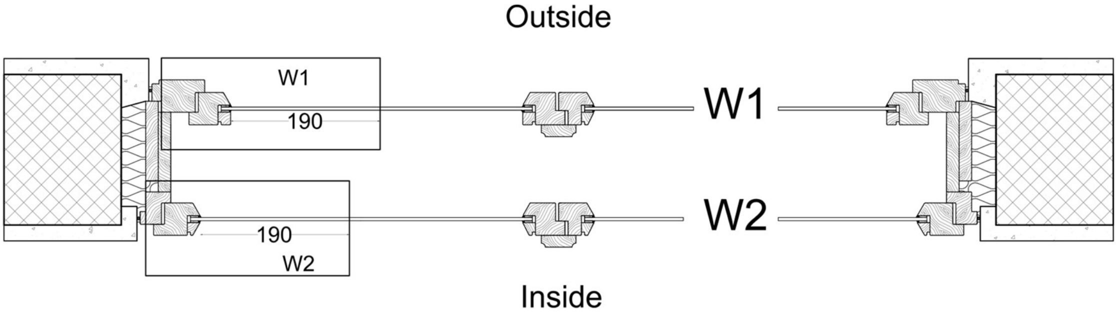


Figure 21. Window detail.1 Section to derive L^{2D} of W1 and W2

By simulating each external and internal window parts using AnTherm software, L_{Ψ}^{2D}(w1) and L_{Ψ}^{2D}(w2) are derived (considering R_{si} = 0.13, R_{se} = 0.04 and the length of the panel in simulation section 190 [mm]

L_{Ψ}^{2D}(w1) = 1.11 [w.m^{-1}.K^{-1}]

L_{Ψ}^{2D}(w2) = 1.08 [w.m^{-1}.K^{-1}]

Calculation of $U_{f\,(w1)}$ and $U_{f\,(w2)}$

The thermal transmittance of the frame U_f can be either derived from Standard (ISO 10077-1:20 /D.3) after calculating the thickness of the frame d_f The external And internal window frame thickness for both W1 and W2 respectively is illustrated in Figure 22

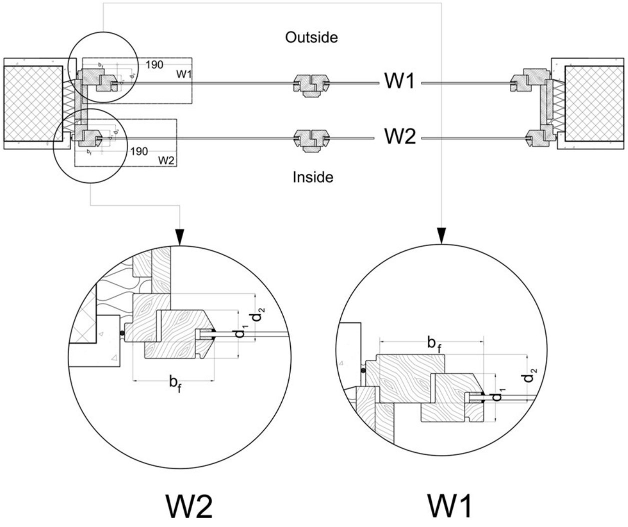


Figure 22. Frame details of external and internal window W1 and W2 respectively (ISO 10077-1:20 2012)

$$d_{f(w1)} = \frac{d_1 + d_2}{2} = \frac{0.041+0.041}{2} = 0.041\ [\mathrm{m}]$$

$$d_{f(w2)} = \frac{d_1 + d_2}{2} = \frac{0.041+0.041}{2} = 0.041\ [\mathrm{m}]$$

From the graph in Figure 23, the $\boldsymbol{U_f}$ for the window in case of the thermal conductivity of the wooden frame is 0.13 [W/m .K], would be 2.15 [W/m² .K]

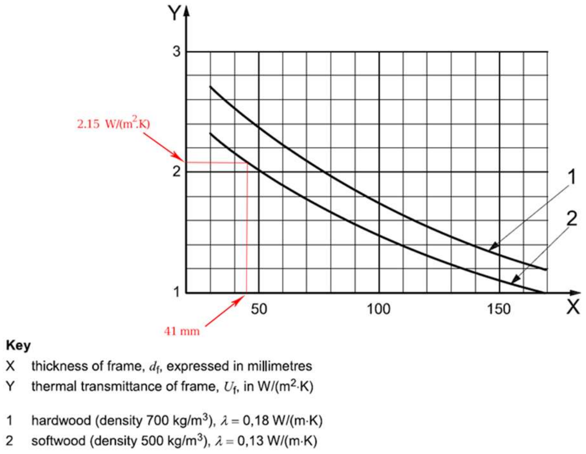


Figure 23. Thermal transmittance for wooden frames depending on the frame thickness (ISO 10077-1:20 2012)

After calculating $d_{f(w1)}$ and $d_{f(w2)}$, the thermal transmittance $\boldsymbol{U_f}$ for each Part of casement window can be derived from the graph in the Figure 23 as mentioned.

The thermal transmittance of frame section can be also calculated according to the equation (3) due to (ISO 10077-2 / C.1) and this was the method used in this thesis since it provides more accurate results.

For the calculation of L_f^{2d} the frame section should be as illustrated in Figure 24

$$\boldsymbol{U_f} = \frac{\boldsymbol{L_f^{2D} - U_p - b_p}}{\boldsymbol{b_f}}$$

where

$\boldsymbol{U_f}$ is thermal transmittance of the frame section, expressed in [W.m^{-2}.K^{-1}];

$\boldsymbol{L_f^{2D}}$ is the thermal coupling coefficient of the section when the glass panel is replaced by insulation panel with thermal conductivity $\boldsymbol{\lambda}$ = 0.035 [W.m^{-1}.K^{-1}] inserted into the frame with same glazing panel thickness;

$\boldsymbol{U_p}$ is the thermal transmittance of the central area of the panel, expressed in [W.m^{-2}.K^{-1}];

$\boldsymbol{b_p}$ is the visible width of the panel, expressed in [m];

$\boldsymbol{b_f}$ is the larger of the projected widths as seen from both sides. b_p is measured on the same side as b_f, expressed in [m];

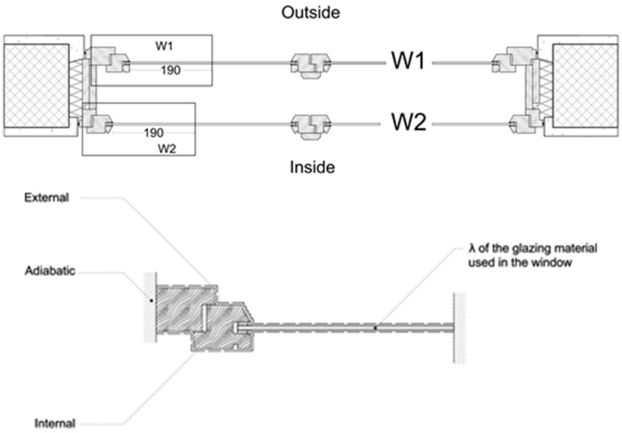


Figure 24. Schematic of profile external window section with insulation panel installed

Calculation of U_p

From the Equation (4)

$$\boldsymbol{U_p} = \frac{\boldsymbol{1}}{\boldsymbol{R_{si} + \frac{d_j}{\lambda_j} + R_{se}}}$$

$$\boldsymbol{U_{p\,(w1)}} = \frac{\boldsymbol{1}}{\boldsymbol{0.13 \quad d_{f(w1)}/\lambda + 0.04}} = \frac{\boldsymbol{1}}{\boldsymbol{0.13 + \frac{0.004}{0.035} + 0.04}} = 3.5175 \ [\text{W.m}^{-2}.\text{K}^{-1}]$$

$$\boldsymbol{U_{p\,(w2)}} = \frac{\boldsymbol{1}}{\boldsymbol{0.13 \quad d_{f(w1)}/\lambda + 0.04}} = \frac{\boldsymbol{1}}{\boldsymbol{0.13 + \frac{0.004}{0.035} + 0.04}} = 3.5175 \ [\text{W.m}^{-2}.\text{K}^{-1}]$$

Calculation of b_f projected width of framing profile:

As illustrated in Figure 22, projected width of framing profile for the external window part is

$\boldsymbol{b_{f(w1)}}$ = 0.088 [m]

Projected width of framing profile for the internal window part is

$\boldsymbol{b_{f(w2)}}$ = 0.067 [m]

Projected width of glazing b_g is:

According to standard (DIN EN ISO 10077-2:2010-06)

$\boldsymbol{b_{g(w1,w2)}}$ = 0.19 [m]

Air cavity:

According to the international standard (ISO 10077-2 / 6.3.1)
air cavities are considered unventilated if they care completely closed or connected either to the exterior or to the interior by a slit with a width not exceeding 2 [mm] and then they are treated as material boxes in the simulation with equivalent thermal conductivity λ_{eq}

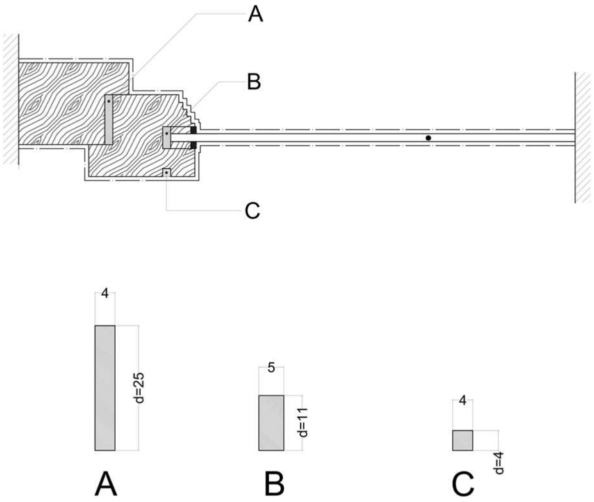


Figure 25. Air cavity in the frame section

Calculation of equivalent thermal conductivity:

It is calculated using the following equation

$$\boldsymbol{\lambda_{eq}} = \frac{d}{R_s}$$

$\boldsymbol{d}$ is the dimension of the cavity in the direction of heat flow Figure 25

$\boldsymbol{R_s}$ is the thermal resistance of the cavity

Calculation of Heat transfer coefficient of the glazing $\boldsymbol{U_g}$:

The U_g value of external and internal part of casement window are

Calculated using Equation (4) as follows

$$\boldsymbol{U = \frac{1}{R_{si}+R_T+R_{se}}}$$

Where:

For $U_{g(w1)}$: R_{si} = 0.13, R_{se} = 0.04, and R_T= $\frac{d}{\lambda}$ = 0.004 / 1 = 0.004 [m^2.K.W^{-1}]

For $U_{g(w2)}$: R_{si} = 0.13, R_{se} = 0.04, and R_T= $\frac{d}{\lambda}$ = 0.004 / 1 = 0.004 [m^2.K.W^{-1}]

$$U_{g(w1)} = \frac{1}{R_{si}+R_T+R_{se}} = \frac{1}{0.13+\ .004+0.04} = 5.74 \quad [\text{W.m}^{-2}.\text{K}^{-1}]$$

$$U_{g(w2)} = \frac{1}{R_{si}+R_T+R_{se}} = \frac{1}{0.13+0.004+0.04} = 5.74 \quad [\text{W.m}^{-2}.\text{K}^{-1}]$$

Calculation of glazing and framing area for each W1 and W2:

As illustrated in Figure 26 glazing area $\sum A_g$ for W1 is:

$\sum \boldsymbol{A_{g(w1)}}$ = (0.616)*2 = 1.232 [m^2]

As illustrated in Figure 26 glazing area $\sum A_g$ for W2 is:

$\sum \boldsymbol{A_{g(w2)}}$ = (0.671)*2 = 1.342 [m^2]

As illustrated in Figure 26 framing area $\sum A_f$ for W1 is:

$\sum \boldsymbol{A_{f(w1)}}$ = (1.5*1.2) – 1.232 = 0.568 [m^2]

As illustrated in Figure 26 framing area $\sum A_f$ for W2 is:

$\sum \boldsymbol{A_{f(w2)}}$ = (1.5*1.23) – 1.342 = 0.503 [m^2]

Calculation of the length of glazing –frame edge $\boldsymbol{l_g}$:

As illustrated in Figure 26 $\boldsymbol{l_{g(w1)}}$ for W1 is:

$l_{g(\boldsymbol{w1})}$ = [(0.455 + 1.341)*2] *2= 7.184 [m]

As illustrated in Figure 26 $\boldsymbol{l_{g(w2)}}$ for W2 is:

$l_{g(\boldsymbol{w2})}$ = [(0.494+ 1.341)*2]*2 = 7.34 [m]

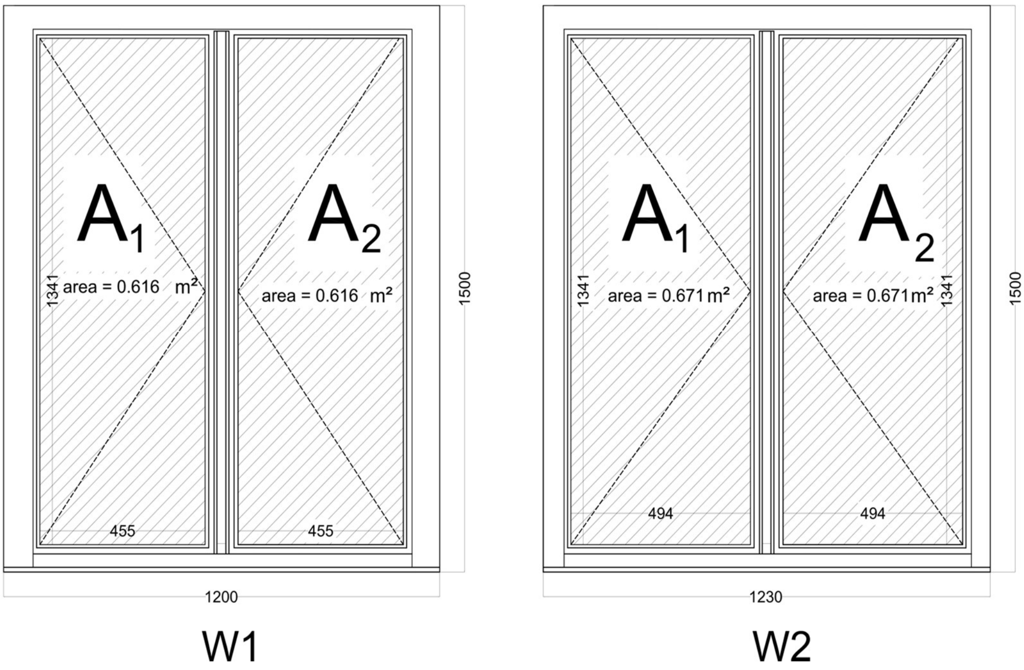


Figure 26. External and internal window view

Calculation of thermal transmittance of the external and internal window $\boldsymbol{U_{w1}}$ and $\boldsymbol{U_{w2}}$:

Thermal transmittance of external and internal window part $\boldsymbol{U_{w(1,2)}}$ is calculated

According to Equation 9 as follow;

$$\boldsymbol{U_{\mathrm{w}(1)}} = \frac{\sum \boldsymbol{A_{g(w1)}}\ \boldsymbol{U_{g(w1)}} + \sum \boldsymbol{A_{f(w1)}} * \boldsymbol{U_{f(w1)}} + \sum \boldsymbol{l_{g(w1)}} * \boldsymbol{\Psi_{g(w1)}}}{\sum \boldsymbol{A_{g(w1)}} + \sum \boldsymbol{A_{f(w1)}}}$$

$$U_{\mathrm{w}(1)} = \frac{1.232*5.74+0.568*2.3+7.184*0}{1.232+0568} = 4.66 \quad [\mathrm{W.m^{-2}.K^{-1}}]$$

$$U_{\mathrm{w}(2)} = \frac{1.342*5.74+0.503*2.3+7.34*0}{1.342+0.503} = 4.80 \quad [\mathrm{W.m^{-2}.K^{-1}}]$$

Calculation of thermal transmittance of the casement window $\boldsymbol{U_{\mathrm{w}}}$:

$$\boldsymbol{U_{\mathrm{w}}} = \frac{\mathbf{1}}{\mathbf{1}/\boldsymbol{U_{w1}} - \boldsymbol{R_{si}} + \boldsymbol{R_s} - \boldsymbol{R_{se}} + \mathbf{1}/\boldsymbol{U_{w2}}}$$

$$\boldsymbol{U_{\mathrm{w}}} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{4.66}} - \mathbf{0.13} + \mathbf{0.1636} - \mathbf{0.04} + \frac{\mathbf{1}}{\mathbf{4.80}}}$$

$$\boldsymbol{U_{\mathrm{w}}} = 2.40 \qquad [\mathrm{W.m^{-2}.K^{-1}}]$$

This is the total thermal transmittance of the casement window that was selected as a representative of the historical windows used in Austria before the year 1955 as in the original case before applying vacuum glazing on external or internal window shells. And the same method of the calculations is applied when calculating thermal transmittance and an interstitial air temperature of the window in all other scenarios.

Evaluation of five different scenarios of window detail 1:

Scenario 1:

This scenario represents the window in its original case as existed with its original materials. This case helps to compare its results with other different scenarios when vacuum glazing is applied in order to investigate the improvements that occur due to applying vacuum glazing. Both interior and exterior traditional wooden frames with 4 [mm] single glass layer and thermal conductivity of the materials as existed original case.

As it is illustrated in the Table 5. The total thermal transmittance of the window is relatively big which causes heat losses through window and the temperature of the interstitial air layer is 5.3 [^{0}C] which leads to risk of mold growth and condensation in the interstitial air layer

Additionally, the internal surface temperatures are too low as it reaches in minimum point 12.7 [^{0}C] which means a big heat loss in the room and further thermal retrofit effort is required.

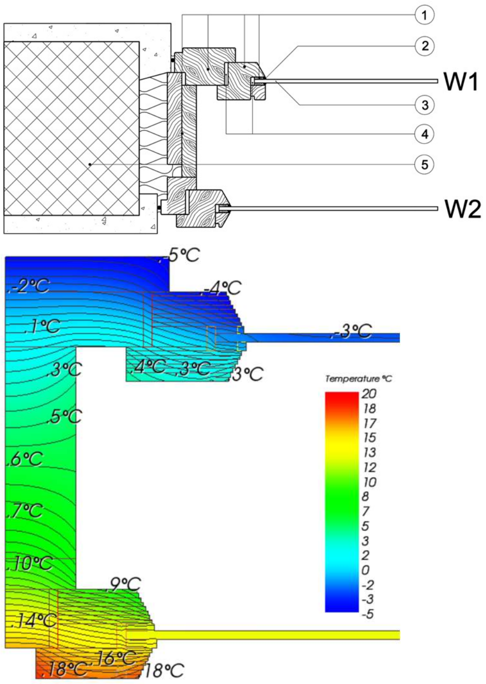


Figure 27. Temperature profile of Detail 1, Scenario 1

Table 5. Simulation and calculation results of Detail 1, Scenario 1

$U_{g(ext)}$ = 5.74	[W.m^{-2}.K^{-1}]
$U_{g(int)}$ = 5.74	[W.m^{-2}.K^{-1}]
$U_{f(ext)}$ = 2.32	[W.m^{-2}.K^{-1}]
$U_{f(int)}$ = 2.5	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(ext)}$ = 1.11	[W.m^{-1} .K^{-1}]
$L^{2D}_{\Psi\,(int)}$ = 1.08	[W.m^{-1} .K^{-1}]
$\Psi_{(ext)}$ = -0.18	[W.m^{-1} .K^{-1}]
$\Psi_{(int)}$ = -0.15	[W.m^{-1} .K^{-1}]
U_{w1} = 4.66	[W.m^{-2}.K^{-1}]
U_{w2} = 4.80	[W.m^{-2}.K^{-1}]
U_{window} = **2.40**	[W.m^{-2}.K^{-1}]

Scenario 2:

In this scenario, a traditional exterior wooden frame with vacuum glazing is installed in the external wing with rebate frame depth just as in the original case while the internal window wing remains as in its original case. The goal of this scenario is to investigate the difference in total window thermal transmittance, interstitial air temperature and the risk of condensation in internal and interstitial air layer to compare it to both scenario 1 and scenario 3 when the vacuum glazing installed in the internal window. As it is illustrated in the Table 6. The total thermal transmittance of the window is considerably reduced comparing to the scenario 1 in original window case and the temperature of the interstitial air layer is 12.84 [^{o}C] which leads to the risk of mold growth and condensation in the interstitial air layer whereas no risk of condensation or mold growth in the internal space. The internal surface temperatures are acceptable on the internal surfaces. With minimum surface temperature 16.47 [^{o}C]. Further improvements can help to increase the internal space temperature.

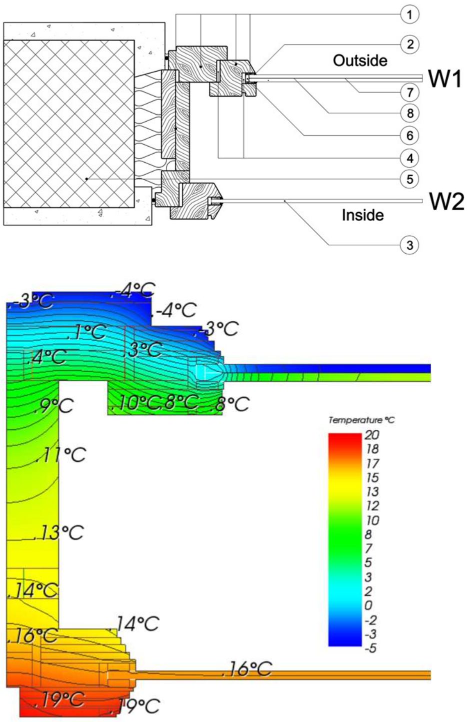


Figure 28. Temperature profile of Detail 1, Scenario 2

Table 6. Simulation and calculation results of Detail 1, Scenario 2

$U_{g(ext)}$ = 0.58	[W.m^{-2}.K^{-1}]
$U_{g(int)}$ = 5.74	[W.m^{-2}.K^{-1}]
$U_{f(ext)}$ =2.30	[W.m^{-2}.K^{-1}]
$U_{f(int)}$ = 2.50	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(ext)}$ =0.42	[W.m^{-1} .K^{-1}]
$L^{2D}_{\Psi\,(int)}$ = 1.08	[W.m^{-1} .K^{-1}]
$\Psi_{(ext)}$ = 0.10	[W.m^{-1} .K^{-1}]
$\Psi_{(int)}$ = -0.17	[W.m^{-1} .K^{-1}]
U_{w1} =1.55	[W.m^{-2}.K^{-1}]
U_{w2} =4.80	[W.m^{-2}.K^{-1}]
U_{window} =**1.18**	[W.m^{-2}.K^{-1}]

Scenario 3:

In this scenario, vacuum glazing is installed in the internal window wing with frame rebate depth just as in the original case while the external window wing remains as in its original case. As it is illustrated in the Table 7. The total thermal transmittance of the window is considerably reduced comparing to original window case in scenario 1 and nearly the same as in scenario 2. The temperature of the interstitial air layer is -0.35 [^oC] which leads to the risk of mold growth and condensation in both interstitial air layer and the internal space. The surface temperatures are relatively low comparing the scenario 1 and 2. The minimum surface temperature is 10.59 [^oC]. Further improvements could help to increase the internal space temperature and avoid the risk or condensation in internal and interstitial space.

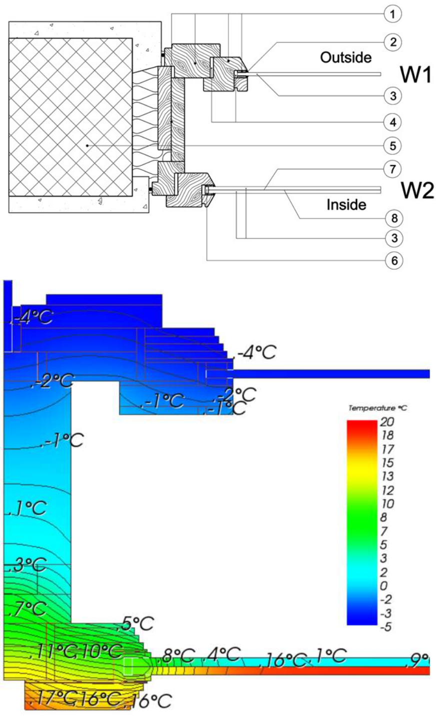


Figure 29. Temperature profile of Detail 1, Scenario 3

Table 7. Simulation and calculation results of Detail 1, Scenario 3

$\boldsymbol{U}_{g(ext)}$ =5.74	[W.m^{-2}.K^{-1}]
$\boldsymbol{U}_{g(int)}$ =0.58	[W.m^{-2}.K^{-1}]
$\boldsymbol{U}_{f(ext)}$ =2.32	[W.m^{-2}.K^{-1}]
$\boldsymbol{U}_{f(int)}$ =2.37	[W.m^{-2}.K^{-1}]
$\boldsymbol{L}^{2D}_{\Psi\,(ext)}$ =1.11	[W.m^{-1}.K^{-1}]
$\boldsymbol{L}^{2D}_{\Psi\,(int)}$ =0.40	[W.m^{-1}.K^{-1}]
$\boldsymbol{\Psi}_{(ext)}$ =-0.18	[W.m^{-1}.K^{-1}]
$\boldsymbol{\Psi}_{(int)}$ =0.13	[W.m^{-1}.K^{-1}]
$\boldsymbol{U}_{w1}$ =4.66	[W.m^{-2}.K^{-1}]
$\boldsymbol{U}_{w2}$ =1.59	[W.m^{-2}.K^{-1}]
$\boldsymbol{U}_{window}$ =**1.19**	[W.m^{-2}.K^{-1}]

Scenario 4:

In this scenario, an improvement on the external window frame is carried out by increasing the glass rebate depth of 13 [mm] more than in original case and in scenario 2 with vacuum glazing installed in the external wing, while the internal window wing remains as in its original case. The goal of this scenario is to reduce the total thermal transmittance via reducing the thermal bridge effect in the glazing-frame junction and consequently increasing the internal surface temperature. As it is illustrated in the Table 8. The total thermal transmittance of the window is relatively reduced comparing to the scenario 2 and 3. The temperature of the interstitial air layer is 13.61 [^{0}C] with no risk of condensation or mold growth in the internal space. The surface temperatures are acceptable on the internal surfaces. With minimum internal surface temperature 16.85 [^{0}C]. Further improvements could be carried out to increase the internal space temperature and total window thermal transmittance.

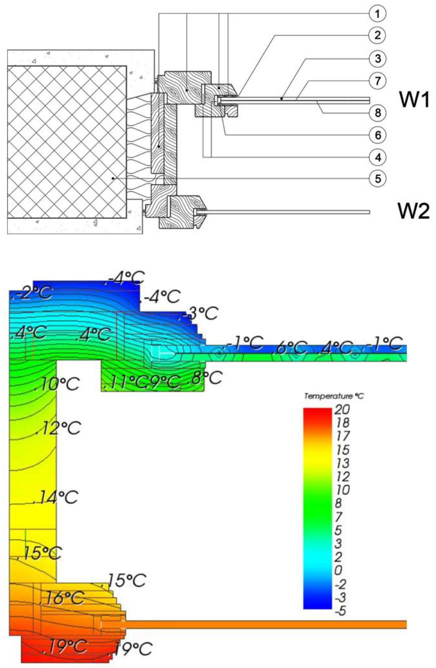


Figure 30. Temperature profile of Detail 1, Scenario 4

Table 8. Simulation and calculation results of Detail 1, Scenario 4

$U_{g(ext)}$ =0.58	[W.m^{-2}.K^{-1}]
$U_{g(int)}$ =5.74	[W.m^{-2}.K^{-1}]
$U_{f(ext)}$ =2.18	[W.m^{-2}.K^{-1}]
$U_{f(int)}$ =2.50	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(ext)}$ =0.35	[W.m^{-1} .K^{-1}]
$L^{2D}_{\Psi\,(int)}$ =1.08	[W.m^{-1} .K^{-1}]
$\Psi_{(ext)}$ =0.052	[W.m^{-1} .K^{-1}]
$\Psi_{(int)}$ =-0.17	[W.m^{-1} .K^{-1}]
U_{w1} =1.29	[W.m^{-2}.K^{-1}]
U_{w2} =4.80	[W.m^{-2}.K^{-1}]
U_{window} =**1.029**	[W.m^{-2}.K^{-1}]

Scenario 5:

In this scenario, Additional improvement on the external window frame is carried out by keeping the glass rebate depth increased with 13 [mm] more than in original case and scenario 2 with vacuum glazing installed in the external wing as well as adding 5 [mm] compact foam layer around the frame-glazing junction as it is illustrated in Figure 38, while the internal window wing remains as in its original case. The goal of this scenario is to reduce the total thermal transmittance via reducing the thermal bridge effect on the glazing-frame junction and as a result increasing the internal space temperature. As it is illustrated in the Table 9. The total thermal transmittance of the window is relatively reduced comparing to the scenario 4 and the temperature of the interstitial air layer is 13.82 [^{0}C] with no risk of condensation or mold growth in the internal space. The internal surface temperatures is acceptable in the internal surfaces. With minimum surface temperature 16.96 [^{0}C].

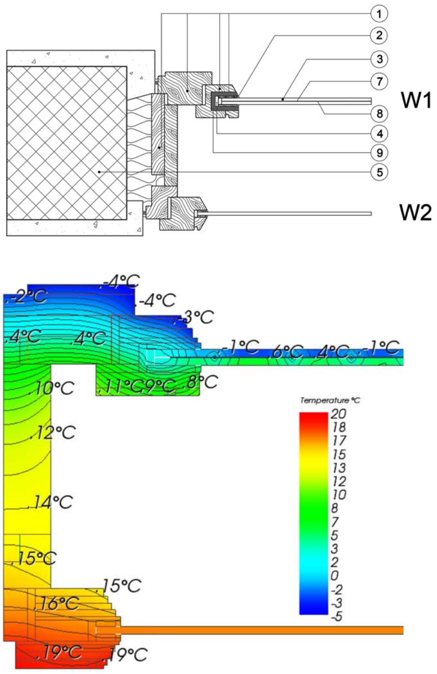


Figure 31. Temperature profile of Detail 1, Scenario 5

Table 9. Simulation and calculation results of Detail 1, Scenario 5

$U_{g(ext)}$ = 0.58	[W.m^{-2}.K^{-1}]
$U_{g(int)}$ = 5.74	[W.m^{-2}.K^{-1}]
$U_{f(ext)}$ = 1.99	[W.m^{-2}.K^{-1}]
$U_{f(int)}$ = 2.50	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(ext)}$ = 0.32	[W.m^{-1} .K^{-1}]
$L^{2D}_{\Psi\,(int)}$ = 1.08	[W.m^{-1} .K^{-1}]
$\Psi_{(ext)}$ = 0.038	[W.m^{-1} .K^{-1}]
$\Psi_{(int)}$ = -0.17	[W.m^{-1} .K^{-1}]
U_{w1} = 4.80	[W.m^{-2}.K^{-1}]
U_{w2} = 1.18	[W.m^{-2}.K^{-1}]
U_{window} = **0.95**	[W.m^{-2}.K^{-1}]

Total thermal transmittance reduction and surface temperatures

In order to illustrate the improvements that occurred on the selected window detail when applying vacuum glazing in external or internal window part, the reduction percentage of total window thermal transmittance is calculated in Table 10. There is a considerable improvement in the window thermal performance when using vacuum glazing in the external window wing with additional compact foam layer around the frame-glazing junction.

Table 10. Total thermal transmittance reduction in different five scenarios

	Original	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
U_{window} [W.m^{-2}.K^{-1}]	2.40	1.18	1.19	1.029	0.95
U_{window} Reduktion [%]	-	50%	50%	57%	60%

The minimum and maximum surface temperatures in the internal, interstitial and external space are illustrated in Table 11 and it shows that using vacuum glazing in internal window wings causes mold growth and risk of condensation in both interstitial and internal spaces whereas no risk of condensation in internal space when vacuum glazing is applied to the external window part in the scenarios 2, 4 and 5.

Table 11. Min-Max surface temperatures and f_{Rsi} values in different five scenarios

		Buffer-Temp [^{o}C]	**Min-temp [^{o}C]**	**Max-temp [^{o}C]**	**f_{Rsi} [-]**	**Condense.RH [%]**
Scenario 1	Buffer Space	5,34	-2,39	12,69	0,25	56,08
	Internal Space	20	12,78	18,53	0,71	63,14
Scenario 2	Buffer Space	12,84	2	16,41	0,39	47,59
	Internal Space	20	16,47	16,41	0,86	80,15
Scenario 3	Buffer Space	-0,35	-3,82	9	0,25	74,77
	Internal Space	20	10,59	18,05	0,62	54,63
Scenario 4	Buffer Space	13,61	7,44	16,79	0,67	66,25
	Internal Space	20	16,85	19,38	0,87	82,1
Scenario 5	Buffer Space	13,82	7,7	16,9	0,68	66,54
	Internal Space	20	16,96	19,4	0,88	82,64

Table 12. Materials and its thermal conductivity and μ-Value of Window detail 1

Material	**Thermal conductivity λ [W.m^{-1}.K^{-1}]**	**μ - Value [-]**
Wooden frame	0.14	100
Window putty	0.50	10000
Glass	1.0	999999
Air	0.05	1.0
Mineral insulation	0.045	2000
Secondary seal	1.0	999999
Vacuum	0.0001	999999
Stainless steel pillar	14.0	999999
Compacfoam	0.04	999999

3.2 Window study case detail.2

Calculation of the buffer space temperature:

Using the Equation 4 and considering Θ_i and Θ_e as in boundary condition in Table 1
Θ_i = 20 [C°] = 273 + 20 = 293 [K]
Θ_e = -5 [C°] = 273 - 5 = 268 [K]

$L^{2D(1)}$ And $L^{2D(2)}$ are obtained from the simulated detail in Figure 32
$L^{2D(1)}$ = 1.99 [W.m^{-1}.K^{-1}]

$L^{2D(2)}$ = 3.02 [W.m^{-1}.K^{-1}]

Note: $L_{2D(1)}$ and $L_{2D(2)}$ calculated by AnTherm considering Rsi = 0.13, Rs of buffer space is 0.13 and Rse = 0.04 [m^2.K.W^{-1}]

$$\boldsymbol{L_{2D(1)} * (\Theta_i - \Theta_b) = L_{2D(2)} * (\Theta_b - \Theta_e)}$$

3.47* (293 - Θ_b)= 4.95* (Θ_b – 268)
Θ_b = 277.93 [K]
Θ_b = 4.93 [C°]

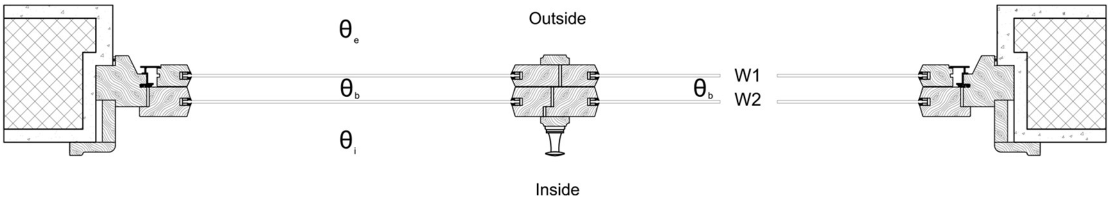


Figure 32. Composite window detail for obtaining buffer space temperature from AnTherm simulation

Calculation of linear thermal transmittance Ψ_w-Value of the external part of casement window:

According to Equation (10), the following elements are needed to be calculated in order to calculate Ψ_{w1}-Value

$$\boldsymbol{\Psi_w = L_{\Psi}^{2D} - U_f * b_f - U_g * b_g}$$

Calculating L_{Ψ}^{2D}

L_{Ψ}^{2D} The thermal coupling coefficient is obtained from a 2-D simulation as illustrated in Figure 33 by using the cropped section W when deriving L_{Ψ}^{2D}

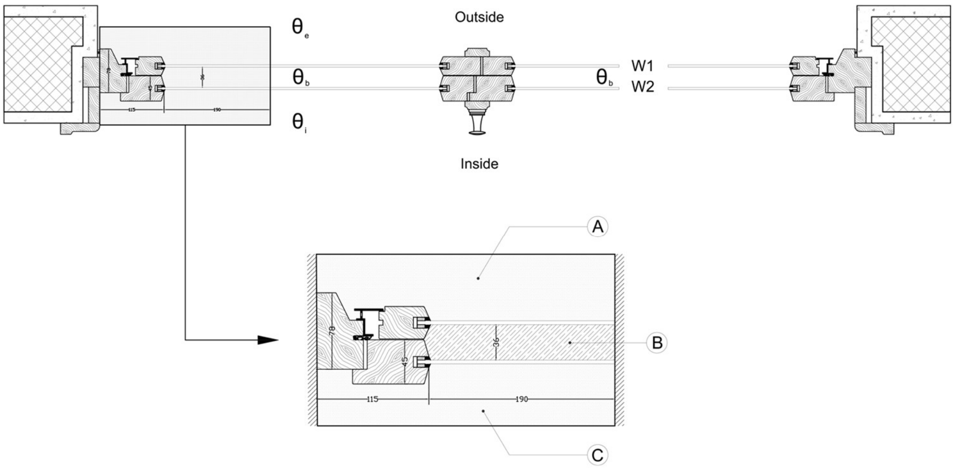


Figure 33. Composite window detail to derive L_{Ψ}^{2D} value

By simulating the section as shown in Figure 33 using AnTherm software, L_{Ψ}^{2D} is derived (considering surface resistance of internal area “C” of R_{si} = 0.13, and Surface resistance of external area “A” of R_{se} = 0.04 whereas the Buffer space considered as material box with equivalent conductivity calculated as follows:

$$\boldsymbol{\lambda_{eq}} = \frac{\boldsymbol{d}}{\boldsymbol{R_s}}$$

Where:

$\boldsymbol{d}$	is air space thickness in [m];
$\boldsymbol{R_s}$	is the thermal resistance of air space between two window wings in [m².K⁻¹.W⁻¹];

R_s is considered 0.17 [m^2.K/W] according to (ISO 10077-1/table C.1)

In original:

d = 0.036 [m]

$\boldsymbol{R_s}$ = 0.17 [m^2.K.W^{-1}]

$\boldsymbol{\lambda_{eq}} = \frac{0.036}{0.17} = 0.211$ [W.m^{-1}.K^{-1}]

Calculating $\boldsymbol{U_f}$

The frame thermal transmittance can be calculated according to (ISO 10077-2:2012 /E) from the equation (3) as follows:

$$\boldsymbol{U_f} = \frac{\boldsymbol{L_f^{2d} - U_p - b_p}}{\boldsymbol{b_f}}$$

$\boldsymbol{L_f^{2d}}$ is the thermal coupling coefficient of the section when the glass panel is replaced by insulation panel with thermal conductivity $\boldsymbol{\lambda}$ = 0.035 [W.m^{-1}.K^{-1}] inserted into the frame with same glazing panel thickness $\boldsymbol{d_j}$ as illustrated in Figure 34

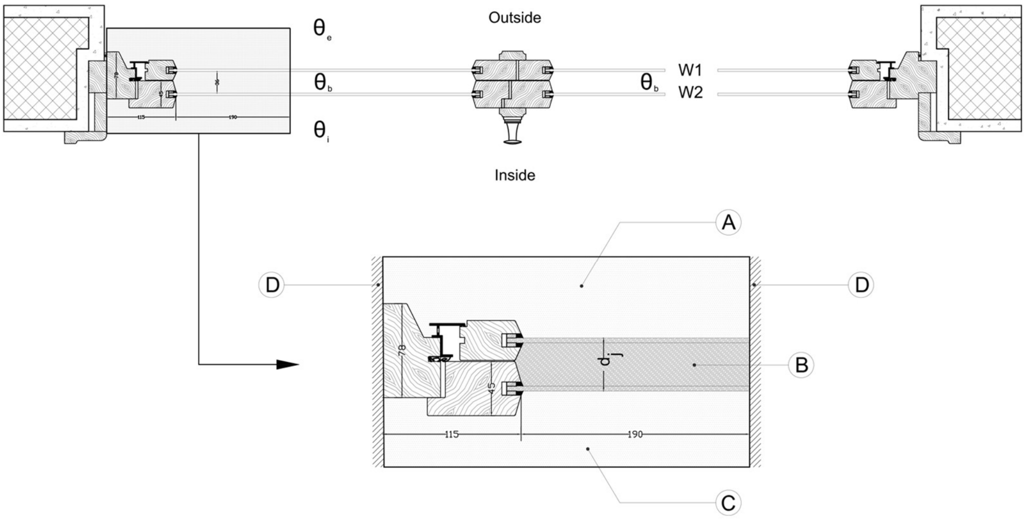


Figure 34. Frame Section to derive L_f^{2D}

And the length of the panel in simulation section $\boldsymbol{b_g}$=190 [mm]

L_Ψ^{2D} = 0.33 [W.m^{-1}.K^{-1}]

$\boldsymbol{U_f} = \frac{\mathbf{0.33 - 0.7 - 0.19}}{\mathbf{0.115}} = 1.74$ [W.m^{-2}.K^{-1}]

Projected width of framing profile b_f :

As illustrated in Figure 34

Projected width of framing profile for the external window part is

$b_{f(w1)}$ = 0.115 [m]

Projected width of glazing b_g is:

According to standard (DIN EN ISO 10077-2:2010-06)

$\boldsymbol{b_{g(w1,w2)}}$ = 0.19 [m]

Calculation of U_g Heat transfer coefficient of the glazing:

The $\boldsymbol{U_g}$ value of external and internal part of casement window is

Calculated using following Equation

$$\boldsymbol{U_g = \frac{1}{\frac{1}{U_{g1}} - R_{si} + R_s - R_{se} + 1/U_{g2}}} \tag{12}$$

Where

For $\boldsymbol{U_{g1}}$: $\boldsymbol{R_{si}}$ = 0.13, $\boldsymbol{R_{se}}$ = 0.04, and $\boldsymbol{R_T} = \frac{d}{\lambda}$ = 0.004 / 1 = 0.004 [m².K.W⁻¹]

For $\boldsymbol{U_{g2}}$: $\boldsymbol{R_{si}}$ = 0.13, $\boldsymbol{R_{se}}$ = 0.13, and $\boldsymbol{R_T} = \frac{d}{\lambda}$ = 0.004 / 1 = 0.004 [m².K.W⁻¹]

$$\boldsymbol{U_{g1}} = \frac{\boldsymbol{1}}{\boldsymbol{R_{si}+R_T+R_{se}}} = \frac{1}{0.13+0.004+0.04} = 5.74 \quad [\mathrm{W.m^{-2}.K^{-1}}]$$

$$\boldsymbol{U_{g2}} = \frac{\boldsymbol{1}}{\boldsymbol{R_{si}+R_T+R_{se}}} = \frac{1}{0.13+0.004+0.04} = 5.74 \quad [\mathrm{W.m^{-2}.K^{-1}}]$$

$$\boldsymbol{U_g} = \frac{\boldsymbol{1}}{\boldsymbol{\frac{1}{5.74} - 0.13 + 0.17 - 0.04 + \frac{1}{5.74}}} = 2.87 \quad [\mathrm{W.m^{-2}.K^{-1}}]$$

After calculating all required elements for Ψ_w:

$\boldsymbol{\Psi_w}$ = 0.51 – 1.74 * 0.115-2.87 * 0.19 = -0.23 [W.m⁻¹.K⁻¹]

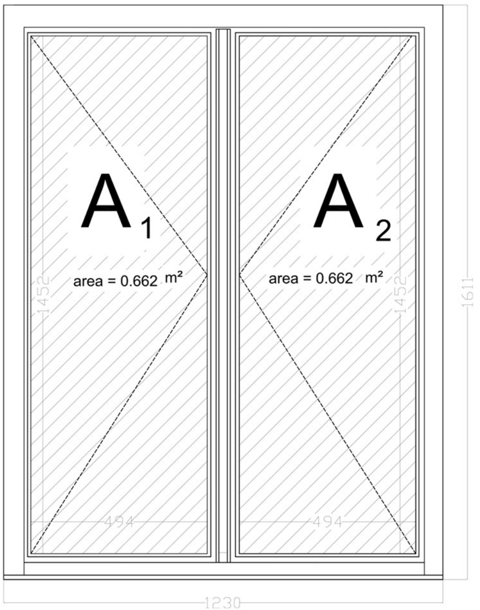


Figure 35. External and Internal Window Facade

Calculation of glazing and framing area of the window W:

As illustrated in Figure 35 glazing area $\sum A_g$ for W is:

$\sum \boldsymbol{A}_{\boldsymbol{g(w)}}$ = $\boldsymbol{A_1}$ + $\boldsymbol{A_2}$= (0.662)*2 = 1.324 [m²]

As illustrated in Figure 35 framing area $\sum A_f$ for W is:

$\sum \boldsymbol{A}_{\boldsymbol{f(w2)}}$ = (2.27) – 1.324 = 0.946 [m²]

Calculation of the length of glazing –frame edge $\boldsymbol{l_g}$:

As illustrated in Figure 35 $\boldsymbol{l_g}$ is:

$l_{g(\boldsymbol{w})}$ = [(0,949 + 1.341)*2]*2 = 7.34 [m]

Calculation of thermal transmittance of the window $\boldsymbol{U_w}$:

Thermal transmittance of the composite window is calculated

According to (ISO 10077-1) from Equation 7 as follow;

$$\boldsymbol{U}_{\mathbf{w}} = \frac{\sum \boldsymbol{A_g}\, \boldsymbol{U_g} + \sum \boldsymbol{A_f} * \boldsymbol{U_f} + \sum \boldsymbol{l_g} * \boldsymbol{\Psi_g}}{\sum \boldsymbol{A_g} + \sum \boldsymbol{A_f}}$$

$$\boldsymbol{U}_{\mathbf{w}} = \frac{\mathbf{1.324*2.87+0.946*1.74+7.34*0}}{\mathbf{1.324+0.946}} = 2.40 \qquad [\mathrm{W.m^{-2}.K^{-1}}]$$

Evaluation of five different scenarios of window detail 2:

Scenario 1:

This scenario represents the window as it exists in the historical buildings with its original materials. Both interior and exterior traditional wooden frames with 4 [mm] single glass layer and thermal conductivity of the materials as in its original case.

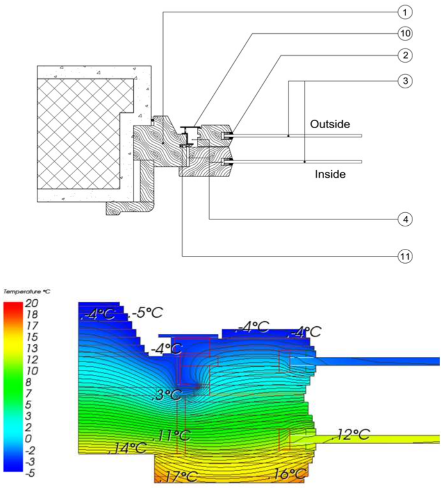


Figure 36. Temperature profile of Detail 2, Scenario 1

Table 13. Simulation and calculation results of Detail 2, Scenario 1

U_g = 2.87	[W.m^{-2}.K^{-1}]
$U_{f(w)}$ = 1.74	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(w)}$ = 0.51	[W.m^{-1}.K^{-1}]
$\Psi_{(w)}$ = -0.23	[W.m^{-1}.K^{-1}]
U_{window}= **2.40**	[W.m^{-2}.K^{-1}]

Scenario 2:

In this scenario, a vacuum glazing was installed in the external window pane whereas the internal window pane remains as in the existed case.

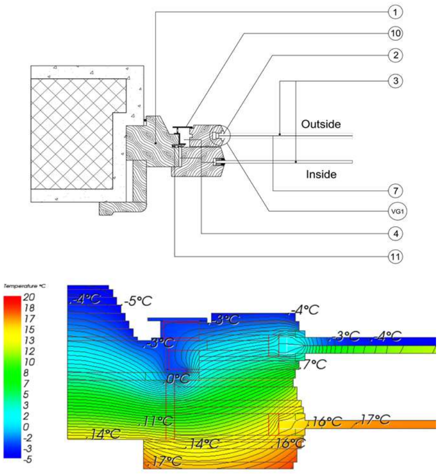


Figure 37. Temperature profile of Detail 2, Scenario 2

Table 14. Simulation and calculation results of Detail 2, Scenario 2

U_g = 0.52	[W.m^{-2}.K^{-1}]
$U_{f(w)}$ = 1.77	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(w)}$ = 0.39	[W.m^{-1}.K^{-1}]
$\Psi_{(w)}$ = 0.09	[W.m^{-1}.K^{-1}]
U_{window} = **1.34**	[W.m^{-2}.K^{-1}]

Scenario 3:

In this scenario, a single glass layer is installed in the external window pane as original case and vacuum glazing is installed in the interior window pane with total glazing thickness of 8.015 [mm].

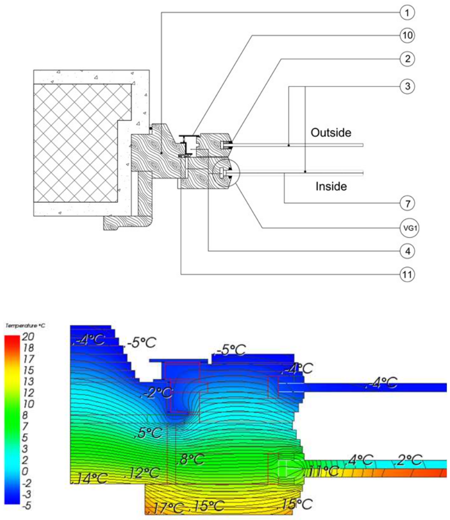


Figure 38. Temperature profile of Detail 2, Scenario 3

Table 15. Simulation and calculation results of Detail 2, Scenario 3

U_g = 0.52	[W.m^{-2}.K^{-1}]
$U_{f(w)}$ = 1.75	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(w)}$ = 0.38	[W.m^{-1}.K^{-1}]
$\Psi_{(w)}$ = 0.09	[W.m^{-1}.K^{-1}]
U_{window} = **1.30**	[W.m^{-2}.K^{-1}]

Scenario 4:

In this scenario, a single glass layer is installed in the internal window part as original case and Vacuum glazing is installed in the exterior window pane with total glazing thickness of 8.015 [mm] with additional rebate depth of 15 [mm].

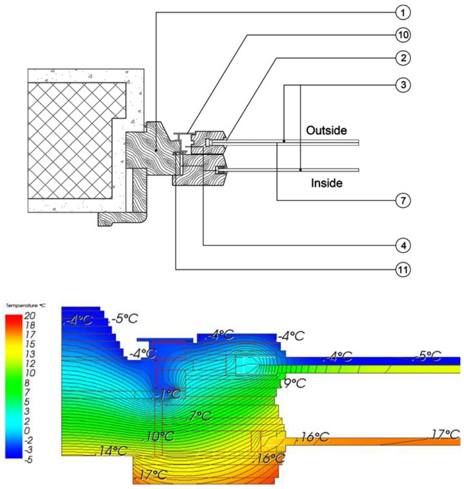


Figure 39. Temperature profile of Detail 2, Scenario 4

Table 16. Simulation and calculation results of Detail 2, Scenario 4

U_g = 0.52	[W.m^{-2}.K^{-1}]
$U_{f(w)}$ = 1.74	[W.m^{-2}.K^{-1}]
$L^{2D}_{\Psi\,(w)}$ = 0.36	[W.m^{-1}.K^{-1}]
$\Psi_{(w)}$ = 0.06	[W.m^{-1}.K^{-1}]
U_{window} = **1.24**	[W.m^{-2}.K^{-1}]

Scenario 5:

In this scenario, a vacuum glazing was installed in the external window layer with increasing rebate depth with 15[mm] and a layer of 5 [mm] Combacfoam was installed around the glass-frame junction as it is shown in Figure 40, whereas the internal window layer remains as in the existed case.

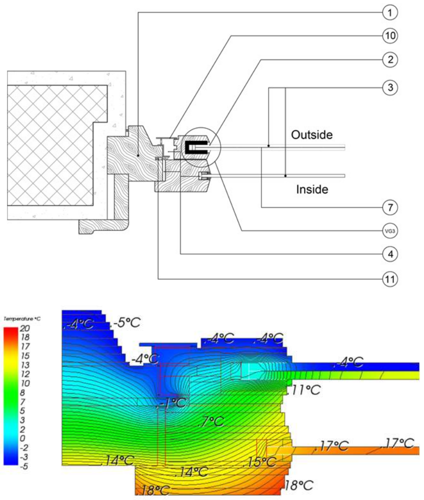


Figure 40. Temperature profile of Detail 2, Scenario 5

Table 17. Simulation and calculation results of Detail 2, Scenario 5

$\boldsymbol{U_g}$	= 0.52	[W.m^{-2}.K^{-1}]
$\boldsymbol{U_{f(w)}}$	= 1.70	[W.m^{-2}.K^{-1}]
$\boldsymbol{L^{2D}_{\Psi\,(w)}}$	= 0.35	[W.m^{-1}.K^{-1}]
$\boldsymbol{\Psi_{(w)}}$	= 0.05	[W.m^{-1}.K^{-1}]
$\boldsymbol{U_{window}}$	= **1.20**	[W.m^{-2}.K^{-1}]

Table 18. Material properties of the detail 2

Material Name	**Thermal conductivity λ** [w.m^{-1}.K^{-1}]	**μ - Value** [-]
1. Wooden frame	0.14	100
2. Window putty	0.50	10000
3. Glass	1.0	999999
4. Air	0.05	1.0
5. Mineral insulation	0.045	2000
6. Secondary seal	1.0	999999
7. Vacuum	0.0001	999999
8. Stainless steel pillar	14	999999
9. Compacfoam	0.04	999999
10. Aluminium	200	100000
11. Silicon rubber	0.3	10

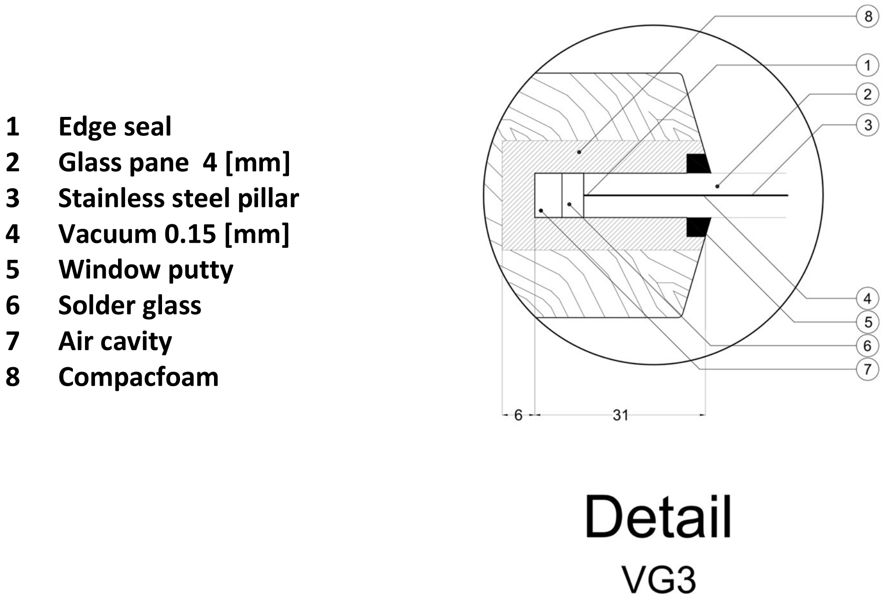


Figure 41. Detail of glazing-frame junction Scenario 5

Total thermal transmittance reduction and surface temperatures of detail 2

In order to illustrate the improvement that occurred on the selected window detail 2 when applying vacuum glazing as it was presented in five different scenarios, the reduction percentage of total window thermal transmittance is calculated as in Table 19. There is a considerable improvement in the window thermal performance when using vacuum glazing in the external window pane with additional compact foam layer around the frame-glazing junction.

Table 19. Total thermal transmittance reduction in different five scenarios

	Original	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
$\boldsymbol{U_{window}}$ [W.m^{-2}.K^{-1}]	2.40	1.34	1.30	1.24	1.20
$\boldsymbol{U_{window}}$ reduction [%]	-	44%	46%	48%	50%

The minimum and maximum surface temperatures in the internal, interstitial and external space of window detail 2 are presented in Table 20 and using vacuum glazing in internal window pane in scenario 2 causes mold growth and risk of condensation in internal and interstitial spaces whereas no risk of condensation in internal space when vacuum glazing applied in the external window pane in all scenarios 2, 4 and 5.

Table 20. Min-Max surface temperatures and f_{Rsi} values in different five scenarios

		Buffer_Temp [ºC]	**Min-temp [ºC]**	**Max-temp [ºC]**	f_{Rsi}	**Condens.RH [%]**
Scenario 1	Buffer Space	4,93	-2,49	12,35	0,25	57,21
	Internal Space	20	11,93	17,97	0,68	59,73
Scenario 2	Buffer Space	13,72	3,34	16,81	0,45	49,47
	Internal Space	20	13,25	18,91	0,73	65,11
Scenario 3	Buffer Space	-1,25	-4,05	7,68	0,25	79,02
	Internal Space	20	10,69	18,44	0,63	54,99
Scenario 4	Buffer Space	14,11	3,87	17,01	0,46	50,05
	Internal Space	20	13,28	18,96	0,73	65,22
Scenario 5	Buffer Space	14,25	3,93	17,08	0,46	49,82
	Internal Space	20	13,34	18,97	0,73	65,47

Thermal coupling coefficient L^{2D} and linear thermal transmittance:

The Ψ (psi) value by definition represents the extra heat flow through the linear thermal bridge over and above that through the adjoining plane elements. From the numerical modelling of a two-dimensional junction, L 2D is the thermal coupling coefficient between the internal and external environments and is calculated from:

$L^{2D} = Q / (Ti - Te)$ [$W.m^{-1}.K^{-1}$]

where:

Q: is the total heat flow from the internal to external environment and

Ti ,Te: are the temperatures of the internal and external environments.

Hence, the linear thermal transmittance, Ψ, of the two dimensional junction is the residual heat flow from the internal to external environment after subtracting the one-dimensional heat flow through all flanking elements, expressed in [$W.m^{-2}.K^{-1}$]and is determined from:

$\Psi = L^{2D} - \Sigma (U \times l)$ [$W.m^{-2}.K^{-1}$]

Where:

L^{2D}: is the thermal coupling coefficient

U: is the U-Value in $W.m^{-2}.K^{-1}$ of the flanking element

L: is the length in meter over which U-value applies.

In the modelled window detail 1, the application of vacuum glazing when it is combined with more effort to improve the frame u-value as well as the frame-glazing joint area, shows a high potential of improving the total window thermal performance. As the vacuum glazing is responsible for the reduction of heat flow through glazing area, more efforts should be given to reducing the thermal coupling coefficient which leads as result to reducing the linear thermal transmittance of the frame-glazing junction, this should be combined with efforts to reduce heat flow through the frame itself, as a result the total window thermal transmittance is reduced significantly. In Figure 42 the thermal coupling coefficient of the frame-glazing junction is decreasing in scenario 2 by 62% in the external window pane where the vacuum glazing is applied comparing to the original scenario.

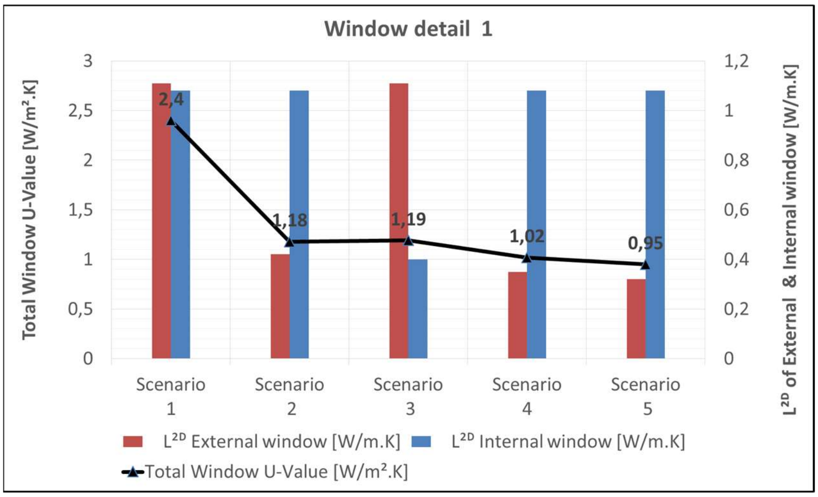


Figure 42. L^{2D} values of external and internal window pane and total window U-value

As the effort was devoted to reduce the thermal bridge effect in frame-glazing area, more reduction of L^{2D} occurred in scenario 4 (68% reduction) and scenario 5 (71% reduction) whereas less improvement occurred in scenario 3 when applying vacuum glazing in the internal window pane (only 61% reduction). The linear thermal transmittance Ψ-value is showing improvement in the different scenarios where the vacuum glazing is applied as it is shown in Figure 43.

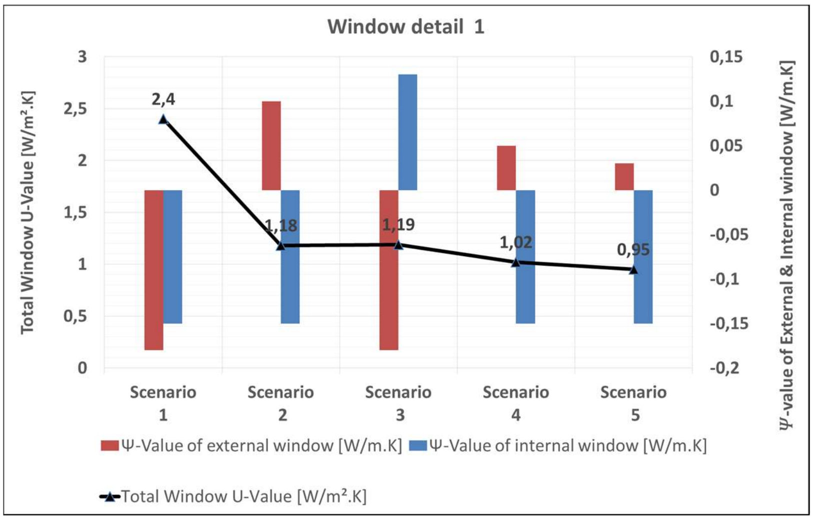


Figure 43. Ψ-values of external and internal window pane and total window U-value

In the modelled window detail 2, In Figure 44 the thermal coupling coefficient L^{2D} of the frame-glazing junction is decreasing by 23%, 25%, 29% and 31% in the scenarios 2, 3, 4 and 5 respectively as the goal was to reduce thermal bridge effect in frame-glazing junction. In the same way the linear thermal transmittance is decreased gradually from scenario 2 to scenario 5 as it is shown in Figure 45.

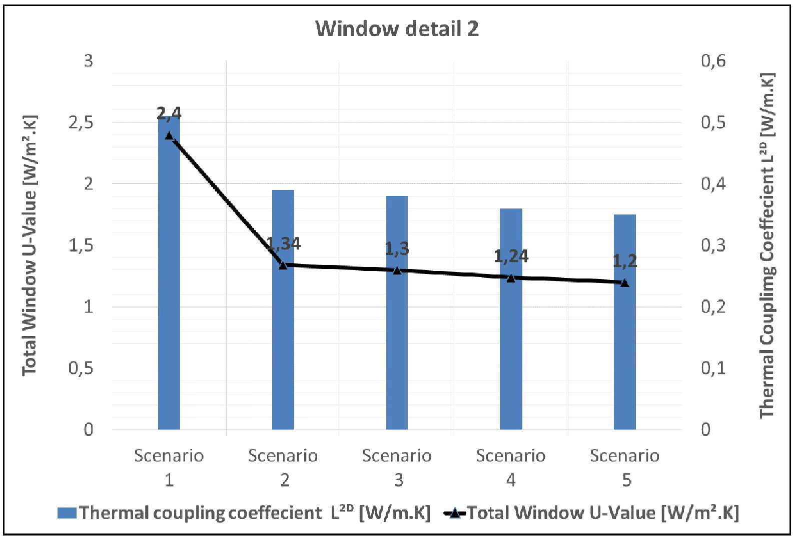


Figure 44. Total window L^{2D} and total window U-value

In both window details 1 and 2 the best case was in scenario 5 when the vacuum glazing is applied to the external window layer combined with more improvement to the frame-glazing edge by increasing the frame rebate depth and installing compacfoam layer around the frame-glazing edge in order to lower the thermal bridge effect in the junction area to minimum level.

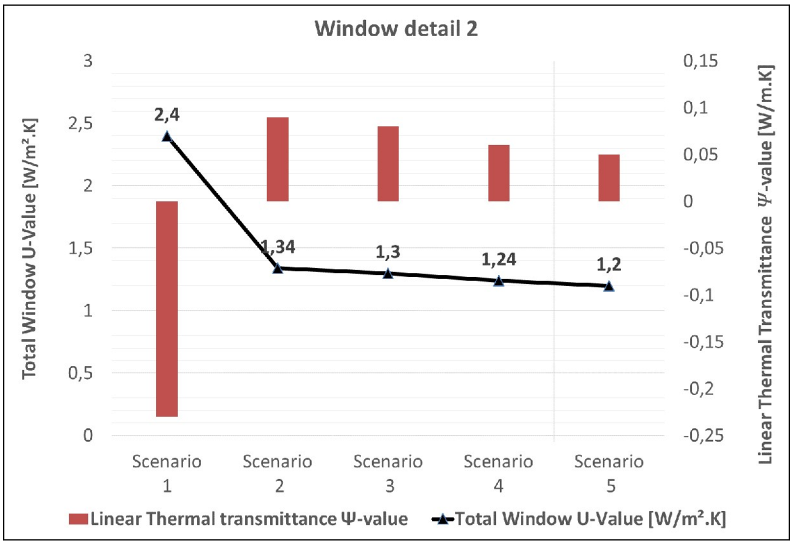


Figure 45. Total window Ψ-value and total window U-value

As a result, the total window U-value of detail 1 was reduced by 60% in the best case scenario which was scenario 5 comparing to the original scenario and by 50% in window detail 2.

Comparison of thermal performance of two window details in all different scenarios

As it is shown in Table 21, in the original window case the u-values for both window details were almost the same which means both windows have the same thermal performance, but considerable difference occurred when applying vacuum glazing in both details. The window detail 1 proved a better thermal performance when using the vacuum glazing in all different scenarios and the maximum reduction in U-value of 60% in the fifth scenario when using the vacuum glazing in the external window pane with additional with 5 [mm] thickness Compacfoam layer installed around the glazing-frame junction. Whereas the second window detail showed some improvements in thermal performance with maximum reduction in U-value of 50% also in the fifth scenario. This different reduction percentages of U-value between two different details is due to different frame sections and different interstitial air layer thickness between two window details 1 and 2.

Table 21. Total thermal transmittance reduction in different five scenarios for window 1 & 2

		Original	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Window Detail 1	U_{window} [W.m⁻².K⁻]	2.40	1.18	1.19	1.02	0.95
	U_{window} reduction [%]	-	50%	50%	57%	60%
Window Detail 2	U_{window} [W.m⁻².K⁻]	2.40	1.34	1.30	1.24	1.20
	U_{window} reduction [%]	-	44%	46%	48%	50%

3.3 Calculation of annual building heating demand building

After calculating the total U-value of selected window details, it is necessary to evaluate the impact of using such developed window details on the building heating demands and then on total building energy demand. To achieve that, two historical buildings located in the first district in Vienna were chosen. The buildings were selected due to many factors as follows:

1-Historical buildings that are under heritage protection, as this study evaluate the vacuum glazing application in thermal retrofit and this would be a good solution for retrofit historical building as the available glazing materials in market are not applicable due its bigger thicknesses and heavy weight therefore it will not be applicable in many retrofit cases as the thick glazing does not fit in the old frames that were used in most historical buildings and requires to replace the frames which is not allowed in many cases of retrofitting historic buildings.

2- Building construction time should be older than 1960 and ideally between 1945s - 1970s

As the selected window details were the most common used in that time, another advantage of those buildings that in many cases, the old building either under retrofit or needs to be retrofitted due to its bad conditions and low energy performance.

3- Glazing percentage of the façade. It is an important issue to decide which building fits in this study because the goal is to evaluate mainly the impact of window retrofit on the whole building thermal performance and specifically the impact of replacing the old window glass with new vacuum glazing while maintaining the original frame, thus historical buildings with different glazing areas to opaque proportion were selected as study cases.

4- Building usage: it is estimated that nearly 75% of buildings blocks in Vienna are residential buildings whereas 20% are under office category usage and still around 5% are in category of educational and other usages, therefor the selected building cases should be a residential buildings as it represent the majority of buildings in Vienna.

5- Building geometry including but not limited to envelope specifications, building height, gross floor area, gross volume, form factor (surface/volume) and a number of building stories. Other factors such as envelope surface properties, local climate and local topography which have an influence on the number of heating days also were considered while selecting buildings as case study and the less influential factors on building heating demands such as building color and building orientation which may influence solar heating gains were given less attention while choosing building case studies.

3.3.1 Annual heating demand of two building cases

In order to assess the impact of the vacuum glazing on the thermal building performance, a building heating demand has to be calculated. In this study as mentioned previously, the ArchiPHYSIK program is used because it has reliable results as it takes into account the climate conditions where the buildings are located in Vienna and it provides results that comply with Austrian standards and building regulation in Austria.

The Figure 45 shows the impact of vacuum glazing on both buildings tends to have similar graph line declination of lowering the building heating demand although the glazing surface

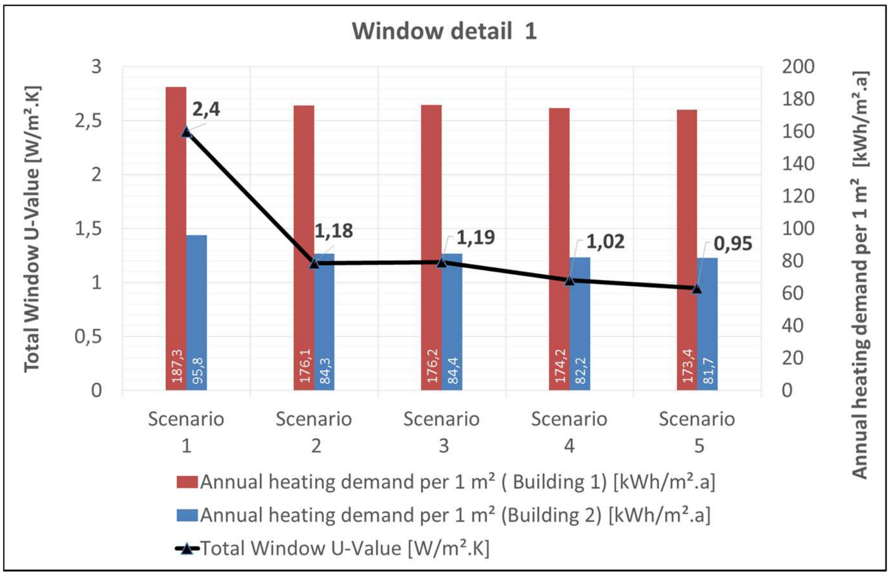


Figure 46. Annual buildings' heating demands of two building cases with window detail 1

area is not same in the two building cases. As the first glazing area in the first building is 10.9% and in the second building is 19.8% and it is illustrated that in in the building with 10.9% glazing area, the building heating demand was reduced in a range between 5.9% - 7.4%. In the same way in the building case 2 that has glazing area of 19.8%, the building heating demands reduction ranges between 12% - 14.7%.

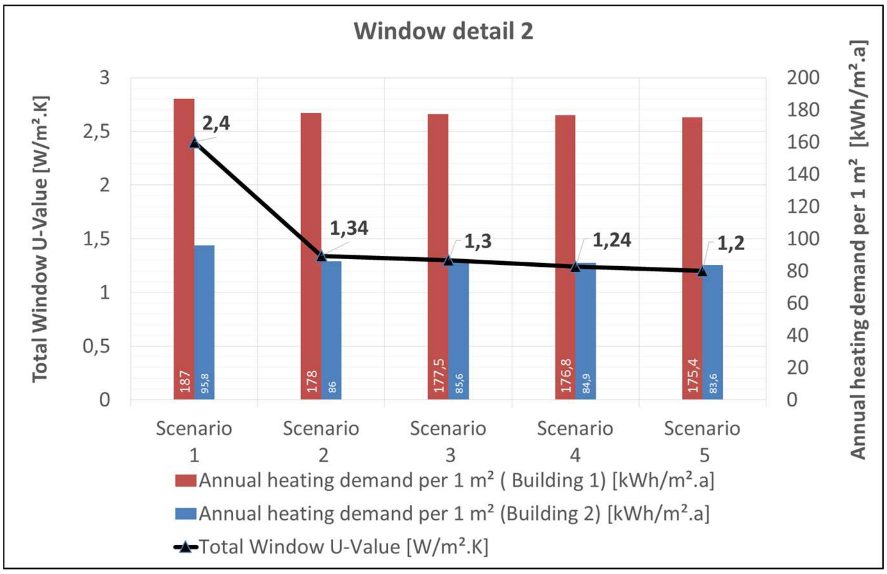


Figure 47. Annual buildings' heating demands of two building cases with window detail 2

In the Figure 47, the impact of applying vacuum glazing on window detail 2 on the building heating demands is shown. As in the case of window detail 1, the graph line in both building cases also has the same declination in the case of window detail 2. In the building with 10.9% glazing area, the building heating demand was reduced in the range between 4.9% - 6.2%. In the same way in the building case 2 that has glazing area of 19.8%, the buildings heating demand reduction ranges between 10.2% - 12.5%.

In comparing the impact of vacuum glazing in two window details as it is shown in the Table 22 it is clear that the vacuum glazing has a greater impact on window thermal performance when applying to the window details 1. This happened due to the fact that the window detail 1 has two separate frames with larger air layer in between which affect the total window U-value as it provides more insulation layer in total window system. While in the window detail 2, the total thickness of two wooden frames which form the whole window frame is less than in the window detail 1, as well as the air layer between two glazing layers, is also less than in the window detail 1 which has a direct impact on the total window U-value and as a result on the total building heating demand.

Table 22. Annual heating demand of two building case study

			Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05
Building_01 **glazing/opaque** **10.9 %**	**Window Detail 1**	**HWB [kWh.m^{-2}.a^{-1}]**	187.3	176.1	176.2	174.2	173.4
		HWB Reduction[%]	-	5.9%	5.9%	6.9%	7.4%
		U-value [W.m^{-2}.K^{-1}]	2.4	1.18	1.19	1.02	0.95
		U-value Reduction[%]	-	50%	50%	57%	60%
	Window Detail 2	**HWB [kWh.m^{-2}.a^{-1}]**	187.3	178	177.5	176.8	175.4
		HWB Reduction[%]	-	4.9%	5.2%	5.6%	6.3%
		U-value [W.m^{-2}.K^{-1}]	2.4	1.34	1.3	1.24	1.2
		U-value Reduction[%]	-	44%	46%	48%	50%
Building_02 **glazing/opaque** **19.8%**	**Window Detail 1**	**HWB [kWh.m^{-2}.a^{-1}]**	95.8	84.3	84.4	82.5	81.7
		HWB Reduction[%]	-	12%	11.8%	13.8%	14.7%
		U-value [W.m^{-2}.K^{-1}]	2.4	1.18	1.19	1.02	0.95
		U-value Reduction[%]	-	50%	50%	57%	60%
	Window Detail 2	**HWB [kWh.m^{-2}.a^{-1}]**	95.8	86	85.6	84.9	83.6
		HWB Reduction[%]	-	10%	10.6%	11.3%	12.7%
		U-value [W.m^{-2}.K^{-1}]	2.4	1.34	1.3	1.24	1.2
		U-value Reduction[%]	-	44%	46%	48%	50%

4 ECONOMIC ANALYSIS

Due to the fact that this study is based on investigating the application of vacuum glazing in thermal retrofit in typical historical window details used in Austria-Vienna and the building case studies are also located in Vienna, it is reasonable to carry out the economic analysis and amortization calculation via using energy costs and all required economical figures in Vienna as reference in this study, therefore it is necessary to calculate the heating costs in Vienna for 1 kWh taking into account the escalation rate 2% for each year. Starting from the capital cost as derived from the ArchiPHYSIK after calculating the heating demands for both building cases.

Table 23. Average Heating cost per 1 kWh between 2017 and 2037

Capital cost [€]	Escalation rate [%]	Number of years	Average cost per 1 Kwh for period of 20 years [€]
0.07	2	20	0.104

4.1 Payback period

4.1.1 Building case 1

This case looks at the payback period of using vacuum glazing in the thermal retrofit of the building while other building component remains in its original case without thermal retrofit in order to assess the exact effect of vacuum glazing application on final building heating price for next 20 years after doing thermal retrofit. Taking the heating demands from the Table 22 of building case 1. And assuming a flat area in building case 1 is 100 m²

Table 24. Heating cost for 100 m² flat in building 1 using window detail 1 for next 20 years after windows thermal retrofit

	Window detail 1		Window detail 2	
	Heating cost in 20 year for a 100m² flat [€]	**Savings after window thermal retrofit in 20 years[€]**	**Heating cost in 20 year for a 100m² flat [€]**	**Savings after window thermal retrofit in 20[€]**
Scenario 1 (original)	38896	-	38896	-
Scenario 2	36628.8	2329.6	37024	1934.4
Scenario 3	36649.6	2308.8	36920	2038.4
Scenario 4	36233.6	2724.8	36774	2184
Scenario 5	36067.2	2891.2	36483.2	2475.2

As it is shown in the Table 24 the heating cost saving occurred when using vacuum glazing in thermal retrofit ranging from €2329.6 in scenario 2 to €2891.2 in scenario 5. As the price of vacuum glazing in the market is not stable and varies due to many factors such as the glazing specifications and the source country so the actual cost of thermal retrofit using vacuum glazing is not available therefore the payback period is given according to the price of savings as it is calculated in table 24. Assuming using the scenario 5 of window 1 in retrofitting a 100 m² flat in building case 1, using vacuum glazing is still economically feasible as long as the window retrofit cost is less than €2891.5 when the aimed payback period is 20 years.

4.1.2 Building case 2

This case as in case 1 also looks at the payback period of using vacuum glazing in thermal retrofit of the building 2 while other building component remains in its original case without thermal retrofit and as it is shown in Table 25 the saving for a 100 m² flat in building 2 assuming using scenario 5 of detail 1 while caring out window glazing retrofit and this shows a little more saving ability comparing to the first building case which means that more glazing surface area has a result of more heating demand cost saving along the years following the thermal retrofit. Using vacuum glazing in building case 2 is still economically feasible as long as the window retrofit cost is less than €2267.2 when the aimed payback period is 20 years.

Table 25. Heating cost for 100 m² flat in building 2 using window detail 2 for 20 years after windows thermal retrofit

	Window detail 1		**Window detail 2**	
	Heating cost in 20 years for a 100m² flat [€]	**Savings after window thermal retrofit in 20 years [€]**	**Heating cost in 20 years for a 100m² flat [€]**	**Savings after window thermal retrofit in 20 years [€]**
Scenario 1 (original)	19926,4	-	19926,4	-
Scenario 2	17534,4	2392	17888	2038,4
Scenario 3	17555,2	2371,2	17804,8	2121,6
Scenario 4	17160	2766,4	17659,2	2267,2
Scenario 5	16993,6	2932,8	17388,8	2537,6

5 DISCUSSION

The application of vacuum glazing element in buildings' thermal retrofit has a results as follows:

-improvement of total U-value of the window where the vacuum glazing is installed either in internal or external window pane.

-improvement in the values of all indicators related to thermal bridges, i.e., thermal coupling coefficient (L^{2D} according to ISO, 2008), linear thermal transmittance "Ψ-value" and thermal transmittance of the frame itself when applying vacuum glazing in a way like in scenario 4 and 5 in both window details 1 and 2.

-improvement of total building thermal performance when using vacuum glazing in window retrofit.

Taking into account that this study investigates the application of vacuum glazing in buildings' thermal retrofit which can be the best option for historical buildings especially buildings under heritage protection. In those buildings, the traditional high insulating glass is not applicable due to specific requirements of Federal Heritage Office which regulates energy-efficient retrofit of historical buildings. The vacuum glazing is considered a very practical and applicable technique in thermal retrofit, especially, due to its unique properties which provides a very light weight glass comparing to traditional insulating glass as well as its big advantage of maintaining the window frame as in its original case that can be a crucial issue in heritage buildings' façade.

Additionally, the vacuum glazing when it is combined with different improvement techniques in glass-frame edges, shows that it can be competitive even with the new insulated glazing that is available in the market nowadays.

As it is illustrated in Table 26 and Figure 48 there are some scenarios shows more potential than others in term of lowering U-value and lowering the risk of condensation and mold growth in internal space. In the window detail 1, the original case has a big U-value which causes a huge heating losses in historical buildings and the assessed four different scenarios show a great impact on reducing the total window U-value to less than 50% of its original value. In scenario 2 and 3 the U-value is almost the same but the scenario 3 is not preferable as there will be a risk of condensation and mold growth not only in interstitial space but also

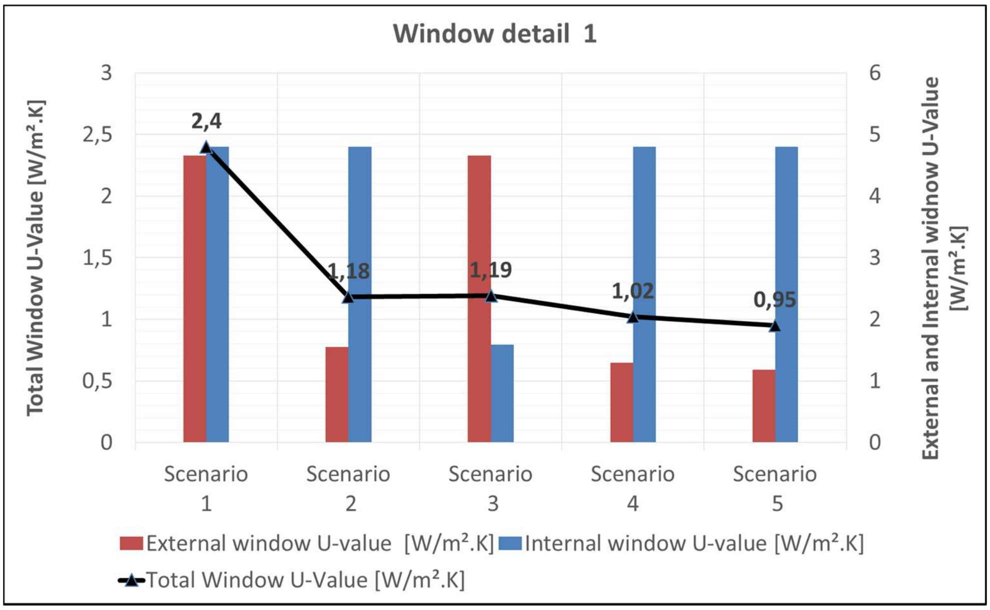


Figure 48. Thermal transmittance of W1and W2 of window detail 1

in internal space thus these results show that applying the vacuum glazing in internal window pane of casement window is not the best solution when carrying out window thermal retrofit.

In scenario 2 the total window U-value is relatively low with no risk of condensation or mold growth in the internal space, and this scenario has an advantage of replacing the old glass layer of external window pane without the need of any further modification on internal or external window pane. This scenario can be a good solution when the wooden frame in a good conditions and there is no need to do any maintenance on it and only replacing the external glass with vacuum glazing after doing a tiny adaptation to install the glass will help a lot to improve the total window thermal performance and as a result the total building thermal performance. In scenario 4, there is a need to do some modification on the wooden frame in external window pane to adapt the vacuum glazing and increasing –at the same time- the frame rebate depth in order to reduce the thermal bridge effect that occurs in glass-frame junction and this can help to reduce the total window U-value comparing to the scenario2. The case of scenario 4 can be a good solution when the there is a need for more low window U-value if the case of the scenario 2 is not sufficient. In scenario 5 the detail shows a great potential of lowering the total window U-value when combining the vacuum glazing in external window pane with using 5 [mm] Compacfoam layer around the vacuum glazing in glass-frame edge area, this has a direct impact on the thermal bridge effect in that area which results in lowering the total window U-value. This scenario is good when the goal is getting a high building thermal performance and the previous scenarios are not enough to reduce the heating demand to the required levels.

In window detail 2; as it is shown in Figure 48, it has the same thermal performance of the window detail 1 in its original case, but using vacuum glazing in all different scenarios showed less impact on the total window U-value comparing to the window detail 1.

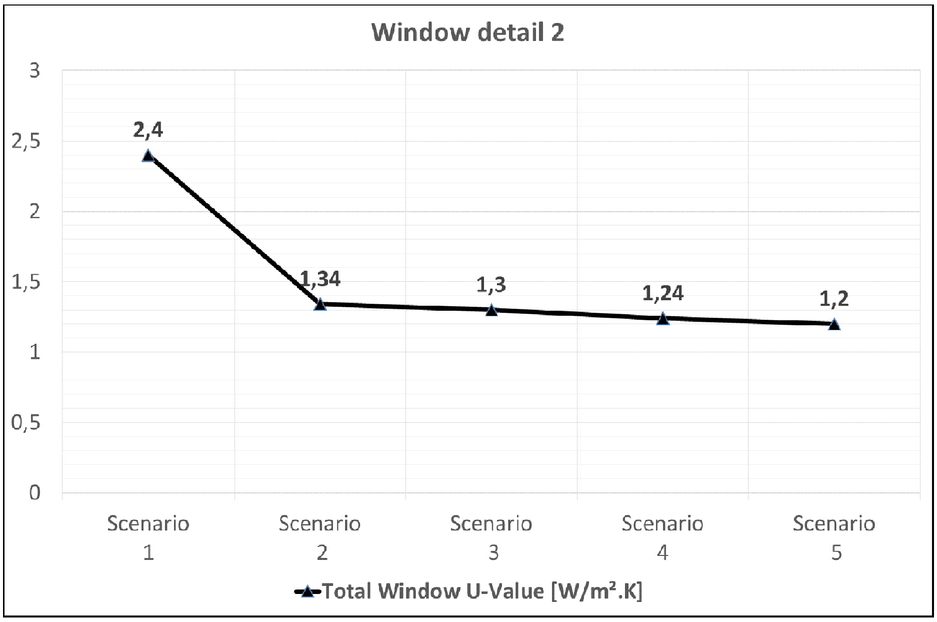


Figure 49. Thermal transmittance of W1 and W2 of window detail 1

There is similarity in the results when comparing the two window details performance when using vacuum glazing in retrofit process. In the scenario 3, there is also risk of condensation and mold growth and that lets the improvement on this scenario is not useful therefore, this scenario is not advisable. In the scenario 2 when the vacuum glazing is installed in the external layer, there is high potential for reducing the total window U-value with no risk of condensation or mold growth in the internal space and as in the previous window detail, this scenario does not require a lot of modification on the original window frame and only tiny modification can be done to adapt the vacuum glazing in the external frame part as the thickness of the original glass layer in original case is 4 [mm] whereas the vacuum glazing layer has 8.15 [mm] thickness. In the scenario 4, there is even lower U-value than in scenario 2 and 3 but it needs a bit more modification on the frame section as the rebate frame depth is much bigger than in scenario 2 and 3, also this scenario shows no risk of condensation or mold growth in the internal space. In the scenario 5, it has considerably low U-value and this scenario can be a good solution when doing a thermal retrofit on such type of windows when high building thermal performance is required when the other scenarios do not satisfy the requirements especially when there is maximum heating demand limit needs to be fulfilled.

Table 26. Summary of calculation and simulation results of window detail 1 & 2 and building 1 & 2

			Window detail 1					Window detail 2					
		Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
U_{window}		[W/m^2.K]	2,4	1,18	1,19	1,02	0,95		2,4	1,34	1,3	1,24	1,2
U_{window} $impr.$		-	-	50%	50%	57%	60%		-	44%	46%	48%	50%
Risk of condensattion		-	Yes	No	Yes	No	No		Yes	No	Yes	No	No
$U_{w(1)}$		[W/m^2.K]	4,66	1,55	4,66	1,29	1,18		-	-	-	-	-
$U_{w(2)}$		[W/m^2.K]	4,8	4,8	1,59	4,8	4,8		-	-	-	-	-
L_{w1}^{2D}		[W/m.K]	1,11	0,42	1,11	0,35	0,32	L_{w}^{2D}	0,51	0,39	0,38	0,36	0,35
L_{w2}^{2D}		[W/m.K]	1,08	1,08	0,4	1,08	1,08						
Ψ_{w1}^{2D}		[W/m.K]	-0,18	0,1	-0,18	0,05	0,03	Ψ_{w}^{2D}	-0,23	0,09	0,08	0,06	0,05
Ψ_{w2}^{2D}		[W/m.K]	-0,15	-0,15	0,13	-0,15	-0,15						
Building Case 1	heating demand (Building 1)	Kwh/m^2.a	187,3	176,1	176,2	174,2	173,4		187	178	177,5	176,8	175,4
	heating demand (Building 1) impr. [%]	-	-	5,90%	5,90%	6,90%	7,40%		-	4,90%	5,20%	5,60%	6,30%
Building Case 2	heating demand (Building 2)	Kwh/m^2.a	95,8	84,3	84,4	82,2	81,7		95,8	86	85,6	84,9	83,6
	heating demand (Building 2) impr. [%]	-	-	12%	11,80%	13,80%	14,70%		-	10%	10,60%	11,30%	12,70%

As it is expected, the reduction in window U-value leads to reduction in the annual building heating demands in both selected building cases. In Figure 45 it is clear in all different scenarios that the less window U-value leads to more annual heating demand savings in both buildings' cases and these savings increase when the glazing area increases and that apply to both window details.

It has been found that one of the main advantages of vacuum glazing beside its high thermal performance, its light weight and low thickness comparing to all other available glazing materials. Which makes its application on weak historical façade that cannot take additional loads possible. In addition, due to its low thermal conductivity; it makes application of vacuum glazing very flexible and quick solution especially due to the fact that most wooden frames in historical buildings can easily adapt the new vacuum glazing as there will be a need only to minor changes on view and structure of the historical building.

As the main outcome of the simulation and the followed calculations, it was concluded that vacuum glazing significantly contributes to high window thermal performance while avoiding condensation and mold growth in internal spaces.

6 CONCLUSION

This study explored the application potential of vacuum glazing in buildings’ thermal retrofit via assessing typical window details of historical buildings in Austria and then investigating the impact of using such techniques on total buildings’ heating demand. The application of vacuum glazing has a high impact on window thermal performance in all assessed window types and thus has a considerable impact on overall building thermal performance. If properly planned, it is possible to significantly reduce the impact of thermal bridges and the heating losses through windows, without compromising the buildings’ architectural surfaces. Concerning the U-value of the window when applying vacuum glazing in the external window pane of a casement window, a reduction of 50-60% the composite window type, a reduction of 44-50% can be realized. The thermal coupling coefficient reduction by application of vacuum glazing ranges between 62-71%. The condensation risk in some scenarios of both window details is reduced comparing to the original window case.

However, an application of vacuum glazing on heritage protected buildings might require a specific approval by relevant authorities due to its very minor changes on the view of the external façade caused by the pattern of pillars between two glass layers of vacuum glazing.

The main challenge during the study was collecting the details and technical specifications of the historical buildings that were built before the 1960s as the details of the buildings that were constructed in that time are not available in many cases especially due to many changes that occurred to the buildings through all years. Thus necessary assumptions have been made according to the Austrian standards and building regulations in Austria. Concerning the calculations of total building heating demand, it is important to mention that all buildings components other than window where assumed to have U-values as mentioned in the Austrian standards in order to get more precise result of the vacuum glazing impact on total building heating demand. Further efforts in the future researches as follows:

- The application of vacuum glazing in both external and internal window pane of casement and composite windows taking into account the condensation risk may occur when applying such system.
- As this study was carried out using 2-dimentional simulations, a three dimensional simulation of thermal bridges to include the 3D effect of window corners to understand in depth the behavior of the details as in the reality situation.

- The impact of vacuum glazing on another window types either were used in historical buildings or even in newly constructed buildings and compare it to the other glazing techniques that are used in modern buildings.
- Further improvements could be conducted on the window details using more different materials that have low thermal conductivity combined with vacuum glazing especially in the frame glass edge area in order to reduce the impact of thermal bridges to as low as possible and as a result lower the total window U-value.
- Further effort could be done on the pillars that locate in the vacuum space in between two glass layers.
- A set of larger buildings sample can be investigated to assess the impact of vacuum glazing on heating demand of more different buildings’ types.

As a conclusion, applying the vacuum glazing when conducting thermal retrofit is highly recommended especially in the historical buildings that are under heritage protection where the regulations greatly limits the use of the available glazing materials in market since vacuum glazing increases significantly the thermal performance of the glazing area and the total building thermal performance without noticeable impact on the external and internal architectural surfaces.

7 INDEX

7.1 List of Figures

7.2 List of Tables

8 LITERATURE

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