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Generation and application of a BIM-based repository of straw bale construction details

unter der Leitung von

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KURZFASSUNG

Die vorliegende Forschung zielt auf den Schluss von Informationslücken, die einen großen Teil heutiger Software in Bezug auf die Verwendung umweltfreundlicher Materialien betreffen.

Während die Bautechnik im Sinne der Nachhaltigkeit fortlaufend verbessert wird, liefern Programme zur Analyse von Materialeigenschaften bisher oftmals keine ausreichend verwertbaren Ergebnisse. In der vorliegenden Studie sollen im Besonderen Strohballen als Vertreter nachhaltigen Materialien untersucht werden. Dabei sollen die Details der wichtigsten Knotenpunkte und Verbindungen von Bauteilen aus Strohballen in einem aus vier Phasen bestehenden Prozess analysiert werden.

Die erste Phase beinhaltet die Erforschung der Literatur und den Bereich der Wissenschaft in Bezug auf Strohballen als Baustoff. Die zweite Phase konzentriert sich auf das architektonische Modellieren ausgewählter Details unter Nutzung des Programms Autodesk Revit, mit entsprechender Verwendung dessen Materialbibliothek bezüglich thermischer Eigenschaften von Stroh. In der dritten Phase geht es um die Untersuchung der Plausibilität des linearen Austauschs von Daten aus BIM-Auswertungen und Analysen der Energiebilanz. Die vierte Phase beschäftigt sich mit der energetischen Simulation von Details in AnTherm, einer Spezialsoftware zur Analyse von Kältebrücken und der Ermittlung von Risiken in Bezug auf Kondensation. Die Untersuchungen ermöglichen eine Berechnung der Temperaturverteilungen, Ermittlung von Wärmeströmungen und Bestimmung der Dampfdiffusion innerhalb von Bauteilen aus Strohballen.
Das endgültige Ziel liegt in der Entwicklung eines Entscheidungswerkzeugs, das als Verbindung und einfach nutzbare Schnittstelle zwischen Bautechnik, Mitteln zur Gebäudedarstellung und Einrichtungen zur Gebäudesteuerung sowohl untereinander, als auch mit dem Endnutzer dient.

Tatsächlich soll die Datenbank standardisierte Details zu wesentlichen Verbindungen und Knotenpunkten aus Strohballen enthalten und leicht verständlich von Baufachleuten, Studenten und Handwerkern als selbstlernendes Werkzeug mit der Möglichkeit zukünftiger Systemerweiterungen genutzt werden können.

ABSTRACT

The purpose of the present research is to fill that void that characterizes most of the software used today, about the use of eco-friendly materials. In fact, while construction techniques are improved in terms of sustainability, programs that should analyse the properties of these materials are often unable to do so. Specifically, in this study, straw bales will be investigated as a representative of sustainable materials. Details of the most important junctions of buildings made of straw bales will be investigated during a process divided into four different phases. The first phase involves the research of the literature and the domain of knowledge related to straw bales as construction material. The second phase focuses on the architectural modelling of the details selected in Autodesk Revit, implementing its material library with thermal properties of straw. The third phase concerns the investigation of the feasibility of a linear flow of data between the BIM tool and the energy analysis tool. The fourth phase is related to the energy simulation of the details in AnTherm, a software specialized in the analysis of thermal bridges and condensation risk. This analysis makes it possible to calculate the distribution of temperature, the heat streams and the vapour diffusion streams within building components made of straw bales.

The final goal is to develop a decision support system that can create a connection and an easy interface among Building Constructions Techniques, Building Representation Tools and Building Performance Tools and each of them with the user. In fact, this database of standardized details of the major junctions made of straw bales, should be easily consulted and understood by specialists, students and craftsmen as a self-learning tool, with the possibility of next expansions of the system in the future.

Keywords

Building Sustainability, Straw Bales, Building Ecology, Thermal Bridges, Autodesk Revit, 3D Modeling, Interoperability, BIM

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Concluding this research work for me is the end of a wonderful journey that, 1400 km away from home, meant a personal growth, an intellectual challenge and a considerable broadmindedness.

CONTENTS

NOMENCLATURE

c Specific heat capacity [$Jkg^{-1}K^{-1}$]

d Thickness [m]

f_{Rsi} Temperature factor [-]

L_{2D} Thermal coupling coefficient [$Wm^{-1}K^{-1}$]

R Thermal resistance [$Wm^{-2}K^{-1}$]

U Thermal transmittance value [$Wm^{-2}K^{-1}$]

θ_{min} Minimum interior surface temperature [°C]

θ_I, θ_e Temperatures of inside and outside space [°C]

λ Thermal conductivity [$Wm^{-1}K^{-1}$]

μ Water vapour resistance factor [-]

ρ Density [kgm^{-3}]

ψ Linear thermal transmittance [$Wm^{-1}K^{-1}$]

1 INTRODUCTION

1.1 Overview

Buildings are one of the leading causes of environmental pollution and CO_2 production after consumption related to industry and transport. Specifically, constructions are the cause of about 20% of CO_2 emissions in the world (International Energy Agency 2010). In the EU, about two-thirds of the energy consumptions in buildings are due to heating and cooling demand. However, the issue is given not only by the energy consumed by buildings, but also by the materials used to build them. For example, concrete is responsible for 5% of global man-made CO_2 emissions (The Cement Sustainability Initiative Progress Report 2005). Nowadays, it is more and more important to find new design solutions and new materials, in order to improve the energy efficiency and sustainability of the buildings.

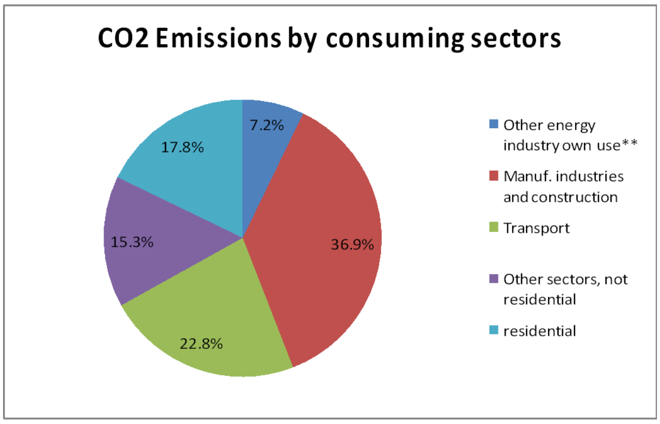


Figure 1: CO_2 emissions by consuming sectors, International Energy Agency (2010)

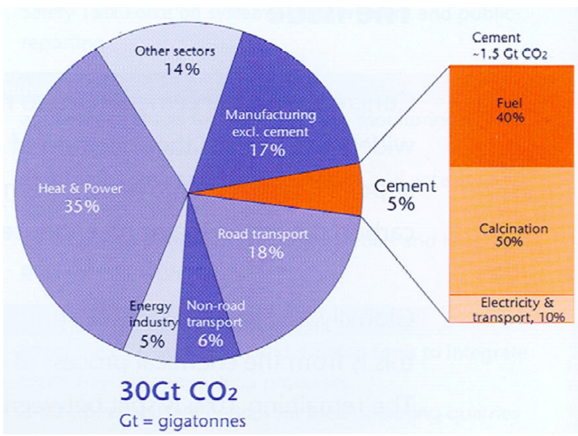


Figure 2: Global CO_2 productions, The Cement Sustainability Initiative Progress Report (2005)

Toward this end, an important contribution can be generated by using eco-friendly materials with high energy saving standard. Therefore, it is necessary to think about the use of sustainable materials in the early steps of the design of a new building. However, although the construction techniques are progressing day by day, software solutions are often not updated quickly. This factor creates a substantial gap among most recent construction details, architectural models and energy models. The purpose of the present research is to fill that void that characterizes most of the software programs used today, about the use of eco-friendly materials, in this case straw bales.

1.2 Motivation

Circumstances related to quantify and qualify energy consumption developed and evolved over time a typically scientific attitude to analyse multiple reactions of the structure in different fields. Many participants and new professional roles were added to the Building Life Cycle, simulating performances of the structure before the construction in order to minimise risk of failure. However, this growth of specializations led to an increased fragmentation of the Building Life Cycle, where communication and flow of information between different steps is inaccurate (Hitchcock 1995). This factor generates a complex transmission of graphical drawings and data with a consequent lack of documentation and inefficiency (O'Donnell 2009).

Moreover, through this process, an Energy Manager conducts his work downstream in the Building Life Cycle that means he is forced to take decisions on a predefined structure designed by the architect in an early stage. For this reason, O'Donnell (2009) states that *„actual building performance evaluation is often inconsistent with design expectations"*.

In this scenario, it becomes important to create a decision support system that can allow having a linear interface between software programs and a sliding flow of information and data. In this way, professional roles involved in the Building Life Cycle are able to operate and exchange data from early design stages, avoiding information loss and forced pre-set design solutions. Furthermore, focusing on straw bales as sustainable material, will finally allow having a set of energy indicators of a building made of straw bales and a consequent larger use of this technology from the beginning of the design phase. Indeed, the lack of this material in most of the software used today plays a main role in a lower diffusion of the material itself. The final goal of this study is to fill that existing gap between new modelling programs and sustainable construction techniques of straw bales and to develop a decision support system that can create a connection and an easy interface among Building Constructions Techniques, Building Representation Tools and Building Performance Tools and each of them with the user.

1.3 Background

1.3.1 BIM

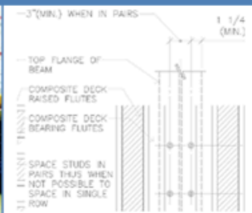
In this approach, Building Information Modeling (BIM) is the best way for sustainable analysis during the first stage of the design process. (Azhar et al. 2009).

Traditional CAD-based software programs consist of a series of 2D elements that require a further retroactive energy analysis at the end of the design process, since these tools are not able to support information regarding building performance evaluation. This process, as stated in paragraph 1.2, is inaccurate, inefficient and time-consuming. (Azhar et al. 2009).

Instead BIM, an innovative process launched by Autodesk in 2002, combines graphic elements as drawings and models with data regarding energy performances. The introduction of BIM allowed easily exchanging data between different project phases, reducing errors and optimizing the operating performances of the building. (Autodesk Revit White Paper 2005).

In Table 1 are highlighted differences between hand drafting, CAD and BIM. It can be easily observed how the passage from CAD to BIM is more radical than the change from board drafting to CAD.

Table 1: *Drafting, CAD, BIM Evolution Table. (Autodesk Inc., 2013)*

	Hand Drafting	CAD	BIM
			
Era	Before 1982	1982 to Current	2000 on
Tools	Triangle and tee square	AutoCAD® software	Revit
Product	Hand-drawn technical artwork	Digital-drawn technical artwork	Database of building objects
Method	Lines, arcs, circles, hatch, and text	Lines, arcs, circles, hatch, and text	Walls, beams, columns, windows, doors
Format	2D and isometric views	2D, 3D, and some solids	2D, 3D, 4D (plus time), 5D (money and time), Dn (energy, materials, and so on)
Summary of Product	Noncomputable data represented in technical artwork	Noncomputable data represented in technical artwork	Database of structure that can digitally interact with many other BIM processes and applications
Way Information is used	Highly trained and skilled professionals must interpret the artwork and manually use the information.	Highly trained and skilled professionals must interpret the artwork and manually use the information.	Highly trained and skilled professionals use the information in an automated format with BIM.

Revit, as BIM tool, creates parametric models where the building is an intelligent representation of objects, defined in terms of building elements. As stated from Azhar (2010), *„a building information model carries all information related to the building, including its physical and functional characteristics and project life cycle information”*. This factor guarantees a good interoperability between different professional roles, an optimized sustainable design from the early steps and to save time.

1.3.2 Straw Bales

In this research straw bales were selected as representative of those materials that can improve the quality of a building, also for achieving the standards of Passive House.

The European Directive on Energy Performance of Buildings in 2002 established to improve the overall energy efficiency of new buildings until achieving nearly zero-energy buildings by the end of 2020 (European Directive on Energy Performance of Building 2010).

In this context a key role is played by the material that acts as insulator in buildings, responsible to ensure a low heating and cooling demand of the building itself.

As EURIMA reports (2007), insulations in buildings *„have the potential to be turned from energy wasters into climate and money savers"*. Therefore, it is clear the important contribution that good insulators could give in order to reach climate change goals.

1.3.2.1 Straw Bales Properties

GOOD INSULATOR

The most significant parameter that must be taken into account about energy performances of a material, is its conductivity. The parameter that defines the quantity of heat transfer is the thermal transmittance, U-value, expressed in $Wm^{-2}K^{-1}$. The thermal transmittance is considered the effectiveness of a material to act as an insulator in buildings and it is given by the formula:

$$U = \frac{1}{R_t} = \frac{1}{R_{se} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + R_{si}} \qquad [Wm^{-2}K^{-1}]$$

where:

R_t is the heat transfer resistance $[Wm^{-2}K^{-1}]$

R_{se} is the exterior heat transfer resistance $[Wm^{-2}K^{-1}]$

d_i is the thickness of a material layer [m]

λ_i is the thermal conductivity of a material layer $[Wm^{-1}K^{-1}]$

R_{si} is the interior heat transfer resistance $[Wm^{-2}K^{-1}]$

The lower is the U-value, the greater are the qualities of the material to act as insulator and the smaller is the quantity of heat loss.

The graph in figure 3 shows the present U-values required respectively for floor, roof and wall, and their optimization, for 25 European capital cities, according to EURIMA (2007). As it can be noted, current U- values are far from acceptable.

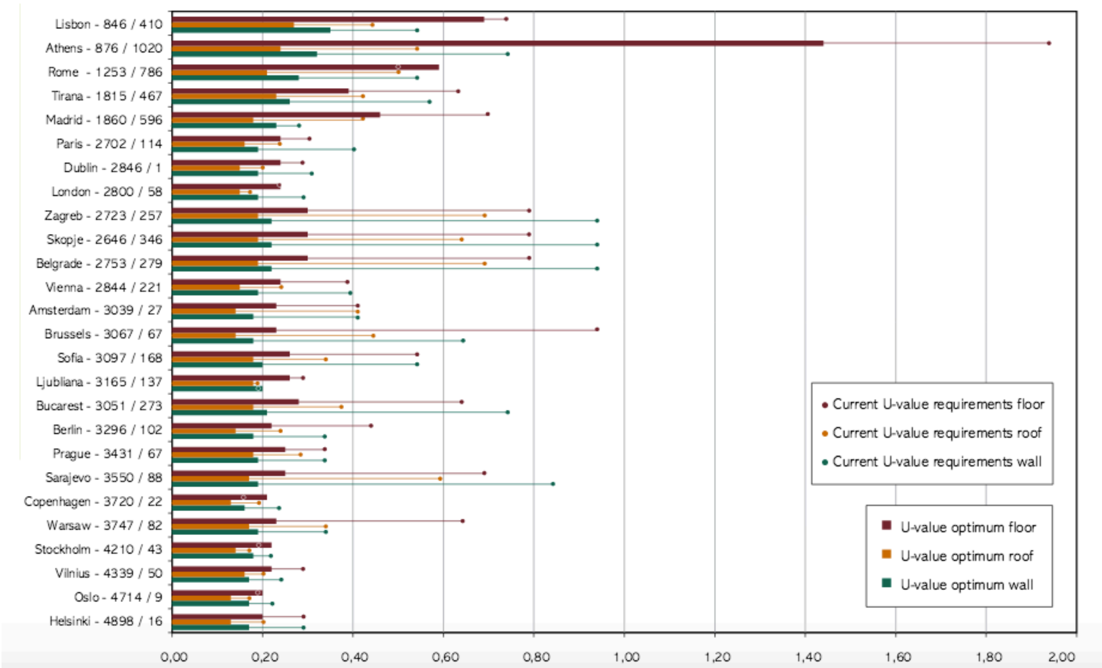


Figure 3: Current and optimized U-values in Europe, EURIMA (2007)

Referring to the graph, the U-value required nowadays for the city of Vienna for outside walls is 0.35 $Wm^{-2}K^{-1}$. Using straw as insulator, gives the possibility to significantly decrease this value. Indeed, straw bales have a thermal transmittance between 0.08 and 0.20 $Wm^{-2}K^{-1}$ and the coefficient of thermal conductivity λ is about 0.0380 $Wm^{-1}K^{-1}$ (GrAT – Gruppe Angepasste Technologie 2000). This means that is possible to have buildings with a strong energy efficiency, with all the criteria for a correct energy saving. In fact, by this way, inside the building will be maintained a constant temperature that ensure not to lose heat during the winter months and to maintain fresh air during the summer months.

CARBON SINK

It is proved that straw bale buildings are healthier than traditional buildings because they don't create pollution. Cereal crops during their growth absorb CO_2 and release oxygen. Every kilogram of straw is able to absorb 1.47 kg of carbon dioxide, acting as a carbon sink (Atkinson

2011). Conversely, traditional buildings made of concrete emit about 50% of the greenhouse gases that are very harmful to the environment (Amazon Nails 2001).

SOUNDPROOFING

Straw provides also high levels of acoustic insulation. Tests carried out at acoustic lab of the Eindhoven University of Technology, have shown that the sound transmission loss through a straw bales wall is around 55 dB (Magwood et al. 2005). Indeed, the layer made of straw determinates an excellent acoustic damping. For this reason, it is not uncommon the use of straw bales close to airports and highways (Adedeji 2007).

LOW FIRE RISK

In spite of the popular beliefs, a straw bales construction has a low fire risk. Indeed, if straw bales are well pressed they lose all the oxygen and without it, the flame can't propagate. Tests demonstrated that, in case of fire, a straw bales wall can resist for 3 hours at 1000°C, like a normal concrete wall of 25 cm (Report to the Construction Industries Commission of New Mexico 1993).

SEISMIC RESISTANT

Furthermore, straw bales have a strong seismic resistance. Recent tests carried out in university laboratories at the University of Nevada, Reno, USA, showed that one straw bale can support weights up to 15 tonnes per square meter. Also the structure is much lighter compared to a concrete building so the stress that it receives is considerably lower. Besides, the flexibility of the material allows the absorption of vibrations, reducing the possibility of a structural collapse (Pakistan Straw Bale and Appropriate Building – PAKSBAB 2009).

NON-TOXIC

Straw, as natural material, is non-toxic and unlike other chemical insulators, it does not emit chemical gas harmful to health, as formaldehyde. Living in a construction made of straw can improve the quality of life thanks to a good quality of indoor air. Indeed, straw is a breathable material that ensures a healthy environment (Jones 2009).

LOW EMBODIED ENERGY

The embodied energy is defined as the total energy that a material requires for its production cycle. That covers material extraction, its transport, its manufacturing and its transfer to the building site, for example. The embodied energy provides all the data regarding the energy consumed to make a building material.

Figure 4 shows embodied energy values of different materials, according to calculations made from the Sustainable Energy Research Team at the University of Bath, 2011. It can be easily observed how materials as aluminum, brick and concrete have a high embodied energy due to their extraction and processing at high temperatures (Atkinson 2011).

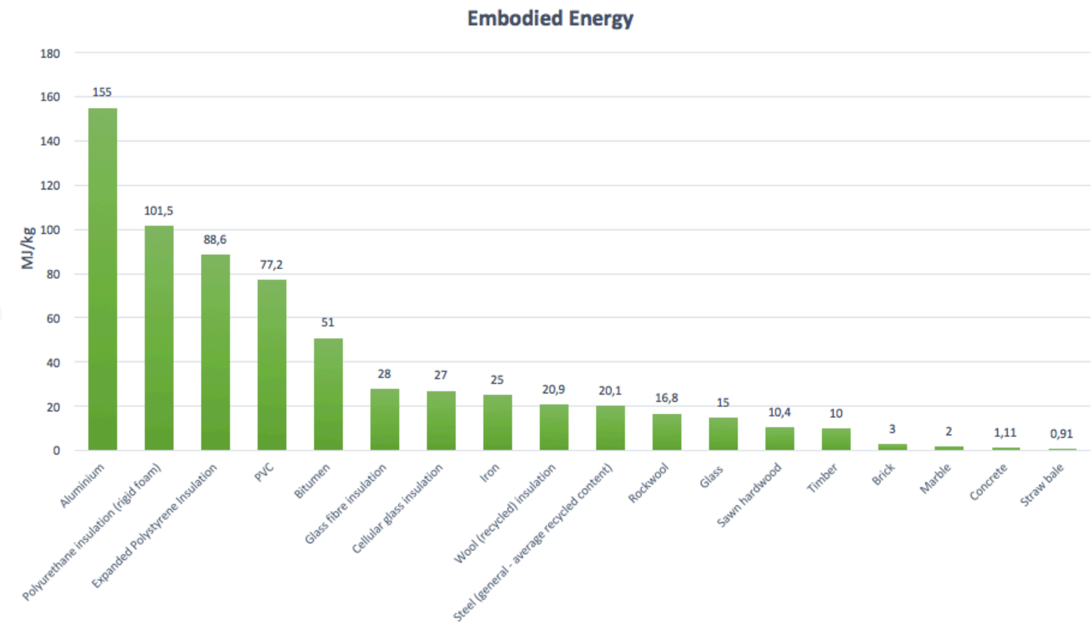


Figure 4: Embodied energy for different materials according to Greenspec, Greenspec (2011)

The graph highlights, on the other hand, how low is the energy needed in making straw bales. This result is due to several factors. Firstly, as the company Amazon Nails states, *„straw is an annually renewable natural product, grown by photosynthesis, fuelled from the sun" (Amazon Nails report 2001, p.6)*. This means that there is no needed energy in the production of straw, that essentially is a waste material generated from residual cereals.

According to a research made in Germany from the Thueringian Regional Institute for Agriculture (TLL), the German Biomass Research Center (DBFZ) and the Helmholtz Center for Environmental Research (UFZ), only in Germany the annual production of straw cereals is approximately around 30 million tons (Helmholtz 2013). 58% of German agricultural waste is made up of straw where 8% is used for agriculture and the remaining 50% is a surplus (Helmholtz 2013).

This abundance makes straw an easily accessible material that doesn't need extra costs for the production. Moreover, the vast amount of cereal fields, means that straw is generally always locally available within few kilometers (Atkinson 2011). This aspect allows to have a considerable decrease of the energy required for the transport. Also, straw is a renewable product that generates no waste, since all the exceeding straw on the construction site can be composted afterwards or used in farms. As natural material it can biodegrade at the end of its life cycle, without any energy needed for landfill (Atkinson 2011).

LOW COST

Being a waste material rather than a manufactured product, straw is a low-cost product. The average cost is around 1.60 € delivered or 1.10 € from the field (Jones 2009). This means that a two-storey, 3 bedroomed house needs around 520 straw bales in order to be built, with a final price of around 830 € (Jones 2009). In addition, the most substantial saving in straw bales houses comes from the properties of the material itself. Indeed, the high level of insulations of straw bales allows to have a noticeable reductions of heating and cooling costs, up to 75% per year compared to traditional houses (Jones 2009).

DURABLE

Tests regarding durability aspects of straw, have been carried out from the Department of Architecture & Civil Engineering at the University of Bath. The team started the researches in 2005, building panels made of straw bale for the investigations. Panels were exposed to water, to test flooding, to fires and to simulated hurricane-force wind loads. Researched ended in 2014 with all certificates and scientific proofs of a durable and suitable house (Loraine 2015).

The most dangerous element for straw, that can compromise its durability, is moisture. Inside bales, moisture content should not be more than 15% and not less than 10% and relative humidity should not exceed 70% (Fawale et al. 2007). Bales must be preserved dense, dry and compact as much as possible.

In order to prevent the mould growth due to the normal activities inside the house, it's recommended the use of natural plasters, as clay plaster or lime plaster, that can control the quantity of water vapour in the air (Szász 2013). Also, with the aim of reducing the vapour coming from outside, the wall must be waterproof and breathable (Downton 2013).

1.3.2.2 Straw Bales Technologies

There are different types of baling machines that generates various shapes and sizes of bales. An average size of bales, good for building constructions, contemplates a width of 450 mm, a height of 350 mm and a length of 1000 mm (Jones 2009). The weight should be between 16 and 30 kg and the density around 100 kgm^{-3} (GrAT 2010).

Different construction methods were developed since the XIX century, however there are basically 3 different building typologies made of straw.

LOAD-BEARING OR NEBRASKA METHOD

This building typology, named Load-bearing system, is also called Nebraska, referring to the settlers who first experimented it in USA, around 150 years ago. This approach does not include any structural framework and all the weight is supported by the bales themselves. More specifically, here bales are used as big bricks and are connected to each other and to foundation with wooden sticks (Magwood et al. 2005). Also, on the bottom and on the top of the wall are located rigid and continuous wooden panels that give more stability to the structure. Nowadays, this is the most used system in Ireland and UK but it is not common in the other countries due to the lack of a proper structural framework.

MORTARED BALE OR MATRIX METHOD

The mortared bale method involves the use of cement mortar as bonding agent between the bales. Bales are positioned in vertical columns, held together by cement pillars. Negative aspects of this technique are the large use of cement and the combination of straw and cement that causes damp and consequently mould growth (Magwood et al. 2005).

INFILL OR NON LOAD-BEARING METHOD

This third typology consists of a predefined structural framework made of wood, concrete or steel, and straw bales are used only as insulation blocks in the construction (Magwood et al. 2005). Definitely here is stressed the great insulation characteristics of the material. This technique is the favorite choice for architects because there are no substantial changes in the construction of the building.

Figure 5: Nebraska method, Grit (2011)

Figure 6: Matrix method, Solar Haven (2003)

Figure 7: Infill method, Ellensburg workshop (2007)

1.3.2.3 Straw Bales in Software

As stated in paragraph 1.2, in general, it is still hard to find a precise catalogue of straw bales in energy simulation tools that allows to have a set of energy indicators regarding it. Indeed, most of the physical measurements regarding buildings made of straw bales are performed in situ by sensors, devices and infrared camera.

This happens because straw is a natural material with variable hygrothermal properties subordinated to different factors as the type of straw (barley, oats, rice, rye or wheat), the position of the straw in the construction (parallel or perpendicular to the heat flow), its degree of compression or its possible chemical treatments (WUFI Software 2005).

Regarding the software analysis, straw as material can be found only in few software as Archiphysik or PHPP, the software used to create energy certificates of buildings. These are certainly good programs in order to have an accurate energy balance of a building, but they are not useful for a creation of an integrated system with other software.

1.3.3 Thermal Bridges in Building Envelope

The introduction of more highly insulated buildings, made of sustainable materials as straw bales, allows having a thermal bridge free design that means improved thermal and energy performances of the whole construction.

A thermal bridge is defined as *„a localised area of the building envelope where the heat flow is different, usually increased, in comparison with adjacent areas"* (The Passive House Institute). It has been recognised that thermal bridges are divided into three categories:

- Repeating thermal bridges
- Non-repeating thermal bridges
- Random thermal bridges

Repeating thermal bridges can be found in timber studs in timber frame walls, or mortar joints in lightweight blocks. As those can be found regularly throughout the element, their evaluation is included in the normal U-value calculations.

Non-repeating thermal bridges occur in geometrical discontinuities of a building where the isothermal surfaces, perpendicular to the heat flow, sag. These geometrical discontinuities are located in junctions between building components as wall-slab junction, roof-wall junction, slab-foundation junctions and around openings as windows and doors.

Random thermal bridges appear when heterogeneous materials, as bad insulators and good insulators, come into contact and allow heat to flow through the path of least thermal resistance created.

In order to evaluate thermal bridges, they have been associated to a coefficient called linear thermal transmittance ψ .

The linear thermal transmittance is defined by:

$$\psi = L_{2D} - \sum_{k=l}^{n} U_k \, l_k \qquad [Wm^{-1}k^{-1}]$$

where:

L_{2D} is the linear thermal coupling term derived by the two-dimensional calculation

U_k is the thermal transmittance of the k^{th} one-dimensional component that separates the internal side from the external environment

l_k is the length (in the two-dimensional model) over which U_k applies

k is the number of one-dimensional components

Negative consequences of thermal bridges concern harmful aspects for the construction that can be enumerated as follows.

- ENERGY ASPECT. Thermal bridges generate a significant impact on the global heat loss. They are responsible of the intensification of the heat flow with a consequent general energy displacement of the construction. These factors increase the costs for heating the building during the winter months and cooling the building during the summer months.

- STRUCTURAL ASPECT. The non-homogeneous temperature distribution inside structural nodes, may cause, in serious cases, internal stresses that lead to a gradual degradation of the material of the node itself.
- ENVIRONMENTAL ASPECT. The increased heat flow decreases the internal surface temperature of the building. As a result, when the internal surface temperature of the structures drops below the condensation temperature of the vapour in the air, the building is exposed to condensation risk and mould growth.

To estimate these risks, a minimum internal surface temperature is defined by a temperature factor f_{Rsi} , given by:

$$f_{Rsi} = \frac{\theta_{min} - \theta_e}{\theta_i - \theta_e} \qquad [\text{ - }]$$

where:

θ_{min} is the lowest inside surface temperature on the thermal bridge

θ_i is the indoor temperature

θ_e is the outdoor temperature

The temperature factor, in order to prevent condensation risk and mould growth, it is supposed to be greater or equal to 0.70. In general, for a good performance, the temperature factor should meet a critical temperature factor f_{CRsi}. Values of f_{CRsi} are strictly connected to the function of the building and are individuated by the paper BRE IP 1/06 (Ward 2006). Table 2 and 3 illustrate the critical temperature factor for avoiding respectively mould growth and surface condensation.

Table 2: *Critical temperature factors for avoiding mould growth in buildings (Ward 2006)*

Type of Building	**f_{CRsi} [-]**
Dwellings; residential buildings; schools	0.75
Swimming pools (including a dwelling with an indoor pool)	0.90

Table 3: *Critical temperature factors for limiting the risk of surface condensation (Ward 2006)*

Type of Building	f_{CRsi} **[-]**
Storage buildings	0.30
Offices, retail premises	0.50
Sports halls, kitchens, canteens; buildings heated with un-flued gas heaters	0.80
Buildings with high humidity, eg swimming pools, Laundries, breweries	0.90

It is reasonable to prevent thermal bridges and their negative effects on the building envelope. The correct way to avoid them is a good specific insulation of the construction defined from The Passive House Institute as the pencil mark that can be outlined around the whole building envelope, without any interruption (The Passive House Institute). In other words, a continuous thermal barrier is needed and a particular attention must be paid to the position of the openings in the early stages of the design process.

The use of eco-friendly insulation materials helps avoiding thermal bridges and reducing energy needs of the building.

In this specific case, straw bales have good thermal insulation properties that allow minimizing heat loss. However, thermal bridges can occur in localized area as the connection or intrusions of other not homogeneous materials, as steel or concrete, and in particular joints as slab-foundations joint.

Therefore, each specific case needs to be tested and verified with proper software, in order to calculate and analyze the distribution of temperature, the heat streams, the vapour diffusion streams and the condensation risks.

2 METHOD

2.1 Overview and Goal

The goal of the entire work is to create a developed framework that gives the possibility to exchange information among Building Constructions Techniques, Building Representation Tools and Building Performance Tools, each of them easily interfaced with the user. In this perspective, also other people as architects, engineers, students and craftsmen will be allowed to use this integrated system in the future as a specific handbook for straw bales construction details, already tested and improved. This decision support system contemplates possible expansions in further researches.

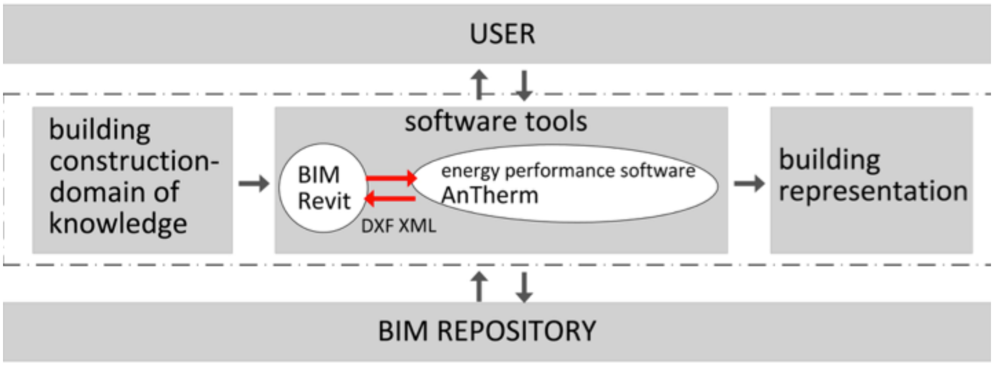


Figure 8: Synthetic flow chart of the research

As figure 9 shows below, the methodology planned, in order to develop this study, involves different stages.

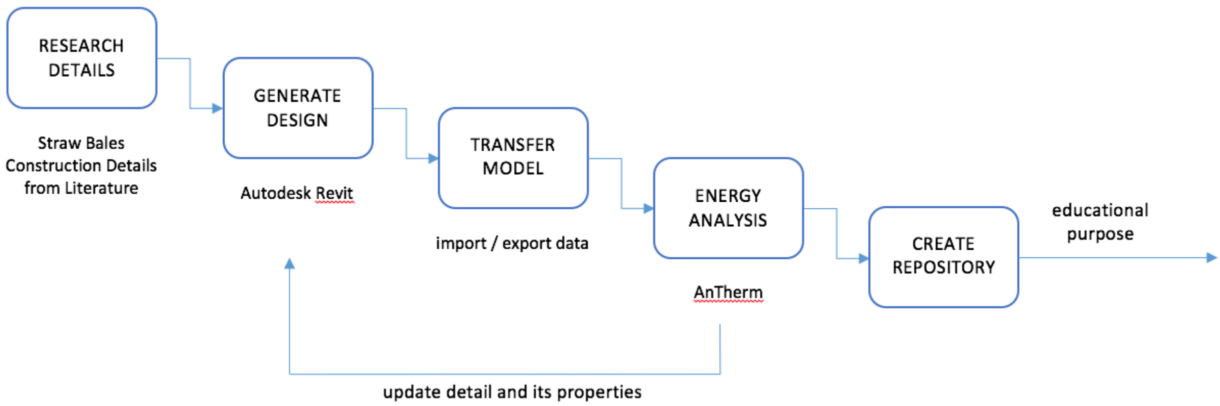


Figure 9: Process of the research work

For this research, the building representation tool planned to adopt is Autodesk Revit. Revit is a BIM tool capable of integrating design and a primary energy evaluation in one stage. As previously stated in paragraphs 1.2 and 1.3.1, it is necessary now to include energy data in the early stage of the design process. Indeed, this paper provides also the opportunity to test how a BIM tool can effectively decrease the fragmentation in the building life cycle and how the flow of information is transferred between tools.

Among the vast amount of energy performance tools, AnTherm was selected to pursue this study due to the assistance from the creator of the software. AnTherm is an energy tool specialized in the evaluation of thermal bridges and condensation risk. AnTherm team, in the person of Ms. Kornicki, provided the license and a free access to the tool during all the time needed for carrying out this paper.

In the last phase, it is expected to generate an interactive and integrated system where geometrical data and energy performances data interface each others. All implemented results obtained are going to create a specific BIM-repository that can be easily consulted and understood by specialists, students and craftsmen.

The work contemplates a cooperation with a colleague of the Master Program who focuses her analysis on high insulated structures instead of straw bales material. All steps of these experimental researches are conducted in collaboration with the Department of Building Physics & Building Ecology of the Vienna University of Technology.

2.2 Literature Review

The first phase consists in a research phase of literature related to straw bales as construction material. The focus here is on all the domain of knowledge concerning straw. Important construction details as well as relevant physical properties regarding straw bales, are now investigated.

It is necessary in this phase of the work to analyze the material and all its characteristics. It is significant to deepen all its parameters as, for example, its thermal transmittance and its coefficient of thermal conductivity and to ensure about their correctness and comprehensiveness. A proper analysis is conducted in cooperation with different research centers specialized in straw bales. One of these is GrAT – Center for Appropriate Technology of the Vienna University of Technology. Its experimental office is the S-House, located in Böheimkirchen, Austria and it is a combination of passive solar house and a house made of materials based on renewable resources. In fact, the building, consisting of two floors, is made of wood and straw bales. GrAT, in the person of the Dipl.-Ing. Stefan Prokupek, provided useful material for this research. Values of thermal conductivity (λ), water vapour diffusion (μ), density (ρ) and specific heat (c) as well as details of most important joints as wall-slab junction, roof-wall junction and slab-foundation junction, are inquired, processed and collected.

All elements acquired in this investigation phase are properly evaluated and selected for the aim of this research.

To pursue this, a series of details of the major architectural joints are chosen for a 2-dimensional thermal bridge evaluation. These joints can be enumerated as follows:

- Basic walls made of straw bales
- Wall-foundation junction
- Wall-slab junction
- Wall-roof junction
- Openings

Therefore, it is determined that a total of 12 varying details are examined in this paper: 2 different variants for each of the 4 joints of the building plus 4 sections of a basic wall, built up of dissimilar materials.

2.3 Building Representation Tool

Information acquired and details chosen in the first stage of the process, are now playing a key role for the progress of the work: these data will be utilized for the implementation of the material library of Autodesk Revit. Details regarding junctions of straw bales buildings are drawn and modeled in Revit. However, this stage does not involve only an architectural representation and a geometric configuration of the element, but prepares a way for a thermal analysis. Indeed, each layer of the detail is associated to a specific material with all its related parameters. Here, thermal properties as thermal conductivity (λ), specific heat (c) and density (ρ) are set. In case that the material, as straw bales, is not yet covered from Revit library, it is manually created as new material and set with its specific attributes.

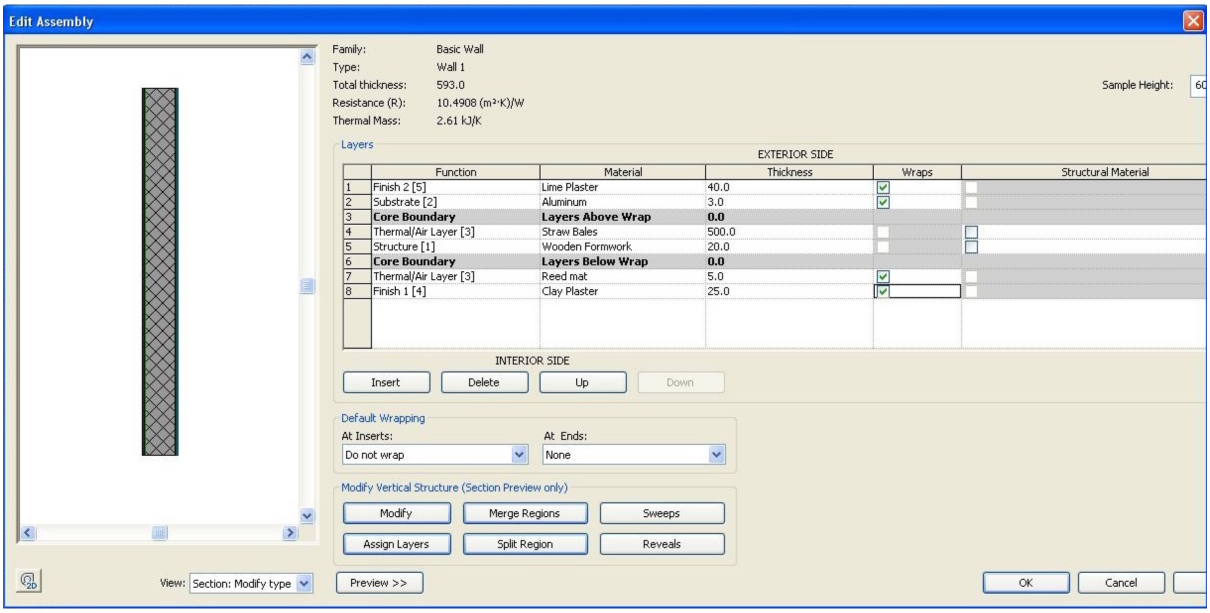


Figure 10: List of materials in Autodesk Revit

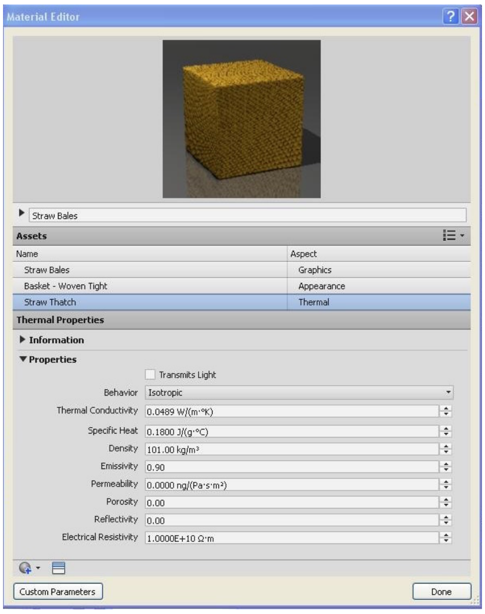


Figure 11: Material editor in Autodesk Revit

2.4 Testing Interoperability between Tools

Detail modeled in Revit are now ready for the energy performance test. The software in charge for this analysis is AnTherm. This stage focalizes the observations on the challenging phase of the transfer of the model from one software to another. After an accurate examination of the capabilities of the tools, it can be declared that the 2 software programs have not a linear interface between them, starting from the assumption that:

- Revit can export the following files:
  CAD (.dwg, .dxf, .dgn, .adsk), Green Building XML (.gbXML), Industry Foundation Classes (.ifc), Autodesk 3ds Max (.3ds), ODBC database
- AnTherm can import the following files:
  waebru 2/3bt, acad/DXF, Heat2, Heat3, Kobru86

Figure 12: Autodesk Revit export options

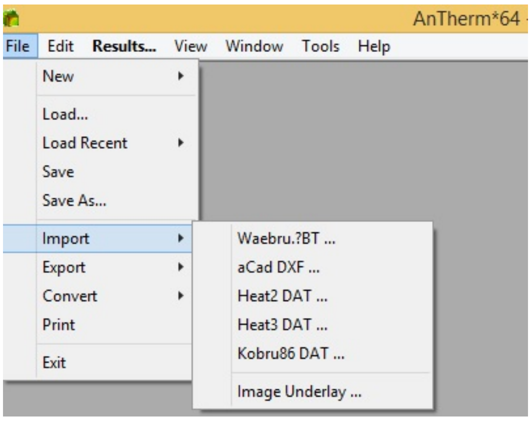


Figure 13: AnTherm import options

In response to this existing gap, a new goal is added to the research work. The aim is investigating the feasibility of a linear flow of data between the BIM tool and the energy analysis tool, in order to create a framework considered as a potential solution for exchanging information between the design stage and the thermal performance stage. To pursue this, different approaches concerning the conversion and the transfer of the files are deeply inquired and verified.

2.4.1 DXF Interface

The first analysis focuses on testing the interface of the tools through DXF files. File DXF, literally Drawing Exchange Format, it's a format for CAD file, developed by Autodesk since 1982 as solution in order to exchange data between AutoCAD and other programs. It consists basically in a regular text files that can be edited with Notepad or other simple ASCII editor (Autodesk Inc. 2000).

For the aim of this research, a basic wall is modelled in Revit and then it is ready to be saved and exported as DXF file. The following step is importing the file in AnTherm. At this point, a fallacy occurs: the software encounters an error in opening the file.

An accurate investigation regarding this gap in exchanging the file, is now conducted.

Different sources consulted, identify the reason of this issue in Revit: more precisely, the program exports DXF files that do not meet requirements for import. Indeed, while AnTherm reads DXF files made of closed polylines, Revit generates parametric 3D details made not only of geometrical data but also of energy data. Models made in Revit are not the common CAD details, but are parameters geometrically interrelated that carry with them most of their thermal properties. This factor involves a major complexity of the detail that cannot be read from AnTherm.

Figure 14: Flow of data using DXF interface

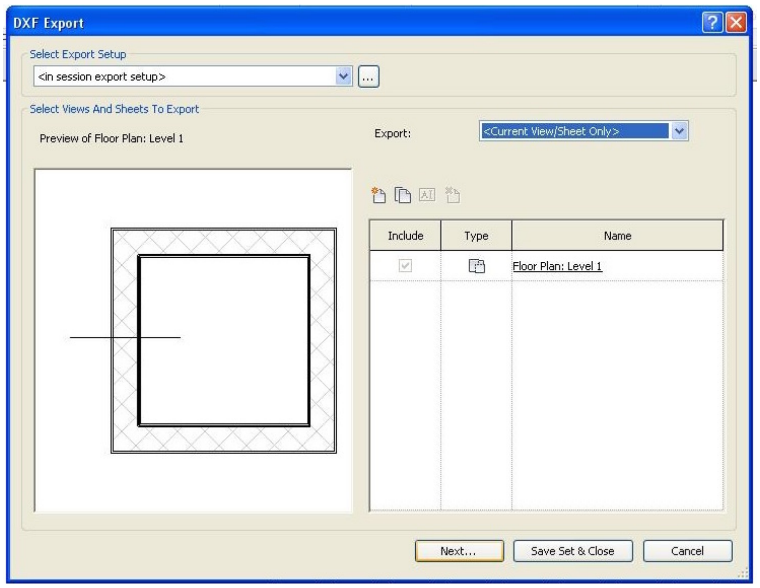


Figure 15: Exporting Autodesk Revit file as DXF file

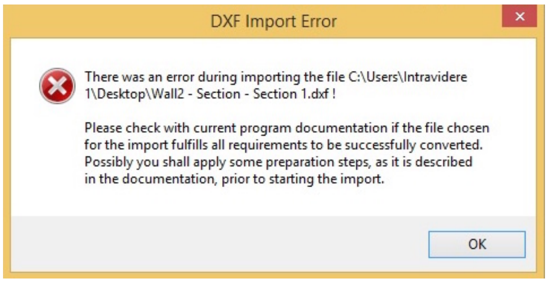


Figure 16: AnTherm DXF import error

A potential solution for non interrupting the flow of information between the software, is a manual adaptation of the Revit model. This process necessitates the use of another software able to transfer DXF files, as Autodesk AutoCAD. The methodology starts realizing the architectural detail in Revit, exported then as DXF file in AutoCAD. In AutoCAD the model is simplified, converting Revit parameters in polylines as closed boxes in different layer styles. The document is now ready for the thermal analysis and from AutoCAD is exported as DXF file in AnTherm. In AnTherm the detail is perfectly readable and prepared for the simulation.

This approach to the problem comprehends positive and negative aspects.

On the one hand, this method ensures that the model created in Revit is transferred to AnTherm and guarantees to run a simulation and have thermal performances results.

On the other hand, it is not the optimal way since it does not provide a linear flow between Revit and AnTherm, but a manual adaptation in between.

Figure 17: Flow of data through Autodesk AutoCAD, using DXF interface

2.4.2 XML Interface

A second analysis, with the aim of finding a direct interface between Revit and AnTherm, concerns tests through XML files. A XML file, that stands for Extensible Markup Language, is a file format used to share common information formats, that is both readable from humans and machines. It was introduced in 1998 from the World Wide Web Consortium as markup language with a definite standard and flexible usability across internet. It became widely used for structure of documents and for exchanging information between different systems.

The introduction of BIM modelling, is related with the developing of another typology of XML file: the gbXML, Green Building XML. The gbXML is an open schema that is in charge for transferring 3D building information models (BIM) to engineering and energy analysis tools (Jalaei et al. 2014). Considered the main export option thanks to its good potentialities, gbXML file is useful for the purpose of this research.

For this case study, the same basic wall modelled in Revit previously, is used now for this different examination. The model, after setting all criteria for the transfer, is exported as gbXML file. In this case, even if Revit is able to export XML files, AnTherm, conversely, cannot import XML files, neither gbXML files.

Figure 18: Flow of data using gbXML interface

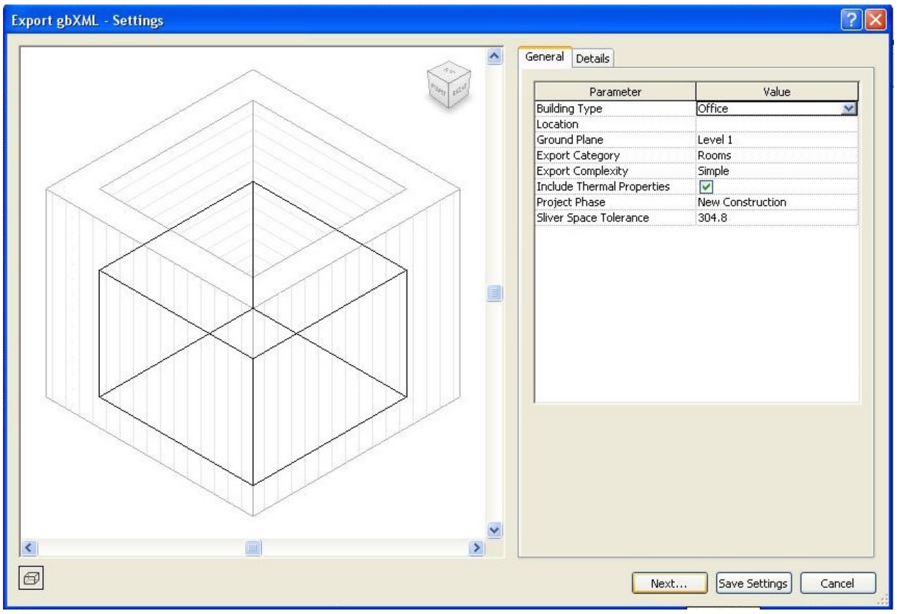


Figure 19: Export gbXML settings in Autodesk Revit

In this context, different ways are investigated in order to make the file readable in AnTherm. A potential approach contemplates the use of a plug-in for Revit, called DB Link. This plug-in allows to import and export data between a Revit project and an external database as Microsoft Access, Microsoft Excel or ODBC database. Here, the information related to a Revit project are presented in a table where they can be edited and adjusted, before being exported again. However, at the end of the process the file generated is again a XML file not importable in AnTherm. As result, it is deduced that this system, that involves the use of the database, gives advantages in reorganizing data inside the Revit project itself but does not provide elements for interfacing with other software.

2.4.3 Mapping Interface

A third method, testing the interoperability between the two tools, involves mapping the two XML files generated separately from Revit and AnTherm.

The first part of the analysis focuses mainly on the comparison of the XML files on Notepad ++. As it can be observed in figure 22 and 23, the two XML report similarities and differences. The XML file originated from Revit presents as thermal properties thermal conductivity (λ), density (ρ) and specific heat (c), instead water vapour diffusion (μ) is missing. On the other side, the XML file derived from AnTherm shows all thermal properties as thermal conductivity (λ), water vapour diffusion (μ), density (ρ) and specific heat (c). Comparing the geometric data, it can be noted that Revit reports the thickness of every singe material layer, instead AnTherm reports the specific 3D Cartesian coordinates of the observed element.

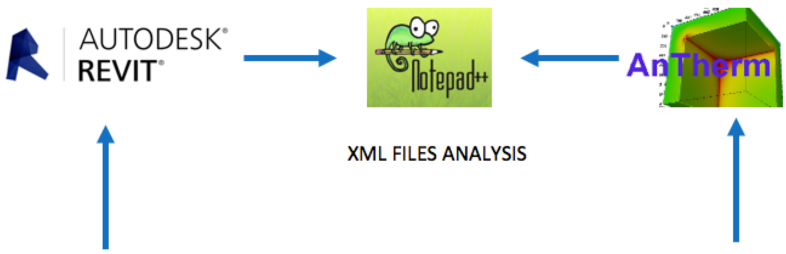
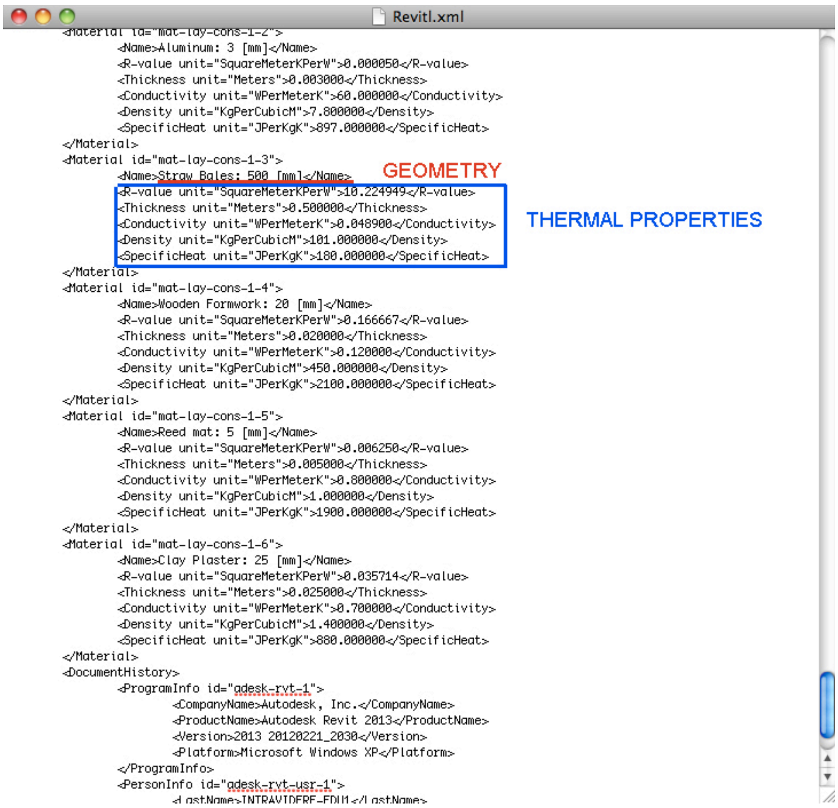


Figure 20: Flow of data using XML files analysis




```xml
<Material id="mat-lay-cons-1-2">
        <Name>Aluminum: 3 [mm]</Name>
        <R-value unit="SquareMeterKPerW">0.000050</R-value>
        <Thickness unit="Meters">0.003000</Thickness>
        <Conductivity unit="WPerMeterK">60.000000</Conductivity>
        <Density unit="KgPerCubicM">7.800000</Density>
        <SpecificHeat unit="JPerKgK">897.000000</SpecificHeat>
</Material>
<Material id="mat-lay-cons-1-3">
        <Name>Straw Bales: 500 [mm]</Name>
        <R-value unit="SquareMeterKPerW">10.224949</R-value>
        <Thickness unit="Meters">0.500000</Thickness>
        <Conductivity unit="WPerMeterK">0.048900</Conductivity>
        <Density unit="KgPerCubicM">101.000000</Density>
        <SpecificHeat unit="JPerKgK">180.000000</SpecificHeat>
</Material>
<Material id="mat-lay-cons-1-4">
        <Name>Wooden Formwork: 20 [mm]</Name>
        <R-value unit="SquareMeterKPerW">0.166667</R-value>
        <Thickness unit="Meters">0.020000</Thickness>
        <Conductivity unit="WPerMeterK">0.120000</Conductivity>
        <Density unit="KgPerCubicM">450.000000</Density>
        <SpecificHeat unit="JPerKgK">2100.000000</SpecificHeat>
</Material>
<Material id="mat-lay-cons-1-5">
        <Name>Reed mat: 5 [mm]</Name>
        <R-value unit="SquareMeterKPerW">0.006250</R-value>
        <Thickness unit="Meters">0.005000</Thickness>
        <Conductivity unit="WPerMeterK">0.800000</Conductivity>
        <Density unit="KgPerCubicM">1.000000</Density>
        <SpecificHeat unit="JPerKgK">1900.000000</SpecificHeat>
</Material>
<Material id="mat-lay-cons-1-6">
        <Name>Clay Plaster: 25 [mm]</Name>
        <R-value unit="SquareMeterKPerW">0.035714</R-value>
        <Thickness unit="Meters">0.025000</Thickness>
        <Conductivity unit="WPerMeterK">0.700000</Conductivity>
        <Density unit="KgPerCubicM">1.400000</Density>
        <SpecificHeat unit="JPerKgK">880.000000</SpecificHeat>
</Material>
<DocumentHistory>
        <ProgramInfo id="adesk-rvt-1">
                <CompanyName>Autodesk, Inc.</CompanyName>
                <ProductName>Autodesk Revit 2013</ProductName>
                <Version>2013 20120221_2030</Version>
                <Platform>Microsoft Windows XP</Platform>
        </ProgramInfo>
        <PersonInfo id="adesk-rvt-usr-1">
                <LastName>INTRAVIDERE-EDU1</LastName>
```


Figure 21: XML file generated from Autodesk Revit

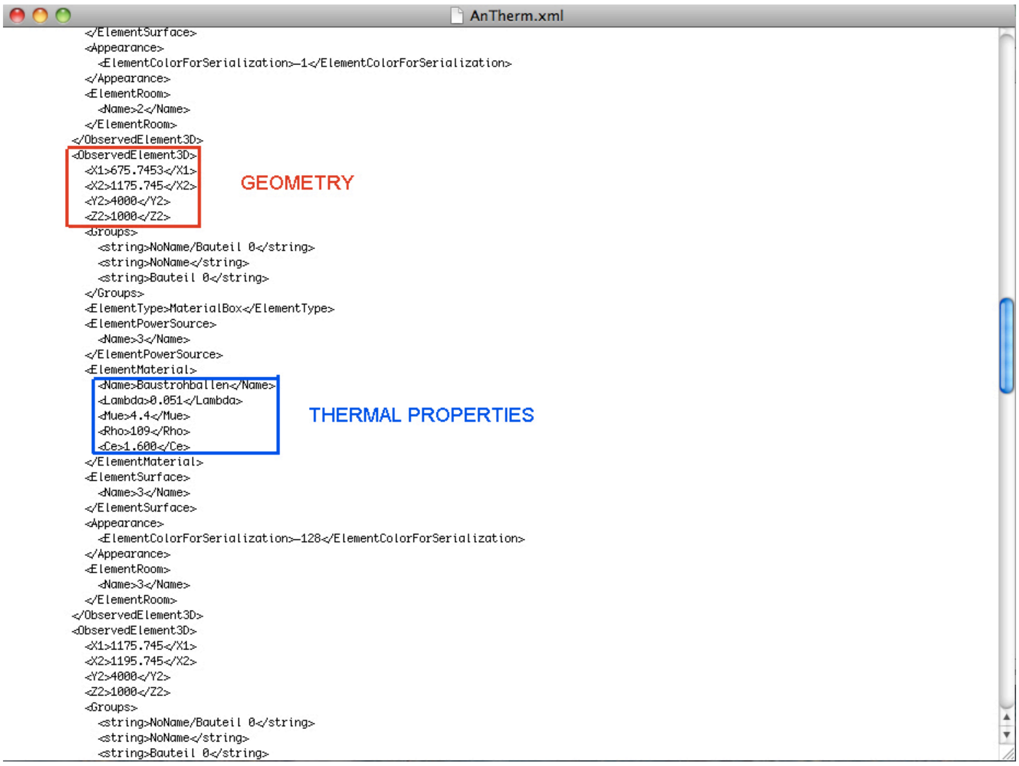


Figure 22: XML file generated from AnTherm

The second part of the investigation is addressed to mapping the XML on a software called Altova Map Force. Figure 24 highlights how thermal properties of the wall interface each others from a Revit XML file to an AnTherm XML file. Nevertheless, XML files present different characteristics that lead to a non-linear 1:1 interface during the mapping process. The test is here conducted on the same basic wall used for the previous tests. It is reasonable that working with more complex architectural details, that involve many different layers, causes a substantial disparity between the two XML files. This factor creates a considerable interference with a 1:1 interface that does not contribute in having a functional interoperability between Revit and AnTherm.

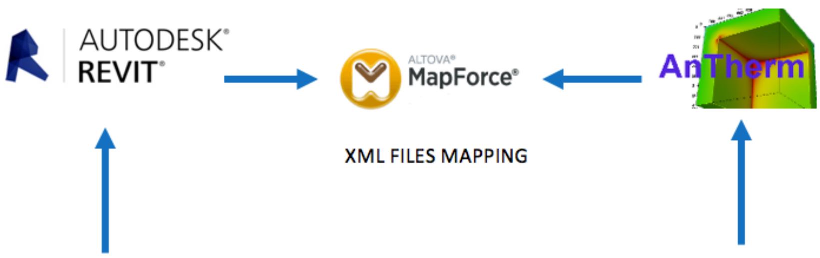


Figure 23: Flow of data using XML files mapping

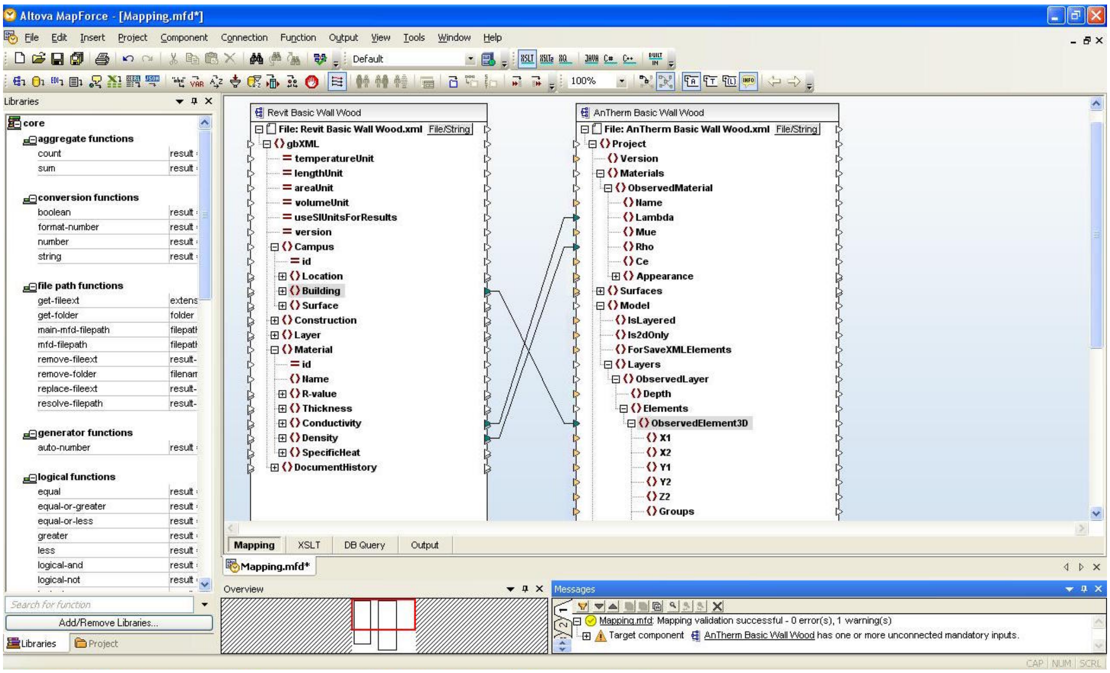


Figure 24: XML files mapping

2.4.4 Graphical Interface

The examination of the three previously identified different case studies, leads the research work to a total different approach. A new criterion, concerning how to exchange information, is accepted, with the principal aim of a not linear interface between the tools but of a parallel work, done simultaneously in the two tools. Indeed, the major goal now is to find standardized detail of building made of straw bale that can improve the quality of a building, reaching a thermal bridge free design that means improved energy performances of the whole construction.

Consequently, the methodology adopted is a graphical interface and comparison between the two software. More specifically, every single detail that needs to be analysed, is modelled both in Revit and AnTherm, starting from the beginning.

The second step of the process concerns the energy simulation of the architectural joint followed by the interpretation of the results. The detail is in this phase examined focusing on its thermal performance and on the amount of heat flow through the architectural element. Details that require a substantial improvement are graphically revised both in Revit and AnTherm and simulated a second time.

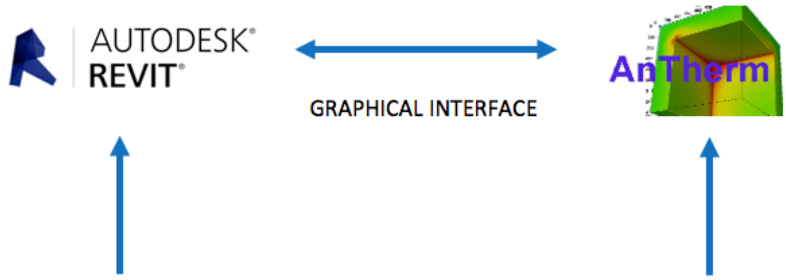
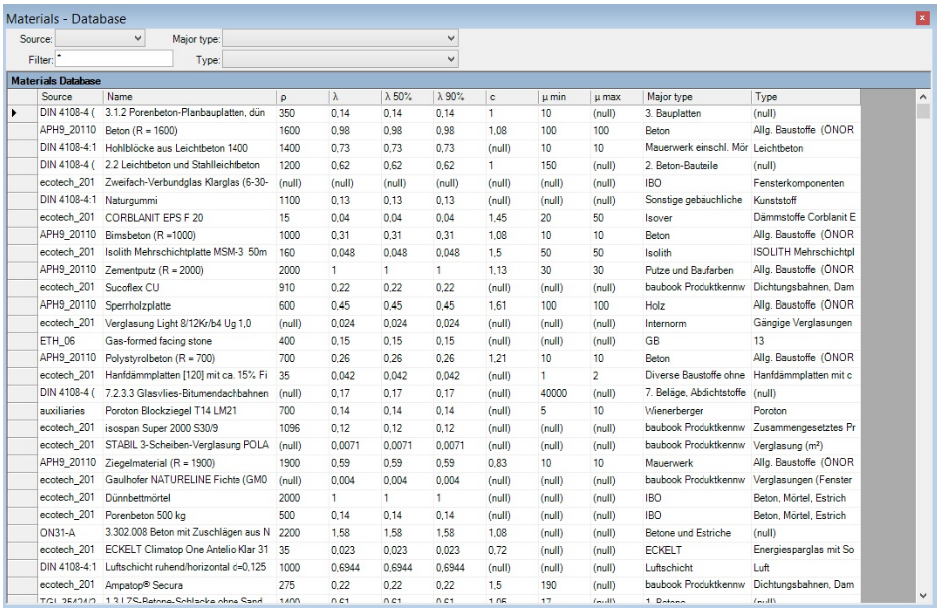


Figure 25: Flow of data using a graphical interface

2.5 Building Performance Tool

AnTherm is a software specialized in the analysis of thermal bridges and condensation risk, adopted in this research in order to inspect the constructions based on straw bales. This evaluation makes it possible to calculate the distribution of temperature, the heat streams, the vapour diffusion streams and the condensation risks within building components made of straw bales.

According to the methodology adopted, architectural elements modelled in Revit will be modelled in AnTherm as well. Here, the geometrical construction of the joints is done separately. Every component of the detail appears as a geometrical box, defined by four Cartesian coordinates X_1, X_2, Y_1 and Y_2. Each layer is then associated to a specific material. Material library includes several alternatives, classified according to thermal properties as thermal conductivity (λ), water vapour diffusion (μ), density (ρ) and specific heat (c). Choices are selected from one of the material catalogues among DIN, IBO, ISO, ONORM standards etc. In case that the material is not available in AnTherm library, it is manually created as new material and set with its specific attributes of thermal conductivity (λ) and water vapour diffusion (μ).



Materials - Database

Source: Major type:

Filter: * Type:

Materials Database

Source	Name	ρ	λ	λ 50%	λ 90%	c	μ min	μ max	Major type	Type
DIN 4108-4 (	3.1.2 Porenbeton-Planbauplatten, dün	350	0,14	0,14	0,14	1	10	(null)	3. Bauplatten	(null)
APH9_20110	Beton (R = 1600)	1600	0,98	0,98	0,98	1,08	100	100	Beton	Allg. Baustoffe (ÖNOR
DIN 4108-4:1	Hohlblöcke aus Leichtbeton 1400	1400	0,73	0,73	0,73	(null)	10	10	Mauerwerk einschl. Mör	Leichtbeton
DIN 4108-4 (	2.2 Leichtbeton und Stahlleichtbeton	1200	0,62	0,62	0,62	1	150	(null)	2. Beton-Bauteile	(null)
ecotech_201	Zweifach-Verbundglas Klarglas (6-30-	(null)	(null)	(null)	(null)	(null)	(null)	(null)	IBO	Fensterkomponenten
DIN 4108-4:1	Naturgummi	1100	0,13	0,13	0,13	(null)	(null)	(null)	Sonstige gebäuchliche	Kunststoff
ecotech_201	CORBLANIT EPS F 20	15	0,04	0,04	0,04	1,45	20	50	Isover	Dämmstoffe Corblanit E
APH9_20110	Bimsbeton (R =1000)	1000	0,31	0,31	0,31	1,08	10	10	Beton	Allg. Baustoffe (ÖNOR
ecotech_201	Isolith Mehrschichtplatte MSM-3 50m	160	0,048	0,048	0,048	1,5	50	50	Isolith	ISOLITH Mehrschichtpl
APH9_20110	Zementputz (R = 2000)	2000	1	1	1	1,13	30	30	Putze und Baufarben	Allg. Baustoffe (ÖNOR
ecotech_201	Sucoflex CU	910	0,22	0,22	0,22	(null)	(null)	(null)	baubook Produktkennw	Dichtungsbahnen, Dam
APH9_20110	Sperrholzplatte	600	0,45	0,45	0,45	1,61	100	100	Holz	Allg. Baustoffe (ÖNOR
ecotech_201	Verglasung Light 8/12Kr/b4 Ug 1,0	(null)	0,024	0,024	0,024	(null)	(null)	(null)	Internorm	Gängige Verglasungen
ETH_06	Gas-formed facing stone	400	0,15	0,15	0,15	(null)	(null)	(null)	GB	13
APH9_20110	Polystyrolbeton (R = 700)	700	0,26	0,26	0,26	1,21	10	10	Beton	Allg. Baustoffe (ÖNOR
ecotech_201	Hanfdämmplatten [120] mit ca. 15% Fi	35	0,042	0,042	0,042	(null)	1	2	Diverse Baustoffe ohne	Hanfdämmplatten mit c
DIN 4108-4 (	7.2.3.3 Glasvlies-Bitumendachbahnen	(null)	0,17	0,17	0,17	(null)	40000	(null)	7. Beläge, Abdichtstoffe	(null)
auxiliaries	Poroton Blockziegel T14 LM21	700	0,14	0,14	0,14	(null)	5	10	Wienerberger	Poroton
ecotech_201	isospan Super 2000 S30/9	1096	0,12	0,12	0,12	(null)	(null)	(null)	baubook Produktkennw	Zusammengesetztes Pr
ecotech_201	STABIL 3-Scheiben-Verglasung POLA	(null)	0,0071	0,0071	0,0071	(null)	(null)	(null)	baubook Produktkennw	Verglasung (m²)
APH9_20110	Ziegelmaterial (R = 1900)	1900	0,59	0,59	0,59	0,83	10	10	Mauerwerk	Allg. Baustoffe (ÖNOR
ecotech_201	Gaulhofer NATURELINE Fichte (GM0	(null)	0,004	0,004	0,004	(null)	(null)	(null)	baubook Produktkennw	Verglasungen (Fenster
ecotech_201	Dünnbettmörtel	2000	1	1	1	(null)	(null)	(null)	IBO	Beton, Mörtel, Estrich
ecotech_201	Porenbeton 500 kg	500	0,14	0,14	0,14	(null)	(null)	(null)	IBO	Beton, Mörtel, Estrich
ON31-A	3.302.008 Beton mit Zuschlägen aus N	2200	1,58	1,58	1,58	1,08	(null)	(null)	Betone und Estriche	(null)
ecotech_201	ECKELT Climatop One Antelio Klar 31	35	0,023	0,023	0,023	0,72	(null)	(null)	ECKELT	Energiesparglas mit So
DIN 4108-4:1	Luftschicht ruhend/horizontal d=0,125	1000	0,6944	0,6944	0,6944	(null)	(null)	(null)	Luftschicht	Luft
ecotech_201	Ampatop® Secura	275	0,22	0,22	0,22	1,5	190	(null)	baubook Produktkennw	Dichtungsbahnen, Dam

Figure 26: AnTherm materials database

Together with information concerning the architectural element, also data regarding boundary conditions are defined. Model in AnTherm requires a series of standards related to the surface resistance of the environment around the building element, both for inside (R_{si}) and outside (R_{se}). These values are regulated by the normative BS EN ISO 6946 (1997) and are effected from the direction of the heat flow. Table 4 reports values according to the scientific normative.

Table 4: Standard surface resistances coefficients (BS EN ISO 1997)

Direction of Heat Flow	R_{si} [m^2KW^{-1}]	R_{se} [m^2KW^{-1}]
Upwards	0.10	0.04
Horizontal	0.13	0.04
Downwards	0.17	0.04

Referring to the German normative DIN 4108-2 (2008), standard conditions of temperatures are -5°C for outside temperature at 80% relative humidity and +20°C for the room temperature at 50% relative humidity. In this paper, boundary conditions are rearranged to -10°C for outdoor space and +20° for indoor space.

Table 5: Temperatures and relative humidity of boundary conditions

Ambient	Temperature [°C]	Relative Humidity [%]
Indoor space	+20°C	50%
Outdoor space	-10°C	80%

It is significant to underline that AnTherm is a rectangular-modelling software, not capable of modelling slope or curved lines but only rectangular shaped objects. Details simulated in this research present only joints parallel to X and Y-axes. The only two scenarios that involve slope lines regard the models of the wall-roof junctions. In those cases it is adopted the methodology presented by Tim Ward and Chris Sanders in the BRE's Information Paper "Conventions for calculating linear thermal transmittance and temperature factors" (2006). The process elucidated from the authors involves the approximation of a slope line by a series of steps. As explained, the slope element can be subdivided into rectangles parallel to X and Y-axes, determined taking into account the angle of the sloping part. The step size does not require the same measurements and can present larger o smaller dimensions than an adjacent step. It is therefore important that, for a correctness of the model, the intersecting line divides each step into two equal triangles, placed one on the upper part and one on the lower part of the line itself. Figure 27 illustrates the method described and figure 28 shows a particular of the stepping arrangement made in AnTherm.

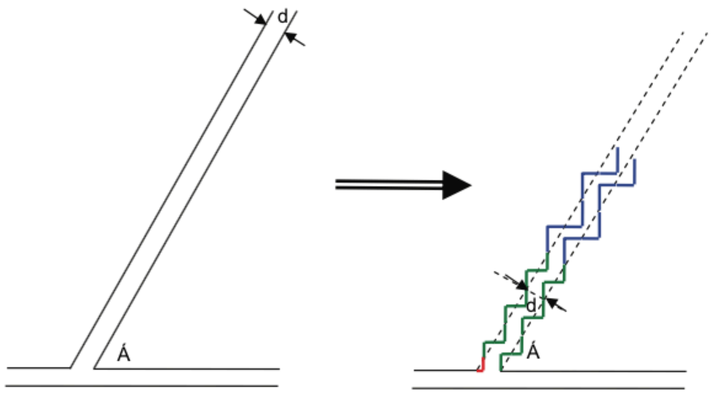


Figure 27: Stepping of slope for rectangular modelling software (Ward 2006)

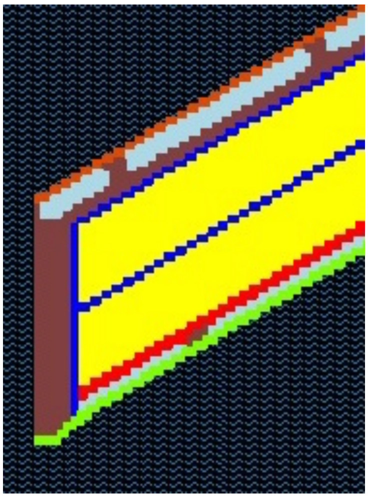


Figure 28: Stepping arrangement in AnTherm, particular of the roof

3 RESULTS AND DISCUSSION

In this section results of the work are presented. The chapter includes processing activities implemented both in Revit and AnTherm. For each detail are here displayed a specific list of materials that build up the element, along with their thermal properties, the Revit model and outputs generated after the thermal simulation made in AnTherm.

AnTherm provides a series of different outputs for the thermal evaluation. Important values that are taken into account for this research are low interior surface temperature (θ_{min}), temperature factor (f_{Rsi}), thermal coupling coefficient (L_{2D}) and linear thermal transmittance (ψ-value). All of them are listed and compared between the different scenarios. AnTherm also generates a graphical visualization of the following outcomes through a specific detail:

- Temperature
- Heat Flux
- Saturation vapor
- Partial pressure
- Pressure difference
- Relative humidity
- Vapor flux
- Condensation, mould and corrosion risk

For what concerns this paper, as visual outcomes are here presented: temperature, heat flux and pressure difference.

As stated before, after the collection and the investigation phase, it is determined that a total of 12 varying details are examined in this paper: 2 different variants for each of the 4 joints of the building plus 4 sections of a basic wall, built up of dissimilar materials. Table 6 offers a general overview of the different scenarios examined.

Table 6: Overview of different scenarios

Scenario	Detail	Description
Scenario A	Basic Wall	Basic wall made of straw, wooden beams, OSB, clay plaster
Scenario B	Basic Wall	Ventilated wall made of straw, timber panels, OSB, wood fiberboard, clay plaster
Scenario C	Basic Wall	Ventilated wall with timber panels, straw bales, wooden formworks, vapour barrier, gypsum board
Scenario D	Basic Wall	Variant of scenario C, adding layers of wood fiberboard and OSB
Scenario D-1	Wall-foundation junction	Wall Scenario D + Foundation slab in concrete
Scenario D-2	Wall-foundation junction	Wall Scenario D + Foundation slab in straw as insulation material
Scenario D-3	Wall-slab junction	Wall Scenario D + Slab made up of a concrete plate
Scenario D-4	Wall-slab junction	Wall Scenario D + Slab made up of wooden beams with straw bales as insulation
Scenario D-5	Wall-roof junction	Wall Scenario D + Roof with a double insulation layer made of straw, interspersed with wooden beams
Scenario D-6	Wall-roof junction	Wall Scenario D + Roof with a single insulation layer made of straw
Scenario D-7	Opening	Wall Scenario D + Window located in the middle of the opening
Scenario D-8	Opening	Wall Scenario D + Window located at the external edge of the wall

3.1 Basic wall made of Straw Bales

Before starting with the thermal simulation of the major joints, four different basic walls made of straw bales are analyzed. This investigation is considered appropriate insofar as it involves different construction methods of a simple wall made of straw bales. The aim is defining among these options, the suitable wall for the other details.

Simulated typologies are divide into four scenarios:

- Scenario A: basic wall with a thickness of 537 mm, made up of straw bales interspersed with wooden beams and an Oriented Strand Board, all coated with clay plaster inside and ordinary plaster outside.
- Scenario B: ventilated wall, coated inside with a clay plaster plate and outside with timber panels. Here straw bales are placed without being interrupted by the wooden beams. Material layers include also an Oriented Strand Board and a wood fiberboard. The total thickness is 472 mm.
- Scenario C: ventilated wall of 498 mm that involves straw bales interspersed with wooden beams, two layers of ventilation with battens, two layers of wooden formworks, a vapour barrier and a wind barrier. Cladding is made of a gypsum board inside and of timber panels outside.
- Scenario D: addition of variants using wall of scenario C as base. The improvement consists in placing a wood fiberboard between the layers of straw bales, having only one layer of ventilation, removing the wind barrier and adding an Oriented Strand Board. The total thickness is 540 mm.

Figures 29 to 32 display every single scenario from A to D modeled in Revit. Here, along with the geometrical configuration, each layer of each detail is associated to a specific material with its thermal properties as thermal conductivity (λ), specific heat (c) and density (ρ). Tables from 7 to 10 illustrate the list of materials that build up each element with all its related parameters.

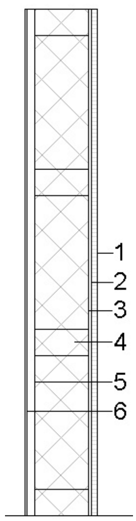


Figure 29: Autodesk Revit model of scenario A of basic wall detail

Table 7: Material properties of scenario A of basic wall detail

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Clay Plaster	45	0.9	9	1580	880
2 Oriented Strand Board	22	0.12	50	640	2100
3 Straw Bales	400	0.05	3	150	1800
4 Wooden Beam	400	0.14	30	350	2100
5 Particle Board	60	0.042	3	160	1700
6 Plaster	10	0.7	10	1400	880

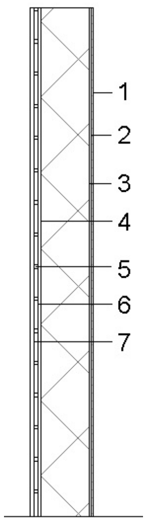


Figure 30: Autodesk Revit model of scenario B of basic wall detail

Table 8: Material properties of scenario B of basic wall detail

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Clay Plaster Plate	20	0.47	5	1200	880
2 Oriented Strand Board	15	0.12	50	640	1700
3 Straw Bales	360	0.049	4	101	1800
4 Particle Board	22	0.10	11	600	1700
5 Wooden Battens	30	0.12	50	500	1700
6 Ventilation layer – Air	-	0.20	1	1	1000
7 Timber	25	0.17	50	700	2100

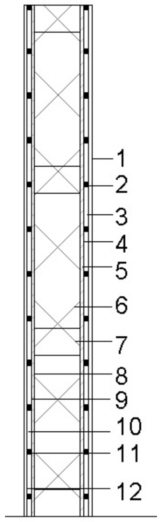


Figure 31: Autodesk Revit model of scenario C of basic wall detail

Table 9: Material properties of scenario C of basic wall detail

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Gypsum Board	30	0.27	10	1180	1000
2, 11 Wooden Battens	30	0.12	50	500	1700
3, 10 Ventilation layer – Air	-	0.194	1	1	1000
4 Vapour Barrier	2	0.5	1000	980	2200
5, 8 Wooden Formwork	24	0.12	50	450	2100
6 Straw Bales	340	0.049	4	101	1800
7 Wooden Beam	340	0.12	50	500	1700
9 Wind Barrier	2	0.5	100	980	2200
12 Timber	20	0.17	50	700	2100

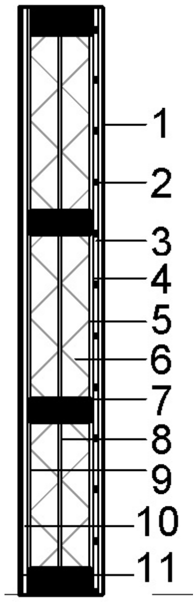


Figure 32: Autodesk Revit model of scenario D of basic wall detail

Table 10: Material properties of scenario D of basic wall detail

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Gypsum Board	30	0.27	10	1180	1000
2 Wooden Battens	30	0.12	50	500	1700
3 Ventilation layer – Air	-	0.194	1	1	1000
4 Vapour Barrier	2	0.5	1000	980	2200
5, 9 Wooden Formwork	24	0.12	50	450	2100
6 Straw Bales	360	0.05	4	101	1800
7 Wooden Beam	360	0.12	50	500	1700
8 Wood Fiberboard	20	0.10	10	400	1700
10 Oriented Strand Board	30	0.12	50	640	1700
11 Timber	20	0.17	50	700	2100

Outcomes from AnTherm start with the temperature analysis. Figures from 33 to 36 show for each of the four different scenarios the simulation model and a graphical visualization of the temperature through the profile. As defined in paragraph 2.5, boundary conditions set are +20°C at 50% relative humidity inside and -10°C at 80% relative humidity outside. From the graphical outputs, it can be observed that the minimum interior surface temperature does not suffer a significant decrease considering the inside temperature at 20°C. Moreover, values of the different cases are not dissimilar among them. The highest value can be found in scenario B with θ_{min}= 19.52°C and the lowest value in scenario C, with θ_{min}= 19.04°C. Scenarios

A and D have the same value of θ_{min}= 19.19°C. For what concerns the temperature factor f_{Rsi}, in all simulated walls it meets the requirement of being above the critical factor of 0.70. Respectively it is f_{Rsi}= 0.97 for scenarios A, C and D and f_{Rsi}= 0.98 for scenario B.

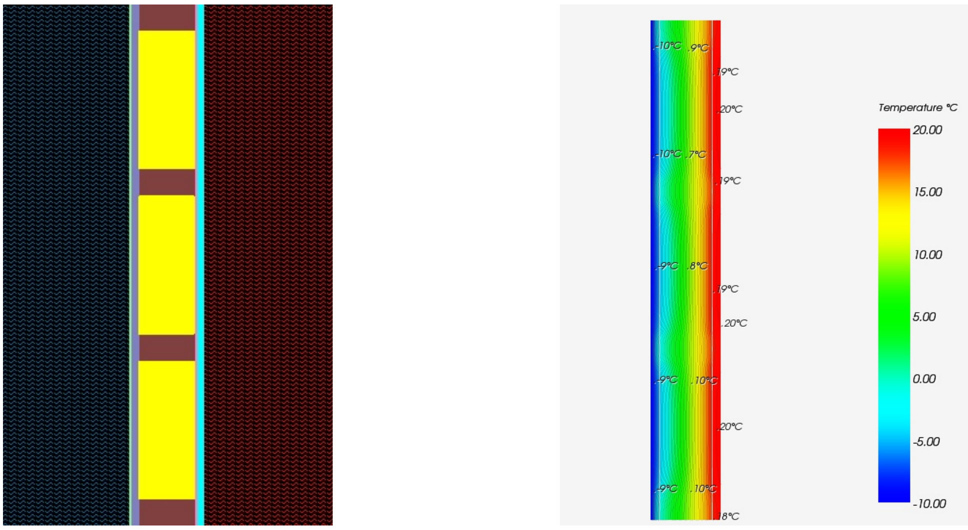


Figure 33: Simulation model and temperature profile of scenario A of basic wall detail

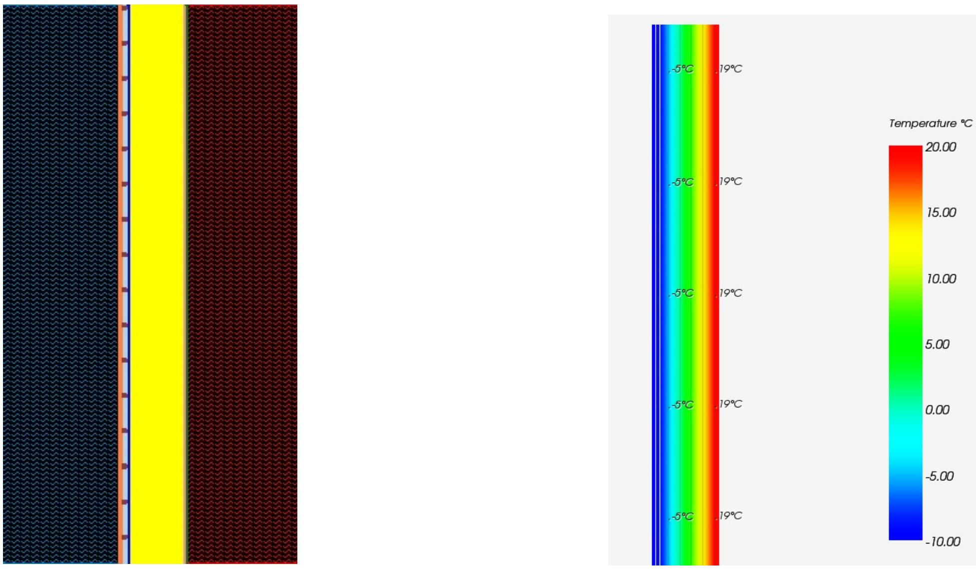


Figure 34: Simulation model and temperature profile of scenario B of basic wall detail

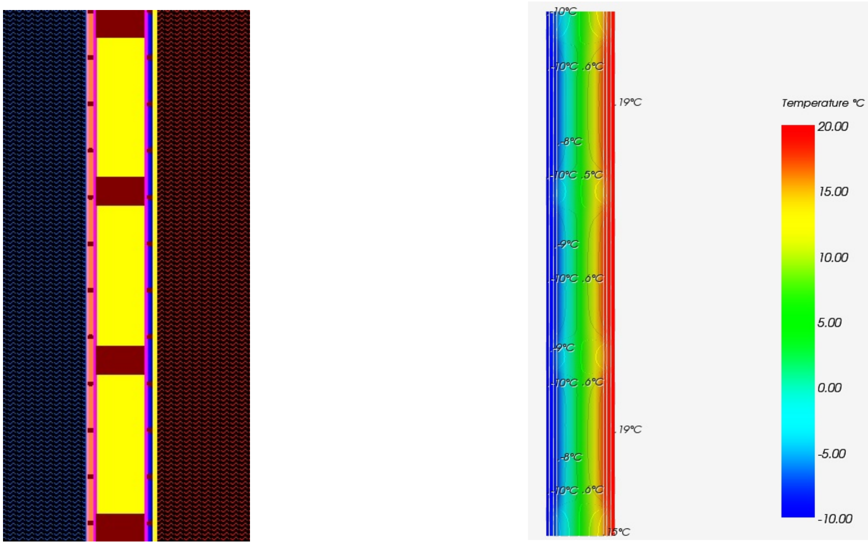


Figure 35: Simulation model and temperature profile of scenario C of basic wall detail

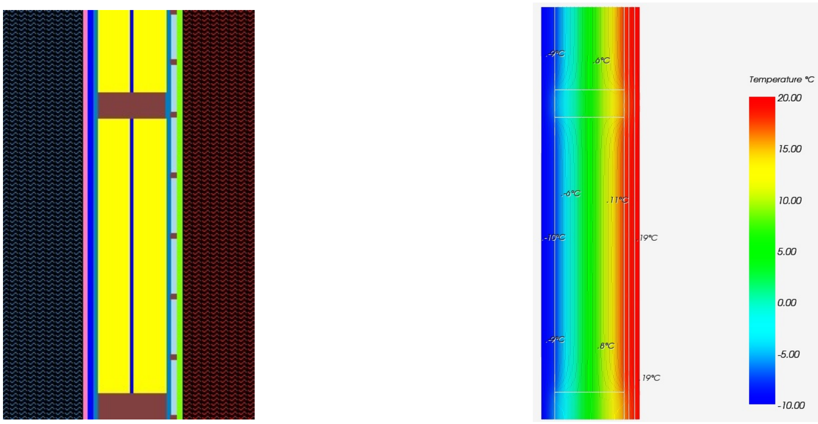


Figure 36: Simulation model and temperature profile of scenario D of basic wall detail

The subsequent evaluation regards the amount of heat that flows through the profile. As it can be noted in figures 37-40, the four cases present a low quantity of heat flux from the inside space to the outside space. This factor is due to the high thermal properties of straw and its strong insulation. Scenario A, C and D show a general uniform heat flux that increases at the points of the wooden beams that intersect straw bales. However, it is an inconsistent increment of about 3 Wm^{-2} that does not affect in a negative way the thermal performance of the walls. Scenario B, instead, has a more homogeneous profile, where straw bales are not divided by any other element, factor that determinates an almost constant flow of 4 Wm^{-2}. As happened with the heat flux, also U-values present low quantities that indicate a good energy performance of the walls. Table 11 illustrates the amount of U-value for each case. Scenario A and D manifest the lower value, equal to U= 0.11 $Wm^{-2}K^{-1}$.

Images from 37 to 40 also offer information concerning the pressure difference of each wall. Scenarios A, B and C do not present negative values related to condensation risk. Scenario D on the other hand, shows values from 0.29 hPa to -2.94 hPa only on the external side of the wall, exposed to -10°C. It is important to consider that for all cases condensation risk and mould growth are not contemplated, since the temperature factor f_{Rsi} has values above the critical value of 0.70.

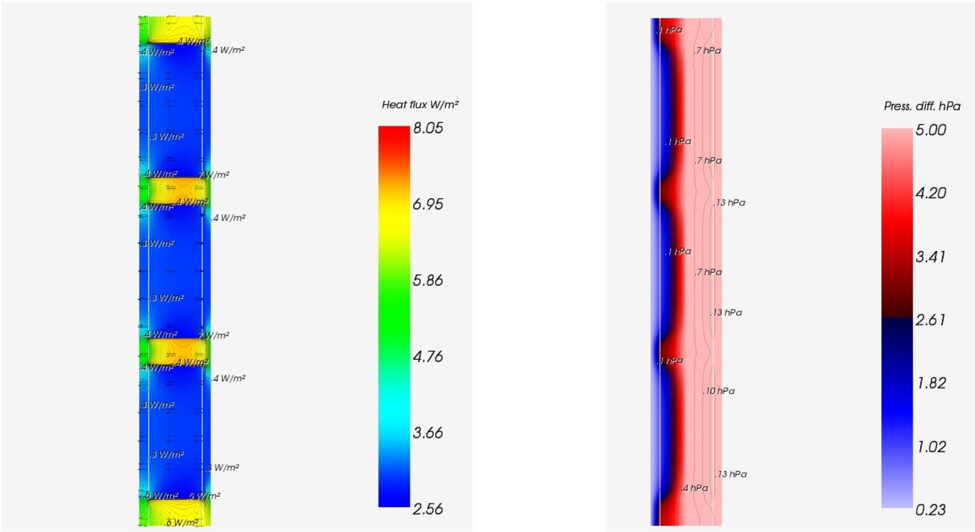


Figure 37: Heat flux and pressure difference of scenario A of basic wall detail

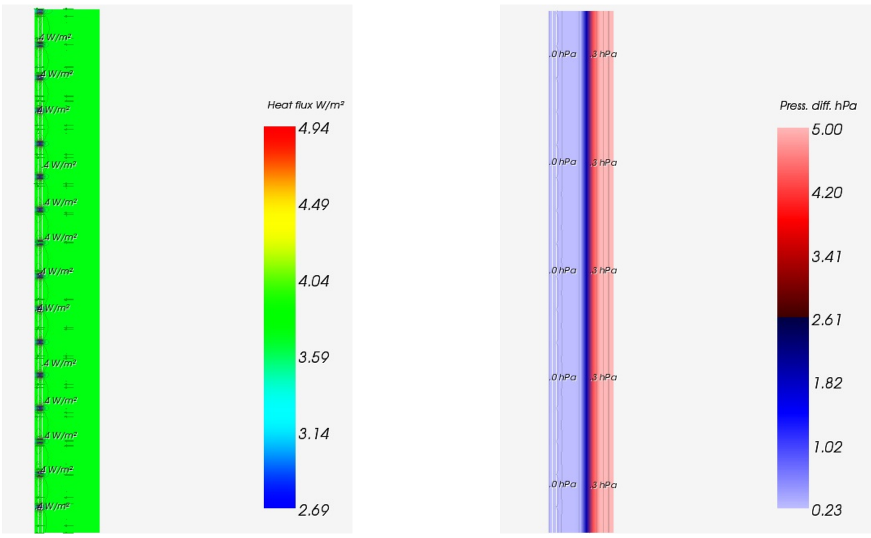


Figure 38: Heat flux and pressure difference of scenario B of basic wall detail

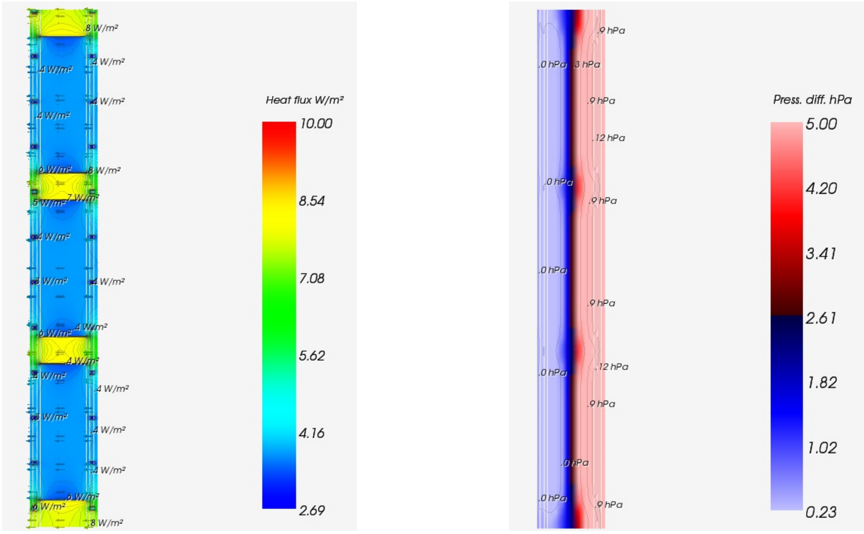


Figure 39: Heat flux and pressure difference of scenario C of basic wall detail

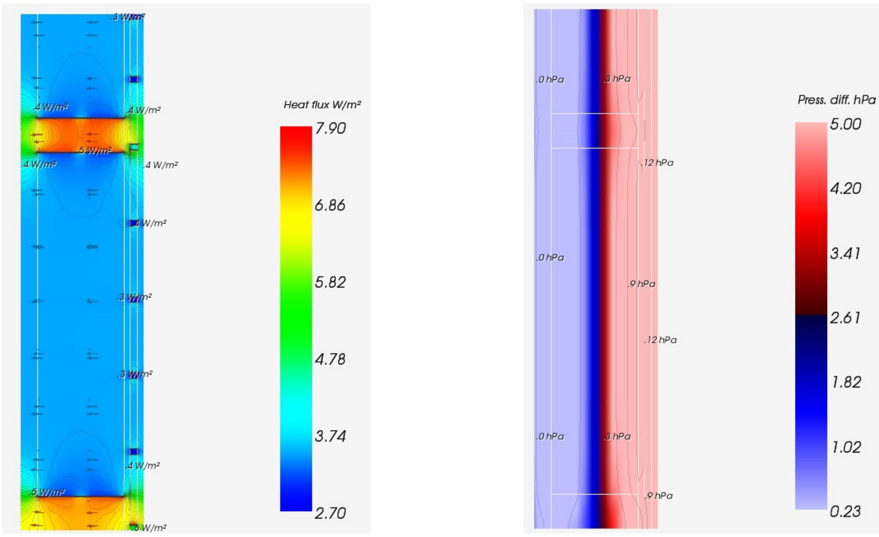


Figure 40: Heat flux and pressure difference of scenario D of basic wall detail

Table 11: Output values of different scenarios

	d [mm]	U-value [$Wm^{-2}K^{-1}$]	θ_{min} [°C]	f_{Rsi} [-]
Scenario A	537	0.11	19.19	0.97
Scenario B	472	0.13	19.52	0.98
Scenario C	498	0.14	19.04	0.97
Scenario D	540	0.11	19.19	0.97

Results of the case studies analysed, provide an interesting general overview of the energy performance of different wall made of straw bales. Indeed, all U-values reached are < 0.15 $Wm^{-2}K^{-1}$, standard set by the Passive House Institute. Among them, scenario D is selected as the most complete and most widely used. This typology of wall will be adopted as basic wall for the major joints, examined in the following steps.

3.2 Wall – foundation junction

The first joint simulated with the aim of evaluating thermal bridges, is the junction between the wall and the foundation. For the energy evaluation, two different cases are taken into consideration. The cases involved present the same external wall, identified as the scenario D previously analyzed, and the same foundation made of concrete. The major difference consists in the foundation slab, made up of different materials. It is important to specified that a typical building made of straw bales is generally raised from the ground in a range from 225 mm to 450 mm, in a way to create a ventilated space between the ground and the slab. Consequently, in both of the cases here tested, the slab is in contact with an unheated space and not directly with the ground.

Simulated cases are divided into two scenarios:

- Scenario D-1: foundation slab adopts concrete as main material also with an OSB plate and a natural insulation as cork.
- Scenario D-2: foundation slab includes the use of straw as insulation material and cellular glass as final material on the exterior side.

Figures 41 and 42 show the profiles modeled in Revit, where are already set thermal conductivity (λ), specific heat (c) and density (ρ). Tables 12 and 13 illustrate the list of materials that build up the junctions and the related properties.

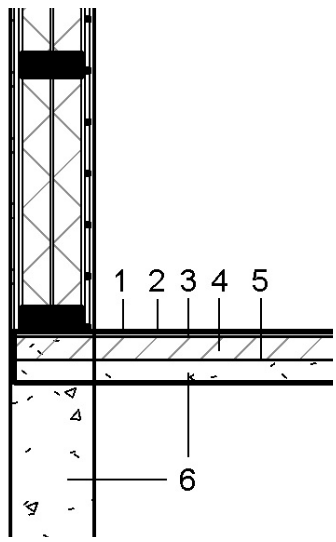


Figure 41: Autodesk Revit model of scenario D-1 of wall-foundation junction

Table 12: Material properties of scenario D-1 of wall-foundation junction

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Wood Flooring	10	0.20	30	800	1700
2 Oriented Strand Board	20	0.12	50	640	1700
3, 5 Vapour Barrier	10	0.5	1000	980	2200
4 Cork insulation	140	0.05	10	100	1560
6 Concrete	140	2.3	130	2300	1000

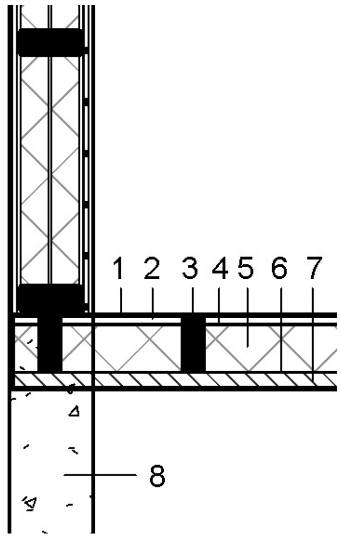


Figure 42: Autodesk Revit model of scenario D-2 of wall-foundation junction

Table 13: Material properties of scenario D-2 of wall-foundation junction

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Wood Flooring	14	0.20	30	800	1700
2 Screed	40	0.11	6	480	1500
3 Wooden Beam	300	0.12	50	500	1700
4, 6 Vapour Barrier	10	0.5	1000	980	2200
5 Straw Bales	300	0.05	4	101	1800
7 Cellular Glass	100	0.052	100000	140	840

As first result from AnTherm, temperature profile is visualized, as shown in figures 43-44. Boundary conditions are defined, as before, with an interior temperature of +20°C and an exterior temperature of -10°C. From the graphical outcomes it is visible that there is a gradual temperature decrease at the points of the junction between the wall and the foundation. This factor locates the minimum interior surface temperature for both scenarios, exactly in the corner of the joint. However, conditions of the two cases are different. Indeed, on one side in scenario D-1 the minimum interior surface temperature decreases to θ_{min}= 15.32°C, instead on the other side, scenario D-2 does not show a substantial influence from variation of the temperature at the junction and preserves a good value for minimum interior surface temperature equal to θ_{min}= 18.28°C. Regarding the temperature factor f_{Rsi}, it is equal to f_{Rsi}= 0.84 for scenario D-1 and to f_{Rsi}= 0.94 for scenario D-2. Then, in both cases it is satisfied the requirement of being above the critical value of 0.70.

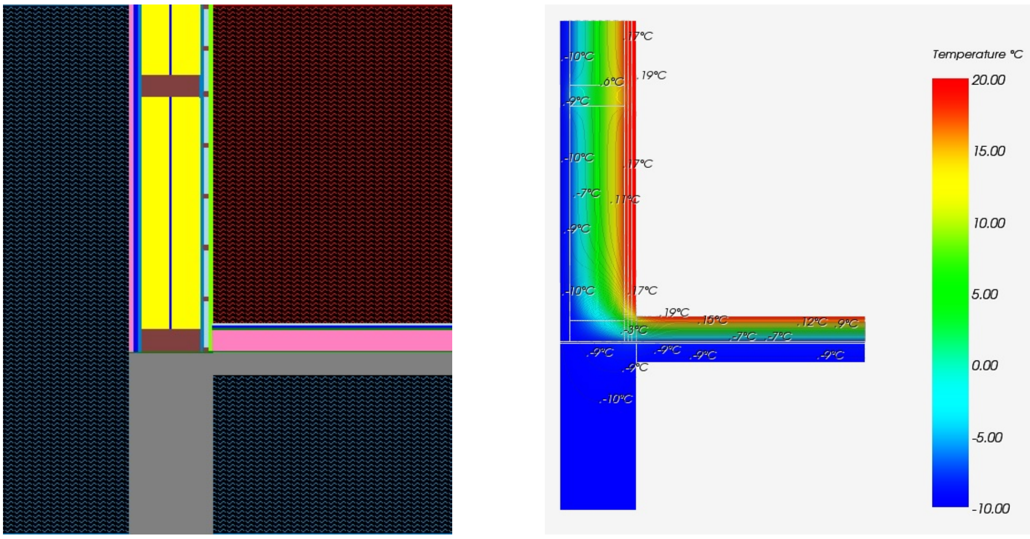


Figure 43: Simulation model and temperature profile of scenario D-1 of wall-foundation junction

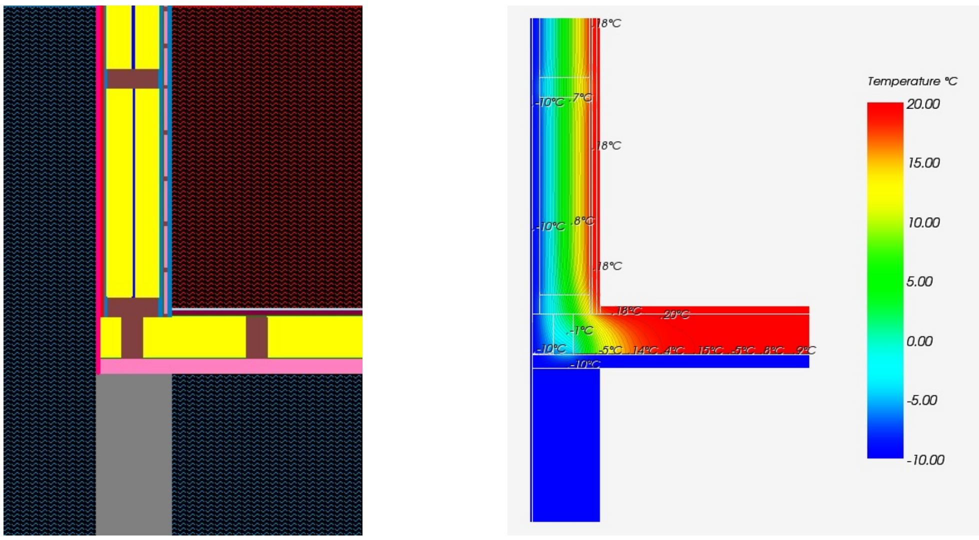


Figure 44: Simulation model and temperature profile of scenario D-2 of wall-foundation junction

The following simulation concerns the amount of heat that flows through the junctions. As it can be observed from the graphical outputs in figures 45 and 46, the two cases reveal a different energy performance. Scenario D-1, built up with a concrete plate, presents a higher dispersion of heat from the interior space to the exterior space, with a peak of 45 Wm^{-2}.

Scenario D-2, instead with the addition of straw bales in the slab, reveals a lower and constant flux of heat through the profile with no critical points at the corner of the joint. Table 14 illustrates ψ-value for each of the details. Scenario D-1 presents a good thermal performance of the junction with a linear thermal transmittance lower than the gold standard 0.01 $Wm^{-1}K^{-1}$ set by the Passive House Institute, with a value of ψ= -0.159 $Wm^{-1}K^{-1}$ and a total heat that flows through the two-dimensional junction equal to L_{2D}= 0.33 $Wm^{-1}K^{-1}$. Figures 45 and 46 highlight also the pressure difference of the two joints. Visual outcomes, even with different profiles, demonstrate for the two scenarios the absence of risk related to condensation and mould verified also by the temperature factor f_{Rsi} that, in both cases, is above 0.70.

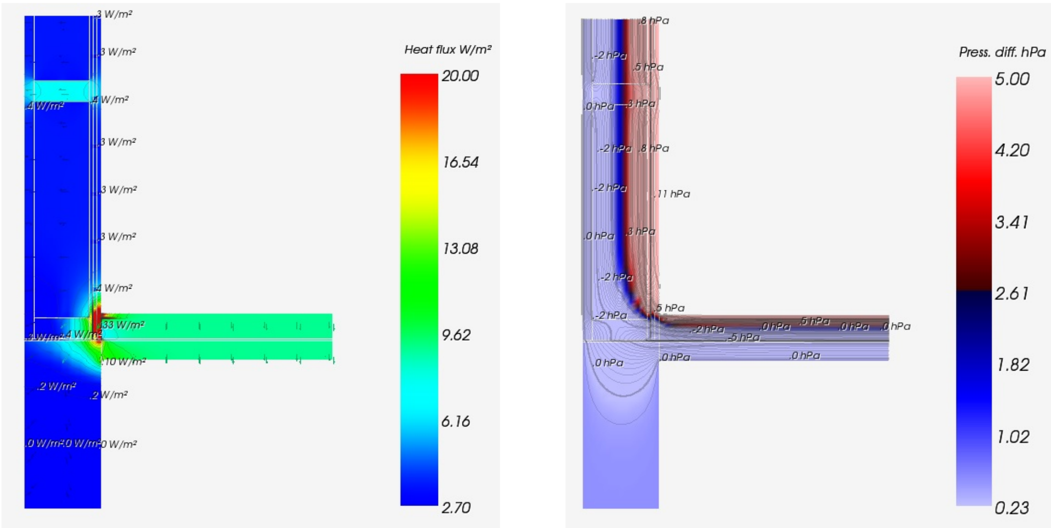


Figure 45: Heat flux and pressure difference of scenario D-1 of wall-foundation junction

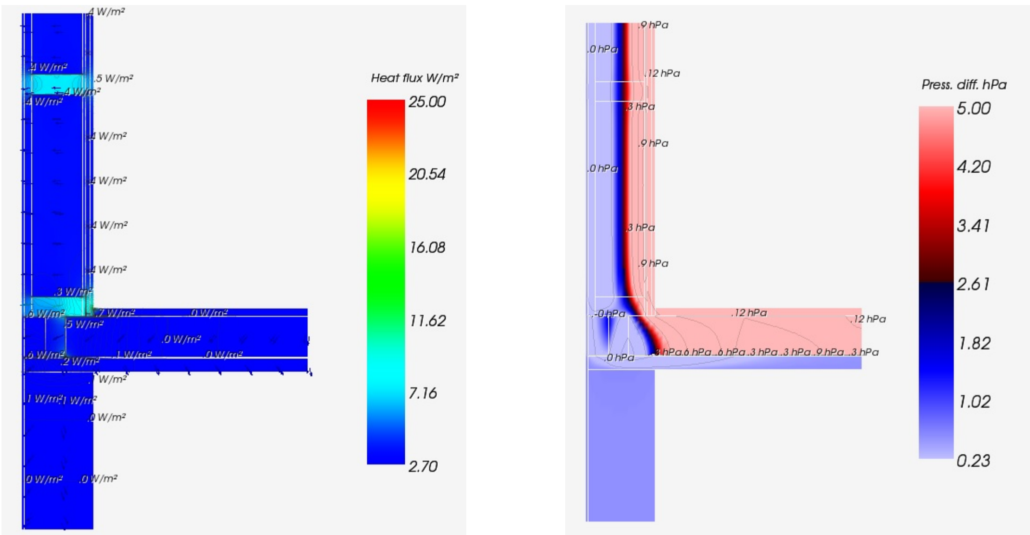


Figure 46: Heat flux and pressure difference of scenario D-2 of wall-foundation junction

Table 14: Output values of different scenarios of wall-foundation junction

	L_{2D} [$Wm^{-1}K^{-1}$]	ψ-value [$Wm^{-1}K^{-1}$]	θ_{min} [°C]	f_{Rsi} [-]
Scenario D-1	0.85	0.127	15.32	0.84
Scenario D-2	0.33	-0.159	18.28	0.94

3.3 Wall – slab junction

The second joint simulated concerns the junction between the wall and the slab. For a proper thermal analysis, two different scenarios are selected. The details consist of the same external wall tested previously in paragraph 3.1 as scenario D and a slab that divides two inner spaces. Also here, the major difference is identified in the materials that build up the two slabs. In both cases the slab is located inside the structure and it is therefore in contact with two heated areas at the temperature of 20°C.

Scenarios simulated are classified into two distinct cases:

- Scenario D-3: slab made up of a concrete plate and a cork insulation layer
- Scenario D-4: slab made up of wooden beams with straw bales as insulation layer and the addition of a plywood layer, a wood fiberboard and an OSB plate

A considerable dissimilarity among the two details is the thickness. This factor is due to the many different layers present in the slab made of straw bales and in the thickness of the bales themselves.

Revit models are shown in figures 47 and 48. The architectural details here bring with them thermal attributes as thermal conductivity (λ), specific heat (c) and density (ρ). Tables 15 and 16 list thermal properties for each material present in the detail.

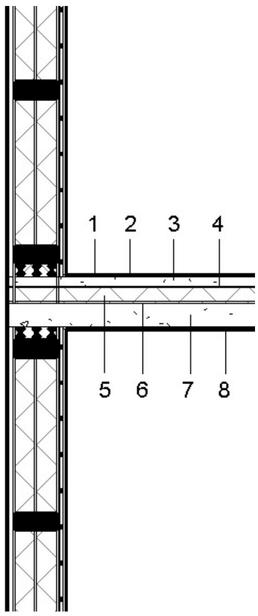


Figure 47: Autodesk Revit model of scenario D-3 of wall-slab junction

Table 15: Material properties of scenario D-3 of wall-slab junction

	d [mm]	**λ** [Wm^{-1}K^{-1}]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [Jkg^{-1}K^{-1}]
1 Wood Flooring	16	0.20	30	800	1700
2 Cork insulation	4	0.05	20	180	1500
3 Screed	80	0.11	6	480	1500
4 Vapour Barrier	10	0.5	1000	980	2200
5 Mineral Wool	130	0.035	1	100	1030
6 Cork insulation	20	0.05	10	100	1560
7 Concrete	220	2.3	130	2300	1000
8 Plaster	20	0.8	10	1400	880

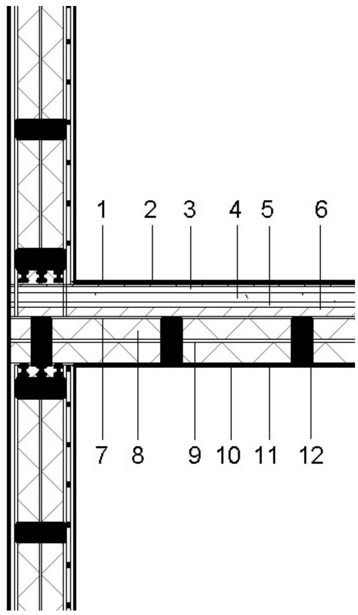


Figure 48: Autodesk Revit model of scenario D-4 of wall-slab junction

Table 16: Material properties of scenario D-4 of wall-slab junction

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Wood Flooring	20	0.20	30	800	1700
2 Plywood	20	0.13	200	500	1600
3 Wood Fiberboard	54	0.12	50	500	2100
4 Screed	76	2	50	1700	910
5 Vapour Barrier	40	0.5	1000	980	2200
6 Cork insulation	80	0.05	10	180	1500
7, 10 Oriented Strand Board	16	0.12	50	640	1700
8 Straw Bales	340	0.05	4	105	1800
9 Wood Fiberboard	20	0.10	10	400	1700
11 Gypsum Board	6	0.27	10	1180	1000
12 Wooden Beam	360	0.12	50	500	1700

After the end of the simulation, the first outcomes displayed regard the temperature profile of both scenarios. As for the details tested before, boundary conditions are defined here with an interior temperature of +20°C and an exterior temperature of -10°C. Figures 49 and 50 illustrate a gradual alteration of the temperature at the points of the joints, higher in the profile of the scenario D-3. This circumstance leads the minimum interior surface temperature in scenario D-3 to θ_{min}= 14.45°C. Scenario D-4 instead, does not suffer a significant variation of temperature in junction and presents an high value of minimum interior surface temperature, equal to θ_{min}= 18.60°C. For what concerns the temperature factor f_{Rsi}, in both cases simulated it meets the requirement of being above the critical factor of 0.70. Respectively it is f_{Rsi}= 0.82 for scenario D-3 and f_{Rsi}= 0.95 for scenario D-4.

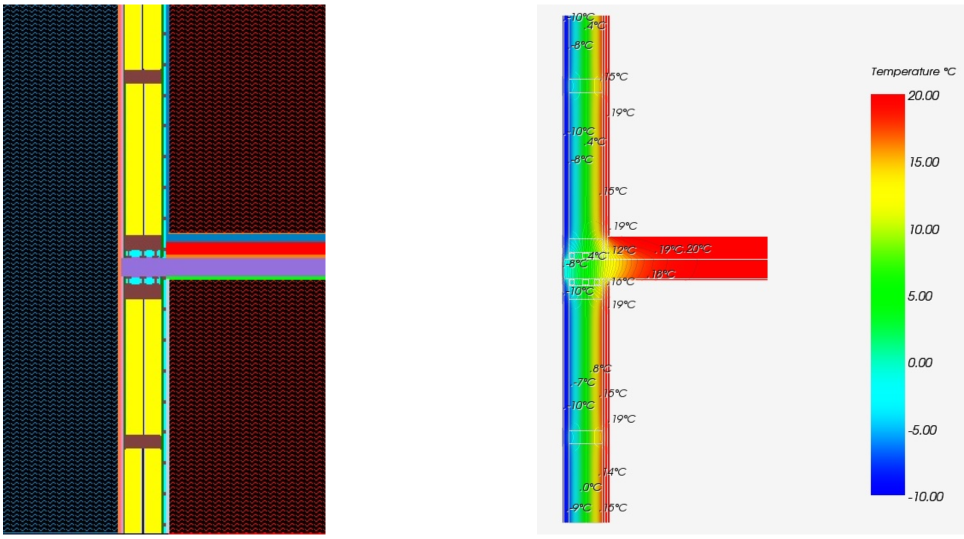


Figure 49: Simulation model and temperature profile of scenario D-3 of wall-slab junction

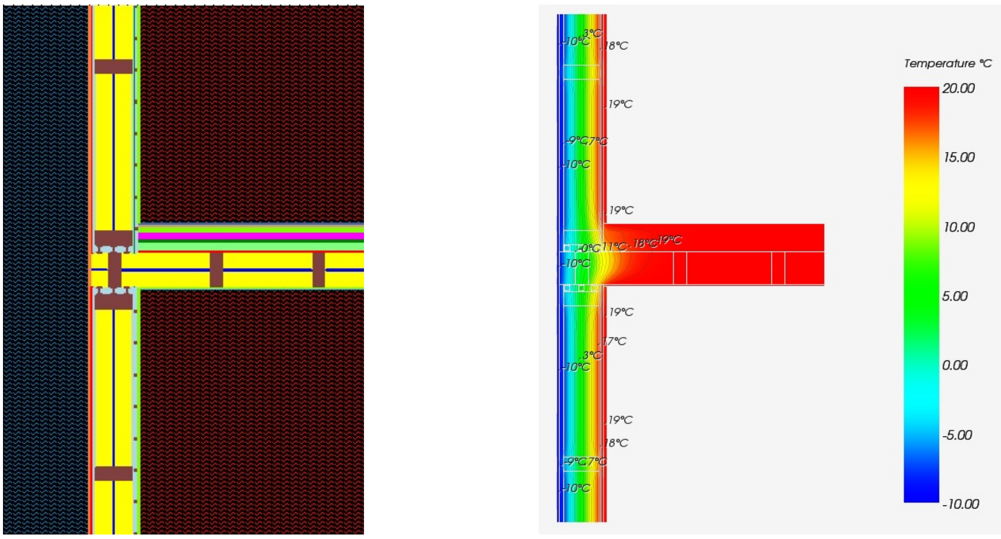


Figure 50: Simulation model and temperature profile of scenario D-4 of wall-slab junction

The next outcomes generated after the simulation regard the heat flux through the profiles. It can be easily noted in the graphical outputs in figures 51 and 52 that the two details present a substantial difference in the energy performance of the junction. Indeed, scenario D-3 built up with a concrete plate, displays a higher amount of heat loss through the wall-slab joint, with peak of heat flux equal to 95 Wm^{-2}. Scenario D-4, on the other hand, reveals a more homogeneous heat flow through the joint with an average of 6 Wm^{-2} and a highest point of 30 Wm^{-2}. Table 17 illustrates ψ-value and thermal coupling coefficient (L_{2D}) value for both scenarios. Even here it is clear the considerable dissimilarity of the energy performance of the two cases. Indeed, in scenario D-3 the linear thermal transmittance presents an unsatisfactory value equal to ψ= 0.527 $Wm^{-1}K^{-1}$. Scenario D-4, conversely, manifests a consistent decreased value equal to ψ= 0.093 $Wm^{-1}K^{-1}$. The reached value highlights an efficient performance of the junction comparing it with a research conducted by ASHRAE that defines the average linear thermal transmittance of a slab intersection with an external insulated concrete block wall, around ψ= 0.570 $Wm^{-1}K^{-1}$ (2011). Images 51-52 also reveal the pressure difference of the two profiles. Graphical results demonstrate that profiles do no present risk of condensation or mould on the interior surfaces, proved also by the temperature factor f_{Rsi} that, for both cases, has positive results, being higher than 0.70

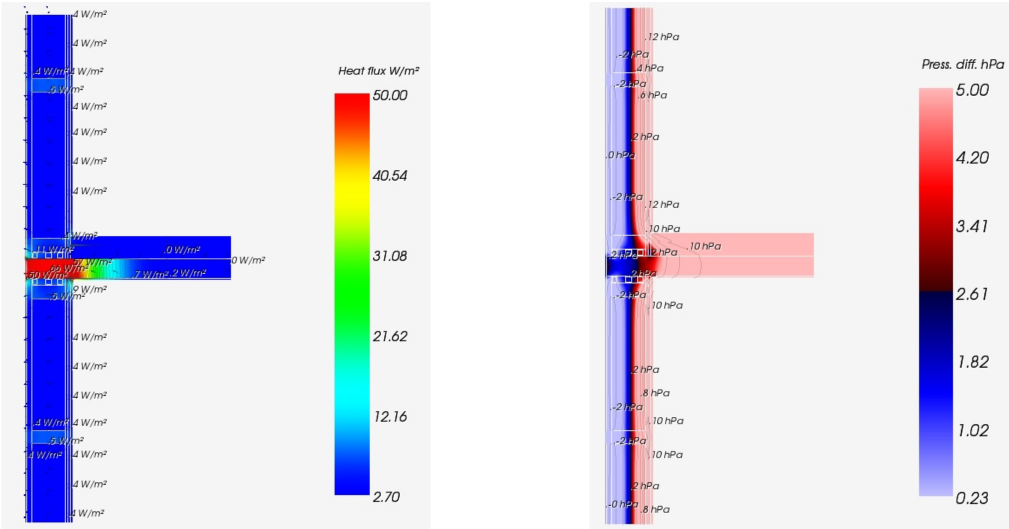


Figure 51: Heat flux and pressure difference of scenario D-3 of wall-slab junction

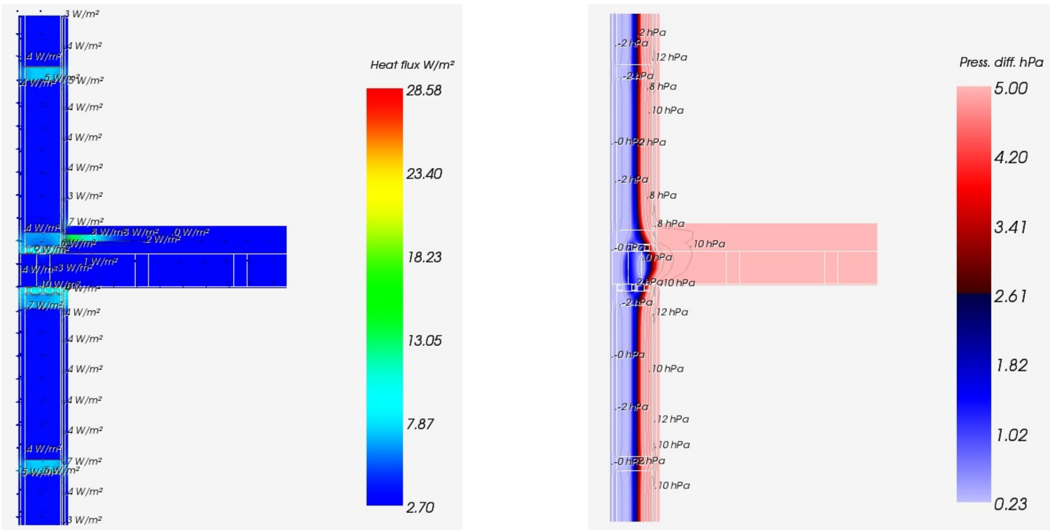


Figure 52: Heat flux and pressure difference of scenario D-4 of wall-slab junction

Table 17: Output values of different scenarios of wall-slab junction

	L_{2D} [$Wm^{-1}K^{-1}$]	ψ-value [$Wm^{-1}K^{-1}$]	θ_{min} [°C]	f_{Rsi} [-]
Scenario D-3	1.19	0.527	14.45	0.82
Scenario D-4	0.73	0.093	18.60	0.95

3.4 Wall – roof junction

The further details simulated regard the junction between the wall and the roof. Also in this case, two different scenarios are contemplated for the simulation. As in the previous joints evaluated, the external wall is identified with scenario D of the walls simulated in paragraph 3.1. In both cases the roof presents an external layer that involves the use of natural roof tiles made of clay and an insulation layer made of straw and both cases do not implicate the use of concrete. Nevertheless, the significant difference among the two junctions consists in the stratum of the straw, arranged observing two various techniques.

More specifically, the two cases taken into account are the following:

- Scenario D-5: the roof presents a double insulation layer made of straw, containing a layer of wood fiber board in between, interspersed with wooden beams
- Scenario D-6: the roof presents only a single insulation layer made of straw with the absence of wooden beams, but with a structure made of battens and rafters

A notable difference among the two details is the thickness of the roof. Indeed, scenario D-5 displays a major thickness in the layer of the straw, equal to 576 mm. Scenario D-6, instead, manifests a layer of the straw equal to 250 mm and a total thickness of the roof of 406 mm.

Figures 53 and 54 show the two profiles modeled in Revit, where are already set thermal conductivity (λ), specific heat (c) and density (ρ). Tables 18-19 illustrate the list of materials that build up the junctions and the related properties.

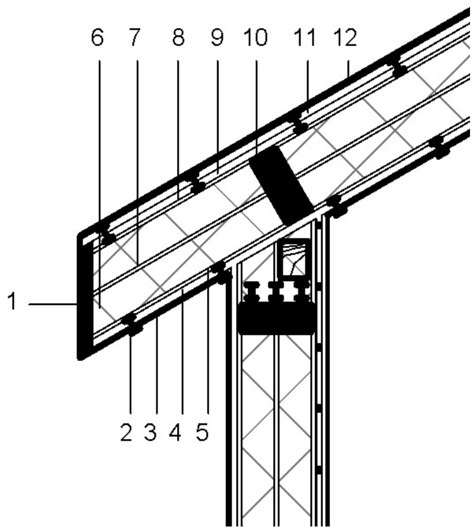


Figure 53: Autodesk Revit model of scenario D-5 of wall-roof junction

Table 18: Material properties of scenario D-5 of wall-roof junction

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Wood	50	0.12	50	500	1700
2 Wooden Battens	40	0.12	50	500	1700
3 Gypsum Board	16	0.27	10	1180	1000
4, 11 Ventilation layer – Air	40	0.194	1	1	1000
5 Oriented Strand Board	20	0.12	50	640	1700
6 Straw Bales	360	0.05	4	105	1800
7, 8 Wood Fiberboard	20	0.10	10	400	1700
9 Wooden Rafters	40	0.12	50	500	1700
10 Wooden Beam	360	0.12	50	500	1700
12 Clay Roof Tiles	20	1	40	2000	800

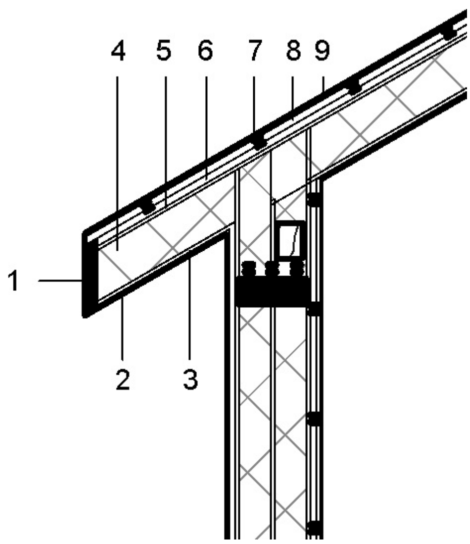


Figure 54: Autodesk Revit model of scenario D-6 of wall-roof junction

Table 19: Material properties of scenario D-6 of wall-roof junction

	d [mm]	**λ** [$Wm^{-1}K^{-1}$]	**μ** [-]	**ρ** [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
1 Wood	50	0.12	50	500	1700
2 Gypsum Board	16	0.27	10	1180	1000
3 Oriented Strand Board	20	0.12	50	640	1700
4 Straw Bales	250	0.05	4	105	1800
5 Wood Fiberboard	20	0.10	10	400	1700
6 Wooden Formwork	40	0.12	50	450	2100
7 Wooden Battens	40	0.12	50	500	1700
8 Ventilation layer – Air	-	0.194	1	1	1000
9 Clay Roof Tiles	20	1	40	2000	800

First graphical results generated from AnTherm regard the temperature profile of the two details. As in the junctions previously simulated, boundary conditions are set to +20°C at 50% relative humidity in the interior space and -10°C at 80% relative humidity in the exterior space. Reports produced at the end of the simulation, evidence a total dissimilarity of the temperature profiles. Indeed, scenario D-5 does not show a significant variation of temperature and the minimum interior surface temperature presents a high value of θ_{min}= 18.50°C. Conversely, scenario D-6 suffers a consistent variation of temperature that leads the minimum interior surface temperature to θ_{min}= 11.18°C and represents an important decrease of the indoor conditions.

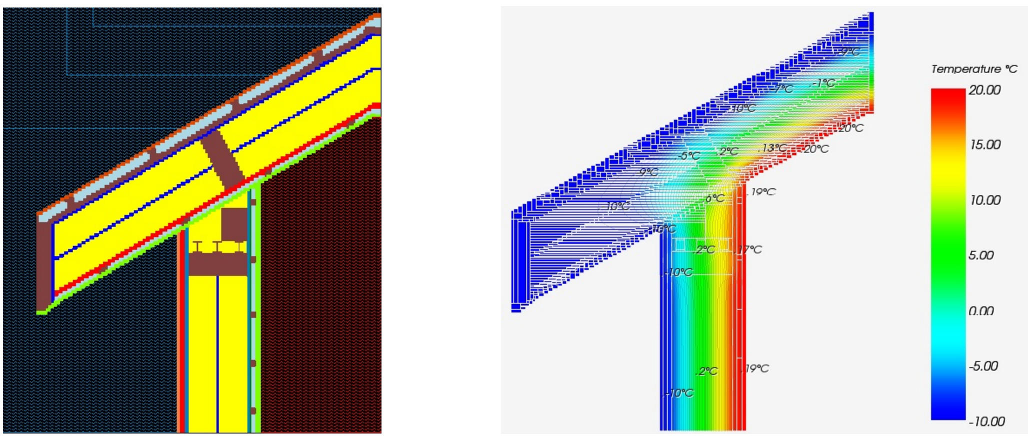


Figure 55: Simulation model and temperature profile of scenario D-5 of wall-roof junction

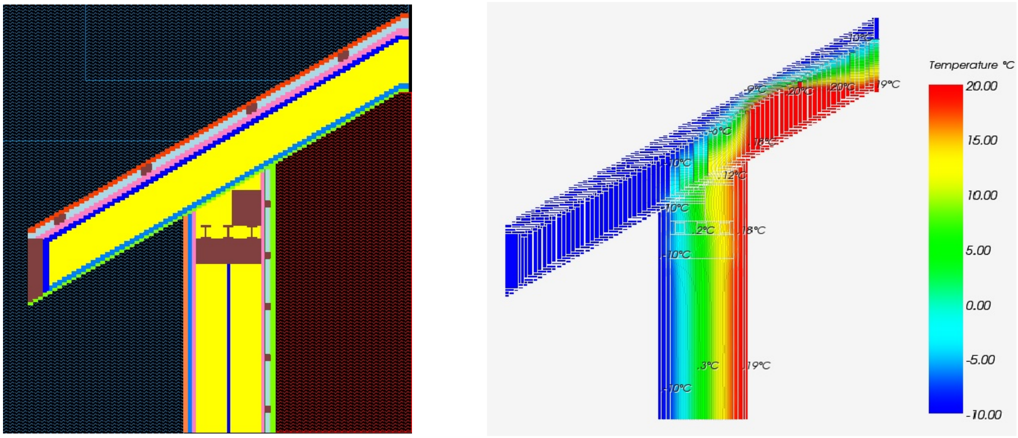


Figure 56: Simulation model and temperature profile of scenario D-6 of wall-roof junction

Following outcomes generated provide data related to the heat flux through the joints. Figures 57 and 58 highlight an opposite situation between the two cases. Indeed, scenario D-5 reveals a homogeneous profile without particular points where the heat flow increases considerably. Scenario D-6, instead, denotes a higher amount of heat loss that can reach peaks of 100 Wm^{-2}. Table 20 offers information related to the linear thermal transmittance ψ-value and thermal coupling coefficient (L_{2D}) value for both scenarios. These values make it clear the significant dissimilarity of the energy performance of the two cases. Indeed, in scenario D-6 the linear thermal transmittance presents an unsatisfactory value equal to ψ= 0.525 $Wm^{-1}K^{-1}$. In contrast with this bad value, scenario D-5 manifests a consistent decreased value equal to ψ= 0.073 $Wm^{-1}K^{-1}$. The reached value highlights an efficient performance of the junction comparing it with a research conducted by ASHRAE that defines the average linear thermal transmittance of a roof intersection with an external insulated precast wall, around ψ= 0.579 $Wm^{-1}K^{-1}$ (2011). Figures 57-58 reveal also the pressure difference of the two joints. Visual outcomes show two various profiles proved by results related to the temperature factor f_{Rsi}. Indeed, scenario D-5, with a temperature factor of f_{Rsi}= 0.95, does not present any risk related to condensation or mould growth. On the other side, scenario D-6 shows a temperature factor correspondent to the critical value of 0.70, being equal to f_{Rsi}= 0.71. This aspect leads to a condensation risk and mould growth assessment criteria not completely fulfilled.

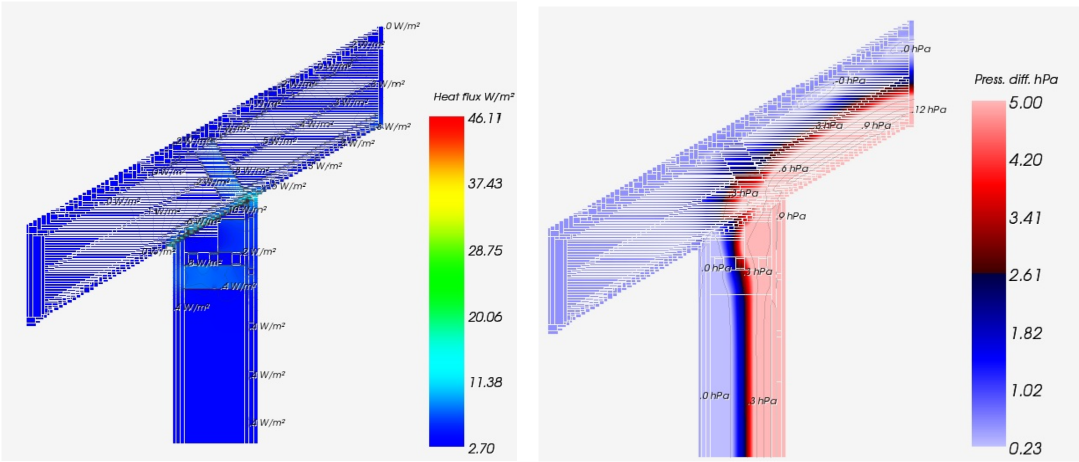


Figure 57: Heat flux and pressure difference of scenario D-5 of wall-roof junction

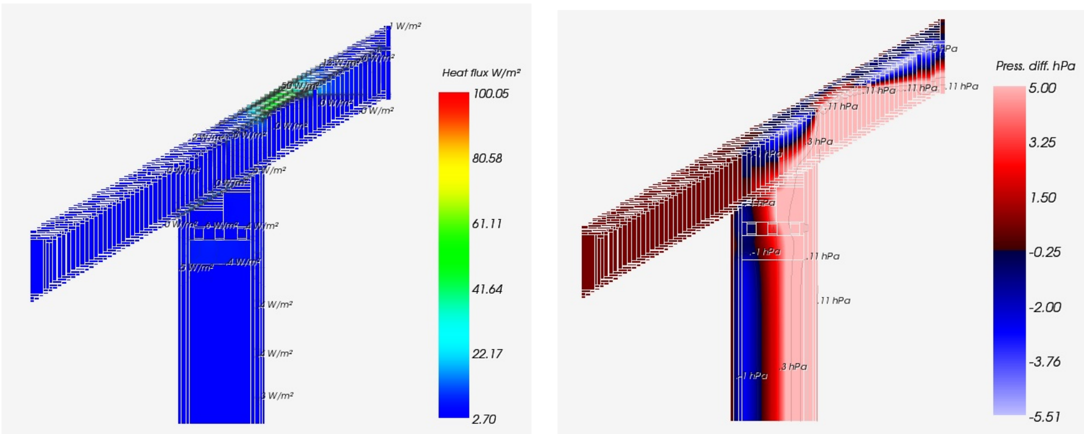


Figure 58: Heat flux and pressure difference of scenario D-6 of wall-roof junction

Table 20: Output values of different scenarios of wall-roof junction

	L_{2D} [$Wm^{-1}K^{-1}$]	ψ-value [$Wm^{-1}K^{-1}$]	θ_{min} [°C]	f_{Rsi} [-]
Scenario D-5	0.38	0.073	18.50	0.95
Scenario D-6	0.89	0.525	11.18	0.71

3.5 Openings

The final case simulated regards the evaluation of thermal bridges that occur around the openings. In the two cases selected, the details concern the same typology of wall, previously adopted for the other simulations, and one window. Both openings are made up of a double-glazing window filled with argon gas in order to have an excellent thermal performance. The substantial difference between the two cases is related to the position of the openings in the wall. Indeed, this factor affects in an important way the thermal performance of this type of thermal bridges.

Simulated cases involve the following scenarios:

- Scenario D-7: window located in the middle of the opening.
- Scenario D-8: window located at the external edge of the wall.

The windows adopted are part of the Revit parametric families and are visible in figures 59 and 60. Each detail is associated to specific thermal properties as thermal conductivity (λ), specific heat (c) and density (ρ). Both cases in exam are presented in horizontal section. Table 21 illustrates the list of materials that build up the window for the two scenarios and the related properties.

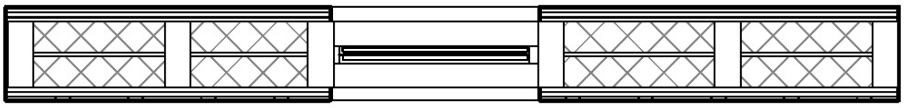


Figure 59: Autodesk Revit model of scenario D-7 of openings

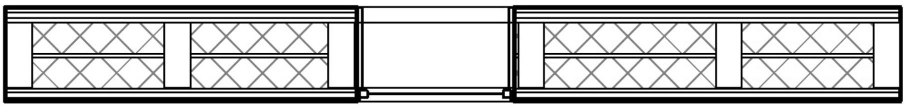


Figure 60: Autodesk Revit model of scenario D-8 of openings

Table 21: Material properties of scenario D-7 and D-8 of openings

	λ [$Wm^{-1}K^{-1}$]	μ [-]	ρ [kgm^{-3}]	**c** [$Jkg^{-1}K^{-1}$]
Glass	0.8	10000	2500	800
Argon Gas	0.017	1	1.7	504

The first results generated after the simulation in AnTherm are the profiles of the temperature. The boundary conditions that the windows face are +20°C at 50% relative humidity inside and -10°C at 80% relative humidity outside. As it can be observed in figures 62 and 64, temperature profile suffers a gradual alteration around the frames of the windows that leads in both cases the minimum interior surface temperature to low values of θ_{min}= 14.63°C for scenario D-7 and θ_{min}= 13.91°C for scenario D-8. However, as it is visible in the graphical outcomes, scenario D-7 reveals a constant temperature at the joint with the opening and a cold profile on the external envelope of the window. Conversely, scenario D-8 preserves a high temperature profile at the joint with the opening and on both surfaces of the window. Regarding the temperature factor f_{Rsi}, in both cases simulated it meets the requirement of being above the critical factor of 0.70. Respectively it is f_{Rsi}= 0.82 for scenario D-7 and f_{Rsi}= 0.80 for scenario D-8.

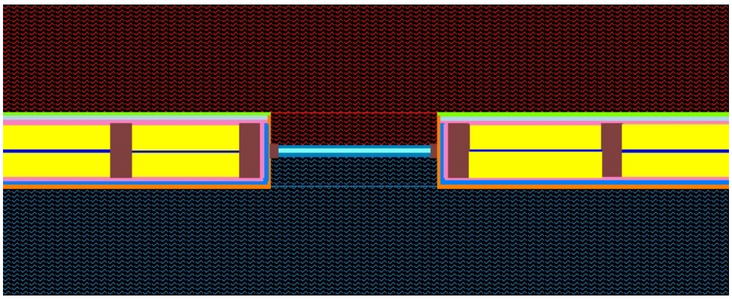


Figure 61: Simulation model of scenario D-7 of double-glazing window

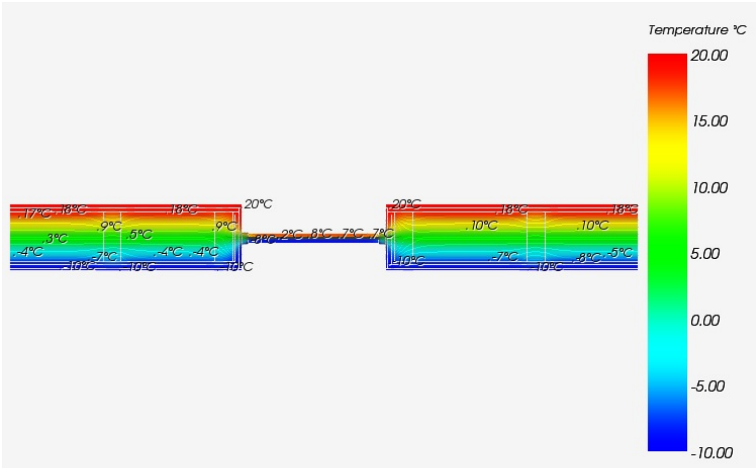


Figure 62: Temperature profile of scenario D-7 of double-glazing window

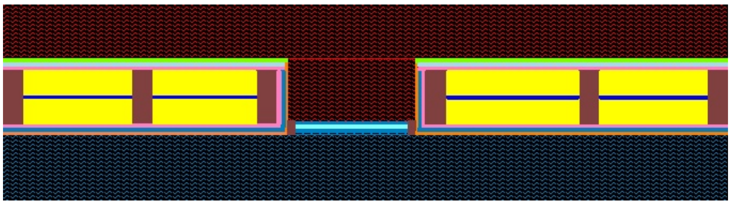


Figure 63: Simulation model of scenario D-8 of double-glazing window

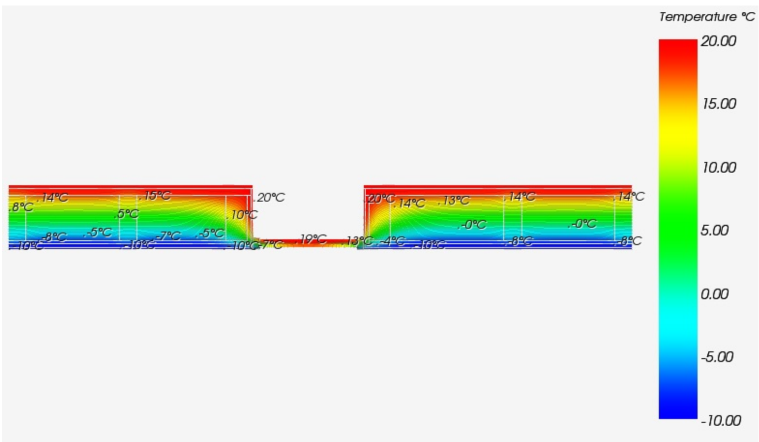


Figure 64: Temperature profile of scenario D-8 of double-glazing window

Subsequent results concern the amount of heat that flows through the openings and in the points around them. Graphical outcomes in figures 65 and 67, demonstrate a different energy performance of the two profiles. More specifically, scenario D-7 presents a higher dispersion of heat through the window with an average flux of 24 Wm^{-2} and a peak of 107 Wm^{-2} at the points of the frame. Conversely, scenario D-8 reveals an uniform profile of heat flux with reasonable critical points at the frame. This difference is clearly visible in table 22 that offers information related to ψ-value and thermal coupling coefficient (L_{2D}) value for both scenarios. Indeed, scenario D-8 presents a good thermal performance of the junction with a linear thermal transmittance lower than the gold standard 0.01 $Wm^{-1}K^{-1}$ set by the Passive House Institute, with a value of ψ= -0.170 $Wm^{-1}K^{-1}$ and a total heat that flows through the two-dimensional opening equal to L_{2D}= 1.02 $Wm^{-1}K^{-1}$. Figures 66 and 68 reveal instead the pressure difference of the two openings. Visual outcomes show two various profiles but in both cases condensation risk and mould growth are avoided as proved by the temperature factor f_{Rsi} greater than the critical factor of 0.70.

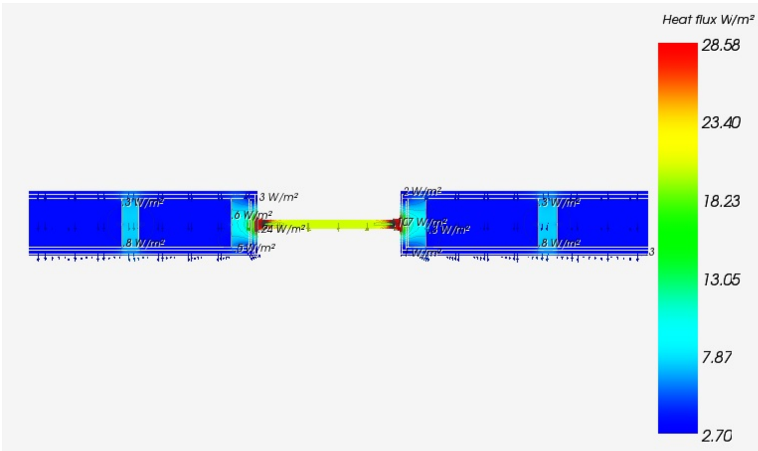


Figure 65: Heat flux of scenario D-7 of double-glazing window

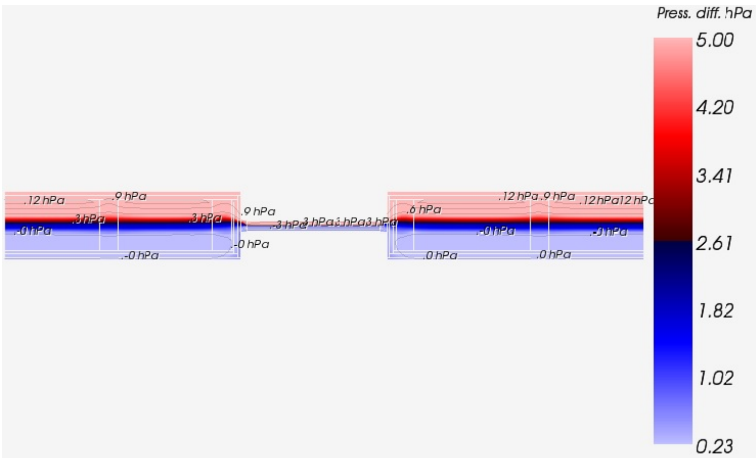


Figure 66: Pressure difference of scenario D-7 of double-glazing window

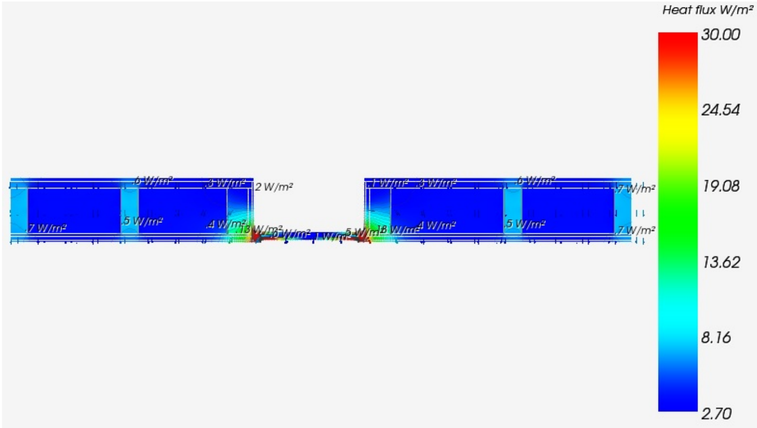


Figure 67: Heat flux of scenario D-8 of double-glazing window

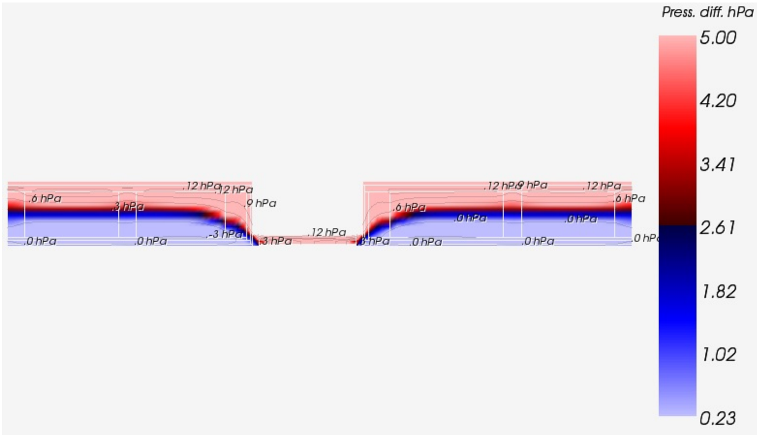


Figure 68: Pressure difference of scenario D-8 of double-glazing window

Table 22: Output values of different scenarios of double-glazing window

	L_{2D} [$Wm^{-1}K^{-1}$]	ψ-value [$Wm^{-1}K^{-1}$]	θ_{min} [°C]	f_{Rsi} [-]
Scenario D-7	1.53	0.924	14.63	0.82
Scenario D-8	1.02	-0.170	13.91	0.80

3.6 Advantages of straw bales

Results gained after the thermal simulation highlight that junctions made entirely of straw bales and other natural materials as wood, allow increasing the insulation and reducing considerably the heat loss through thermal bridges with all the positive aspects strictly connected to this factor. Therefore, it seems necessary now to emphasize the different reasons why a straw bale construction should be preferred to a traditional brick construction.

Table 23 compares a wall made of straw bales and an usual brick wall, following different criteria.

Table 23: Comparison of a straw bales wall and a brick wall

	Straw Bales Wall	Brick Wall
U-value [$Wm^{-2}K^{-1}$]	0.08 < and < 0.20	0.20 < and < 0.40
Embodied Energy [$MJkg^{-1}$]	0.91	3
Minimum Thickness [mm]	400	250
Total annual heating demand [$kWhm^{-2}a^{-1}$]	36	44
Global Warming Potential [$kgCO_2eqm^{-2}$]	-50	61
Primary Energy Content [MJm^{-2}]	104.83	985.65
Acidification Potential [$kgSO_2eqm^{-2}$]	0.052275	0.216688
Renewable	Yes	No
Biodegradable	Yes	No
Fire resistant	Yes	Yes
Earthquake resistant	Yes	Yes
Affected by moisture	Yes	No

Straw, being a sustainable material, reaches good values of thermal transmittance, in a range of 0.08 and 0.20 $Wm^{-2}K^{-1}$ (GrAT 2000). The U-value of a brick wall conversely, is between 0.20 and 0.40 $Wm^{-2}K^{-1}$. Nevertheless, it has to be observed that these quantities are strictly related to the thickness of the walls. A wall built up of straw bales required a minimum thickness of

450 mm. A brick wall instead, needs only 250 mm to be completed and, when its construction is improved adding different layers with low thermal conductivity, it can also reach 500 mm of thickness and then even its thermal transmittance can decrease up to 0.12 $Wm^{-2}K^{-1}$ (Brojan et al. 2013).

The embodied energy is defined as the total energy that a material requires for its production cycle. That covers material extraction, its transport, its manufacturing and its transfer to the building site, for example. As the table 23 shows, there is a different quantity of embodied energy between straw and brick (Greenspec 2011). Indeed, straw instead of brick, is essentially a waste material generated from residual cereals, that does not need plus energy for its production. Also, straw is a renewable product that generates no waste, since all the exceeding straw on the construction site can be composted afterwards or used in farms. As natural material it can biodegrade at the end of its life cycle, without any energy needed for landfill (Atkinson 2011).

The total annual heating demand presented in table 23, based on a dynamic thermal simulation conducted on a comparative research study between a straw bale building and a brick building done in 2013 by Bianka Szász, does not manifest a substantial difference between the two typologies of materials. However, the straw bale building requires 17% less heating demand than the brick building, circumstance that still proves a general better energy performance of straw bales (Szász 2013).

The Global Warming Potential, factor that expresses the contribution to the greenhouse effect relative to the production of CO_2, indicates that the straw bales wall has a negative value of -50 $kgCO_2eqm^{-2}$ instead the brick wall has a value of around 61 $kgCO_2eqm^{-2}$ (Brojan et al. 2013). This consistent increased value for bricks implies an impact on the environment higher for 121 $kgCO_2eqm^{-2}$ (Brojan et al. 2013).

Defined as the overall energy needed in order to product a good, the Primary Energy Content of a wall made of straw bales is around 9 times less than a brick wall, being 104.83 MJm^{-2} instead of 985.65 MJm^{-2} (Brojan et al. 2013).

In spite of the popular beliefs, a straw bales constructions has a low fire risk. Indeed, if straw bales are well pressed they lose all the oxygen and without it, the flame can’t propagate. Tests demonstrated that, in case of fire, a straw bales wall can resists for 3 hours at 1000°C, like a normal concrete wall of 25 cm (Report to the Construction Industries Commission of New Mexico 1993).

Furthermore, straw bales have a strong seismic resistance. Recent tests carried out in university laboratories at the University of Nevada, Reno, USA, showed that one straw bale can support weights up to 15 tonnes per square meter. Also the structure is much lighter compared to a building made of bricks or concrete, so the stress that it receives is considerably lower. Besides, the flexibility of the material allows the absorption of vibrations, reducing the possibility of a structural collapse (Pakistan Straw Bale and Appropriate Building – PAKSBAB 2009).

It is significant to underline that, in order to achieve their optimum performance, building made of straw bales must follow certain principles. First of all, the straw must be protected from direct contact with the atmospheric agents and needs to be raised from the ground in a range from 225 mm to 450 mm. The most dangerous element for straw, that can compromise its durability, is moisture. Indeed, moisture content of straw should not be more than 15% and not less than 10% and relative humidity should not exceed 70% (Fawale et al. 2007) in a way that bales must be preserved dense, dry and compact as much as possible. Doubtless, the use of natural plasters, as clay plaster or lime plaster, help in controlling the quantity of water vapour in the air inside straw bale structures although, as demonstrated in this paper, also a straw bale wall coated with gypsum board inside and timber panels outside, prevents the condensation risk and mould growth due to the normal activities inside the building. In any case, regions with an extremely humid and rainy climate, may be not appropriate for straw bale constructions. Another factor, considered negative for straw bale buildings, consists in the attack by parasites. However, once straw bale walls are plastered, any chance of entry for vermin and other rodents is eliminated.

It can be assumed that, in light of the different findings here exposed, straw is a good alternative to brick considering the environmental factors.

4 CONCLUSIONS

This research presents a scientific work conducted in order to achieve two main goals, summarized below:

- The generation of an integrated system where geometrical data and energy data are able to interface each other, testing how a BIM tool can effectively decrease the fragmentation in the building life cycle and investigating the feasibility of a linear flow of data between the BIM tool and the energy analysis tool.
- The creation of a list, available for various users, of standardized details of the major junctions of a building made of straw bales, proving how straw bales as insulation material improves the energy performance of the building avoiding thermal bridges.

Here are presented the main findings and the main shortcomings of the work.

4.1 Software Interface

The major limitation of the research regards the lack of interoperability between the two tools, Autodesk Revit and AnTherm.

As it is strongly remarked in this paper, BIM is conceived to favour the cooperation and the team work among different professional roles involved in the Building Life Cycle and to mediate among various software programs adopted by architects, engineers, energy managers and builders.

However, as tested in this research, circumstances related to the interoperability issues restrict the easy exchange of data and affect workflows. Generally, the intelligent model defined in Revit faces limits in the compatibility with software that require uniquely CAD-based workflows. In this specific case, AnTherm, chosen as energy simulation tool, is capable to import CAD files generated with standard closed polylines. Revit models, instead, even when exported as DWG or DXF files remain extremely complex. Indeed, the amount of information that a BIM-based file carries does not provide a simplified representation of the objects but always a parametric design that involves geometrical data and energy data.

Examined case leads to a general important consideration.

On one hand, a large amount of energy evaluation software currently used, is able to manage greater geometric complexity and to import gbXML file format generated by Autodesk Revit. On the other hand, as this paper proves, it is still present a considerable number of software programs, as AnTherm, that is not set to interface with the latest version of energy file format and that is still slow to embrace BIM-based energy analysis applications. This factor implies that not all the design community is prepared to interact with BIM-based work process and that several programs require a manual adaptation or the adoption of other software as step in between, where redefine and manipulate BIM elements in order to allow the transfer of the files. Nevertheless, this process can lead to a loss of model accuracy and data.

Despite the interoperability issues, BIM maintains a leading role among the number of contemporary design programs and, as BIM evolves quickly, there will undoubtedly be improvements of the current limitations.

4.2 Educational Tool

The main findings of this study is that the use of straw bales as construction materials and thermal insulation layer allows to decrease considerably the heat loss through thermal bridges. The important contribution of this paper regards the collection and analysis of the major junctions of a building made of straw bales. Examined details can be easily consulted in this paper with a graphic representation in Autodesk Revit and an energy evaluation in AnTherm both accompanied by a table that offers information concerning the materials adopted with the thickness and all the related thermal properties. In this context, the present research represents an useful handbook of specific straw bales details, easily interfaced with specialists, as architects and engineers but also with students and craftsmen as a self-learning tool.

In addition, this study proves that the mixed use of straw and cement or concrete in a same structure is not appropriate. As stated by many different books and sources, the combination of straw and concrete exposes the building to condensation risk. Details tested in this paper, demonstrate that in all junctions that include the use of the two materials there are no issues related to condensation risk and mould growth, as proved by the temperature factor f_{Rsi} that in all simulated joints meets the requirement of being above the critical factor of 0.70. However, the thermal performance of these specific details is not comparable with the energy outcomes of the same junctions built only with straw bales and other natural elements.

Therefore, it can be assumed that junctions made entirely of straw bales and other natural materials as wood, allow increasing the insulation and reducing the thermal bridges with all the positive aspects strictly connected to this factor.

4.3 Future research

In regard to foreseen future challenges, it is desirable to find a proper linear flow of data between Autodesk Revit and AnTherm, solving the basic conflict in the interface of the two software. The research can be implemented testing different ways of interoperability even with the contribution of computer scientists with programs that involve a high-level programming language.

Further researches in the field of straw bales details involve the extension of the basic details, here tested, to a larger number of junctions. Moreover, the same details can be implemented with the combination with other insulating materials made of natural fibers as reed, hemp, sheep's wool or coconut fiber panels. Also, the analysis can be enlarged from 2D simulations to 3D simulations of thermal bridges with the addition of dynamic model that allow to have not only a static evaluation of the profiles of temperatures and heat flux. Finally, it is also interesting inquiring how straw can help in retrofitting existing junctions of traditional buildings where thermal bridges occur.

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