Review of the CUT technique

Analysing Modifications, Performance, and Professional Practices

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

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Abstract

Bio-based and ecological buildings are gaining global importance, with straw bale constructions as one of the possible choices in Europe. Straw bale buildings are classified into load-bearing, non-load-bearing, and hybrid techniques. Load-bearing and non-load-bearing methods have been studied extensively in past decades whilst hybrid methods, such as CUT (Cells Under Tension) techniques have been somewhat neglected, despite its significant potential for advancing sustainable building practices. This master thesis presents a comprehensive review of the CUT techniques, a hybrid methods of straw bale building, which are used by approximately 50 builders and architects in Europe and South America, and more than a few hundred of buildings have been erected since 1995. Twenty builders and architects working with CUT techniques answered survey and analysis of their knowledge was performed to form the basis of this thesis The thesis also presents aspects of the CUT techniques such as CUT method modifications, mould growth analysis with the VTT model, Life Cycle Assessment, and a list of building details. By providing a comprehensive overview of the CUT technique, this research aims to highlight its significance in the context of ecological building practices and the findings of the thesis aim to contribute to the builders and architects working with straw bales and the CUT technique.

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Helsingborg, May 2024

Josef Podmolík

Table of content

Abbreviations

Abbreviation	Full form
ACH_{50}	Air Changes per Hour at 50 Pascals
CUT	Cell(s) Under Tension
DIY	Do It Yourself
EPD	Environmental Product Declaration
EN	European Norm
GREB	Groupe de Recherches Écologiques de La Baie
GWP	Global Warming Potential
HDF	High Density Fibreboard
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MDF	MediumDensity Fibreboard
MI	Mould Index
OSB	Oriented Strand Board
RH	Relative Humidity
RH_{crit}	Critical Relative Humidity
VTT Model	Viitanen Model
WFB	Wood Fibre Board

1 Introduction

1.1 Background

Straw bale construction is recognized as an ecological, affordable, and economically promising construction method, yet its wide adoption is slow, mainly due to a lack of understanding (Krick, 2008). Straw bale building systems are divided into Load-bearing, Non-load-bearing, and Hybrid techniques. The CUT (Cell Under Tension) technique is a hybrid method of straw bale building, used mostly in Europe and South America. In hybrid methods, all, or some of the used materials within the wall create a bearing system. In the CUT technique, wooden construction, plaster material, and straw, together create a load-bearing system. The CUT technique was invented in 1995 by Tom Rijven. Three promising, but unofficial structural tests of the Original CUT method were performed over the years. The technique spread from the Netherlands and France to different countries because of workshops and lectures given by Tom Rijven and other straw bale builders. By the time, the CUT technique was modified by builders and architects due to their preferences, different building regulations, or geographical factors. Several different ways how to build with CUT techniques are in use nowadays and the CUT techniques can be classified into the original CUT construction and modified CUT constructions. In countries where plaster capacity to transport vertical and horizontal loads cannot be considered in structural calculations because of building regulations, the CUT technique had to be modified and the walls had to be braced with planks or boards. The CUT technique can be also used in combination with a post and beam structure (Post and Beam CUT), for wrapping of buildings (CUT Wrapping), or to create organic shapes such as vaults domes, and curved walls (OrganiCUT).

The building industry is one of the main environmental threats, around 45–50 % of the worldwide energy used is consumed on material production, building raising, building operation, and material disposal. Transportation, including also transportation of building materials, takes up of 20 % worldwide energy, is in second place (Márton et al., 2014). As an example, in the UK, 50 % of net energy consumption is spent on dwelling occupation and 8 % of net energy is spent on material production and transportation (Morel et al., 2001). Building industry can play a major role in cutting worldwide energy consumption in the future if using resources more responsibly (Márton et al., 2014).

While the efficiency of the buildings during their operational phase was the main interest in past decades, the environmental impact of material production, transportation, and end-of-life disposal was somehow neglected and has gotten more attention only in past years. Those emissions related to material production have severe importance and two important factors must be considered. Firstly, the construction sector is hard to decarbonize (Committee on Climate Change [CCC], 2018) while the global demand for newly built dwellings will drastically increase. Secondly, it is estimated that the built-in area will increase by 230 billion m^2 by 2060. The ongoing reliance on traditional construction materials presents substantial challenges related to carbon lock-in, as the emissions associated with producing steel and cement are currently generated using energy sources high in carbon content. It appears that the most effective strategy to reduce embodied emissions is to make changes at the material level (Pomponi et al., 2018). Suggested measures would be to use less of the currently used materials or/and substitute the material with materials with lower embodied emissions (Churkina et al., 2020). The CUT techniques are using none or very few of currently used materials and the structural properties of materials in the CUT construction are used to their maximum (Gruber, 2020a).

1.2 Objective

This thesis seeks to enhance the understanding of straw bale constructions, aiming to contribute to the increased knowledge of the CUT technique. The objective of this thesis was to create an overview of the CUT technique and its modifications. This includes systems descriptions and development, usage, moisture performance as well as environmental performance. Additionally, the thesis sought to gather the knowledge and insights of builders and architects regarding these techniques. Lastly, the thesis aimed to create a list of building details based on professional practice.

2 Literature review

2.1 Straw bale as a building material

Straw as a crop can be harvested every year. It is a widespread resource that does not harm the environment if grown responsibly. In the end of the life cycle of a building, it can be easily removed from the construction and might be used as a mulch in the garden (Minke & Krick, 2020). Straw bales' main advantage as building material is their excellent insulation property and wide range of use in the building industry. Utilization of straw and other natural materials assures a healthy indoor environment. Using straw bales reduces the transport emissions connected to material production since straw bale is a local co-product of agriculture (Márton et al., 2014). Moreover, it might help to develop a more circular construction industry that could lessen its environmental footprint (Kanters et al., 2023). Straw is a residual material from grain farming and is an annually renewable and locally sourced by-product. In Germany, about 20 % of the straw yield is surplus, which could potentially be used to construct as many as 350,000 family homes yearly and the production of straw bales is likely to involve minimal expenses (Fachverband Strohballenbau [FASBA], 2019b).

Straw bales are created during the grain harvest in a bale press. The height and width of the bale depends on the bale chamber diameters, the length of the bale can be changed accordingly. Typical dimensions of the bales are 36 · 49 · 50 to 130 cm (Minke & Krick, 2020). A bale is composed of flakes and is bound with two or three strings (Austrian Strawbale Network [ASBN], 2015a).

2.1.1 Thermal conductivity of straw

Since straw bale is a biological, orthotropic and non-homogenous material, the thermal conductivity coefficient changes and depends on several factors (Mesa & Arenghi, 2019). The thermal conductivity of straw depends on the direction of stems within the bale. Figure 1 shows three possibilities of small bale placement in constructions. In infill construction, straw bales should be laid flat in floors, roofs, and ceilings and on edge in the walls. The lower coefficient of thermal conductivity is achieved when the stalk direction is perpendicular to the heat flow (FASBA, 2019b). Mesa and Arenghi (2019) determined the thermal conductivity of straw bales on edge as 0,045 W/(m·K) in their laboratory measurements, as well as Minke and Krick (2020) reporting a similar value of 0,0456 W/(m·K), however, the specified value for thermal conductivity, which is recognized across the EU, is 0,048 W/(m·K) (FASBA, 2019b).

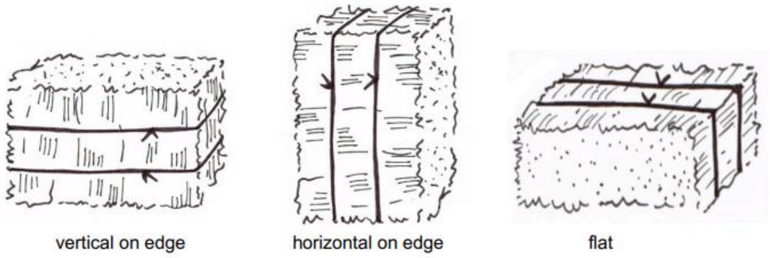


Figure 1: Possible straw bale placement in straw bale building constructions (FASBA, 2019b).

2.1.2 Specific heat capacity

The specific heat capacity c kJ/(kg·K) of a material indicates the amount of energy needed to increase the temperature of one kilogram of the material by one Kelvin. For common cereal straw, the specific heat capacity is given as c = 2.0 kJ/(kg·K) (FASBA, 2019b).

2.1.3 Water vapour diffusion factor

The water vapour diffusion resistance factor μ (-), a dimensionless measure, indicates the extent to which the considered material offers resistance to water vapour diffusion compared to an equivalent thickness of stationary air. According to ETA-17/0247 Building Straw, the μ = 2 (-) (Deutsches Institut für Bautechnik [DIBt], 2017) and according to French strawbale network Réseau français de la construction paille (RFCP, 2015), μ = 1,15 (-) for dry straw bales having a density of about 100 kg/m^3.

2.2 Straw bale building overview

Straw has been used as a building material for thousands of years, and after the baling machine invention dated back to the early 1900's, it was possible to compress straw in the form of bales and use it as the primary building component for the exterior walls (Straube, 2000). For a short period, straw bale houses were popular in Nebraska but approximately after 50 years they lost in favour of cement based constructions and were not used anymore. Later in the 1970's, pioneers of strawbale building, Judy Knox, Matts Myhrman and others began to rediscover and spread the awareness about straw bale buildings (Jones, 2002). In the past years, the interest in sustainable and traditional construction techniques has been on the rise, particularly in the use of natural and unprocessed materials for buildings (Pierzchalski, 2022). Straw bale constructions produce highly efficiently insulated and fire-resistant structures using a convenient, cost-effective, and easily accessible agricultural by-product. Effective design and appropriate constructive protection prevent moisture intrusion while allowing water vapour to escape the construction. This can be achieved through building parts such as roof overhangs, breathable coating, and well-designed foundations (California Straw Building Association [CASBA], 2019).

There are several methods of Straw bale building constructions and the approach varies based on whether the straw bales have a structural function or not, shown in Figure 2 (Grelat, 2003).

1. Load-bearing straw bale construction
2. Non-load-bearing straw bale walls (Minke & Krick, 2020)
3. Hybrid construction (Gruber, 2020b)

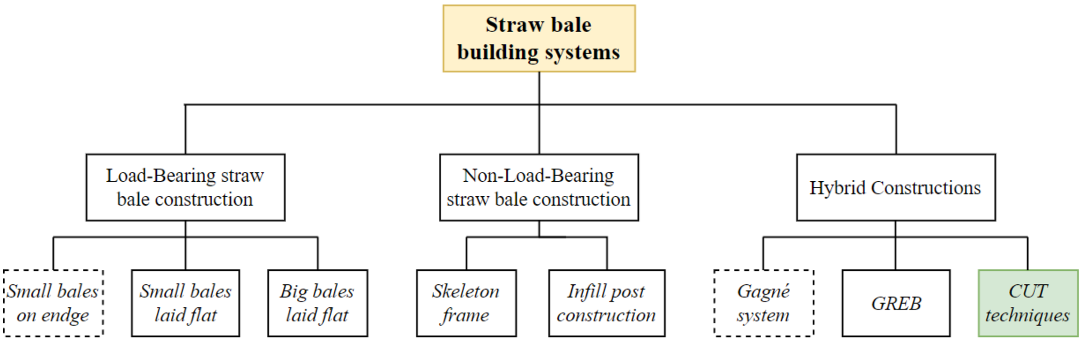


Figure 2: Overview of straw bale building systems

2.3 Load-bearing straw bale construction

Load-bearing straw bale construction, where the bales itself are load-bearing, is also called the "Nebraska" style after its origin. It was developed by European settlers in the USA at the end of the 19th century after the invention of the baling machine (Jones, 2002). In the Nebraska wall system, straw bales under compression are the load-bearing elements. The straw bales transport horizontal loads from the roof to the foundation (Minke & Krick, 2020). The loads from the roof need to be evenly distributed on the wall and the loads at one point are not permissible, therefore they have to be distributed with a ring beam (Márton et al., 2014). This load-bearing technique requires careful planning and introducing the bales size early in the planning process. An example of load load-bearing wall using straw bales as a modular, load-bearing material can be seen in Figure 3.

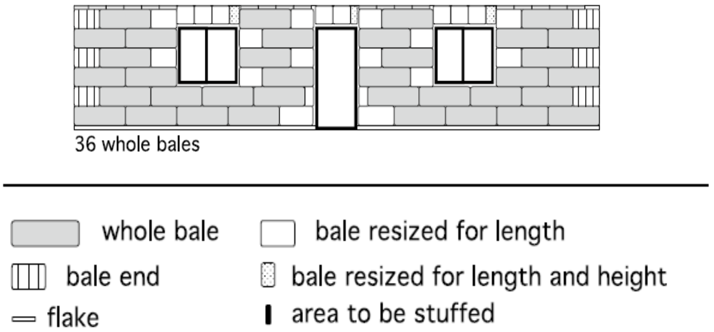


Figure 3: The bale module in design (CASBA, 2019)

The first row of bales starts with a full bale, the second row starts with half a bale or bale end in the corners (CASBA, 2019). By this, the needed overlapping of straw bales is achieved, which is stated as a minimum of one third of the bale length. Since there is no an industry “standard” for bale dimensions, it needs to be clarified with the bale provider. As it is usually demanding for farmers to produce bales of the same length and quality, companies started to produce certified straw bales with guaranteed length, moisture, grain content, and moisture content in recent years, however this practice is used only in a few countries (ASBN, 2015a).

2.3.1 Static of load-bearing walls

The load-bearing straw bale wall system is a composite structure that collaborates to withstand lateral forces and gravity. Straw bale walls are coated with a layer of plaster on the interior and layer of render on the exterior (King, 2006). These coating are crucial for the structural function of the construction, it is the main bracing element of the building (ASBN, 2020). These coatings can be made from lime, cement, or an earthen mixture (King, 2006).

Structural loads that acting on the wall (roof, floor, bales etc.), would cause a settling of the walls and cracks in the plaster. Therefore, before the coating is applied, it is necessary to compress the wall with lorry straps. These straps are connected to the top plate and base plate and the walls are evenly compressed (ASBN, 2020). In a seven bale-high wall, compression between 12 and 50 mm is expected if good bales are used (Jones, 2002). The wall is secured with packaging straps that can be overplastered, the lorry straps are removed and plaster can be applied (ASBN, 2020). There are other options how to compress the walls such as using metal wires, or let the walls to settle for several months (Hollis, 2005).

Proper connection of the coating to the straw surface is crucial for the function of the system, coatings should be pushed into the straw surface with hand tools or plaster spray machine (ASBN, 2020). To increase the durability and strength of the wall, a reinforcing mesh should be embedded into the coating (Jones, 2002; King & Aschheim, 2006). Research has demonstrated that load-bearing straw bale walls equipped with unreinforced render achieve lower loads compared to their reinforced counterparts (Ash et al., 2003). Moreover, the application of a thicker render layer not only supports a greater load but also provides enhanced protection against hazards that might cause lateral damage (Ash et al., 2004).

2.4 Non-load-bearing straw bale constructions

In non-load-bearing straw bale construction, the straw bales have no structural function and serves as insulation, the wooden frame and/or sheathing of the building transports all horizontal and vertical loads (Márton et al., 2014; G. Minke & Krick, 2020). The straw bales are used as infill between the posts of timber frame or post and beam construction (Gruber, 2020b; Márton et al., 2014).

Straw bales can also form a continuous layer either on the interior or the exterior of the post and beam construction, however, the continuous straw bale wall needs to be connected to the load-bearing structure to ensure that the straw layer won’t displace (Minke & Krick, 2020). One of the solutions when the straw bale wall does not need to be connected to the load-bearing structure is the use of the non-load-bearing CUT technique, or if the bales are properly compressed between the foundation and ring beam (Minke & Krick, 2020). Figure 4 displays possible locations of wooden load-bearing elements. It is important to add that render and plaster on straw bale wall adds to the stiffness of the structure, but depending on the legislation of the country, this might not be taken into consideration (Minke & Krick, 2020).

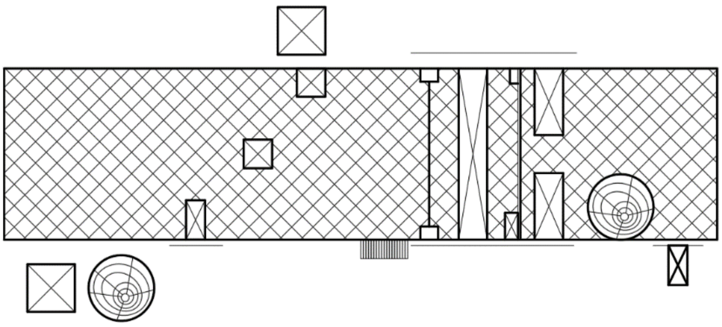


Figure 4: Possible position of wooden elements in a non-load-bearing straw bale walls. Based on Márton et al., (2014)

2.5 Hybrid constructions

Throughout the history of straw bale construction, several methods that use combinations of bales with other materials have emerged (Márton et al., 2014), hybrid techniques are based on new ideas or on the combination of load-bearing and non-load-bearing straw building techniques (Jones, 2002).

Hybrid systems are generally divided into three construction methods:

1. Gagné system
2. GREB (Groupe de recherches écologiques de La Baie)
3. CUT techniques

2.5.1 Gagné system

This construction method was developed in Canada. The straw bales are used as bricks without binding, laid on cement mortar. This creates a grid of vertical and horizontal connections, providing the walls with ultimate strength. The walls are also plastered with the cement mortar. The method is rarely used, as we already know simpler methods of working with straw bales without excessive thermal bridges (Márton et al., 2014). It is fully certified in Canada, however it is highly labour intense and straw decay is a common problem (Jones, 2002). The Gagné system is shown in Figure 5.

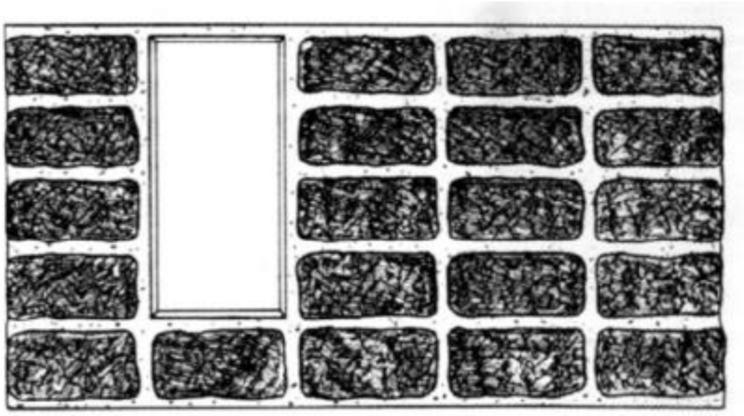


Figure 5: Schematic picture of Louis Gagné method (Steen and Bainbridge, 1994)

2.5.2 GREB

The GREB system was developed by a group of researchers in Québec (Groupe de recherches écologiques de La Baie [GREB], 2024). The technique is a combination of a load-bearing wooden structure, which is reinforced with metal parts such as screws, nails, and metal lings (Arnaud et al., 2009), see Figure 6. Mortar is poured inside the cavity between the timber structure, straw bale, and formwork (Evrard et al., 2016). This mortar is not windproof, therefore it needs additional lime rendering. Up to today, this system is used mostly by self-builders in France (Deveria, 2020; Arnaud et al., 2009), where an association APPROCHE-Paille is actively promoting and teaching the GREB technique (APPROCHE-Paille, 2024). Since 2002, 20 to 30 % of on-site straw bale buildings in France were built with GREB (Arnaud et al., 2009). GREB technique is a technique that aims for DIY builders, it is a complete construction system using only four components:

1. Wood with unified dimensions 100 · 40 mm
2. Small straw bales
3. Metal parts (screws, nails, and metal lings)
4. Aerated mixed concrete (4 parts wood chips, 3 parts of sand, 1 part of calcic lime, 1 part of grey cement)

Figure 6: Four components of GREB system (Thévard, 2007)

GREB walls need 2 m^3 of wood and 10 m^3 of straw for 100 m^2 of structural wall (Thévard, 2007). It has several advantages such as the use of uniformed wood dimension, suitable for DIY, and continuous layer of straw bales with no thermal bridges (Deveria, 2020).

2.6 Original CUT construction

The Original CUT technique is also known as Centered CUT construction was invented by Tom Rijven in the year 1995 (Flexagone, 2024). The CUT technique is based on intuitive technical considerations and may be more complex to employ, nevertheless, it is gaining traction among natural builders that prefer ultra-local building materials (Evrard et al., 2016). The main advantage of the Original CUT technique is its simplicity and specific combination of wood, straw bales, and clay, which all together create a load-bearing system. In the CUT technique, an ability of each material is used at its maximum (Gruber, 2020a).

CUT constructions have several benefits:

1. Very simple to build
2. Wide field of application, suitable for renovation (CUT wrapping)
3. Suitable for self-builders
4. Uses a minimum amount of resources while maximizing the properties of each material (Gruber, 2020a)

2.6.1 Suitable straw bales for CUT constructions

As Krick (2008) mentioned, it was proven that the strength of individual bales is highly affected by the straw structure. For non-load-bearing straw bale walls where straw does not play a structural role, the bale strength is not crucial. As for hybrid construction, where straw has some structural function, the assumption is that the same principles applied. Krick (2008) later suggested that combined harvesters with tangential threshing units without downstream separating drums were identified as being gentle, meanwhile axial threshing units destroy the straw structure considerably. With growing density, the strength of the bale is growing as well as the edge fidelity improves. To achieve sufficient density, the harvester/tractor should not drive fast while maintaining low speed.

Enhanced density can be attained by having a regular swath of crop flow and narrowing the channel's sides, such as incorporating plywood panels in the rear section of the press channel. A four percent density increase per centimetre of channel construction was observed (Krick, 2008).

According to Gruber (2015), ideal bales for CUT buildings need to follow six basic requirements:

1. Yellow or golden colour
2. Cubic shape
3. Moisture content under 14 %

4. Straw from hard cereal cultivars
5. Free from hay, green and grains
6. Sufficient density between 85 – 120 kg/m^3

Straw cultivated through biological methods frequently exhibits the drawback of having proportionally higher green matter content compared to conventionally grown crops. In the presence of moisture, these greens work as a starter for mould growth (Gruber, 2015).

2.6.2 Technical description of the Original CUT technique

Before being used, the straw bales are straightened and soaked in slurry:

1. Straightened: The round edges are reworked by hand to obtain a cubic shape. Straightening helps to obtain a uniform straw surface and lowers the amount of stuffing.
2. Soaked in a liquid clay slurry: Both sides of the bale are soaked to a depth of approximately 5 cm (Evrard et al., 2016). The soaking of the bales, also called "the French dip" is not a necessary step and is no longer implemented by Tom Rijven (T. Rijven, personal communication, 6 February 2024).

Wooden posts (25 to 35 mm · 150 to 190 mm) are placed at the centere of the wall and connected to the top plate and base plate. These posts are distributed with a slightly (five centimeters) shorter distance than a bale length. The straw bales on edge are inserted between the posts in horizontal layers. After the first straw bale row is infilled, two strings that hold the bales are cut, releasing the pressure in the horizontal direction that was built up within the bale during the baling process (Rijven, 2007). The expanded bales enclose the gaps around the posts and create a continuous plaster ground (Gruber, 2020a). The next step of the wall erection is to insert two horizontal battens into the top side of the bales – the grooves to insert the battens are cut on the top of each straw bale row, the battens are inserted into the groove and are pressed in the vertical direction, either by human weight or a lever (see Figure 7) pressing to two battens and when the battens are in the desired position, they are screwed or nailed into the posts (Rijven, 2007).

Figure 7:Compressing the bales in vertical direction with a lever machine commonly called "mammoth" (Rijven, 2024)

These steps ensure that the bale is under tension in the horizontal and vertical direction. Releasing the horizontal force and usage of the two battens prevents the buckling of the posts and thus allows to use smaller post dimensions, therefore the bales and battens also have a bracing function to some extent. This is visualized in Figure 8. After the walls are infilled with straw bales, nonuniformities, and holes are filled with cob or stuffed with loose straw (Rijven, 2007). However, using cob is not recommended by Gruber (2020a) since it creates additional thermal bridges.

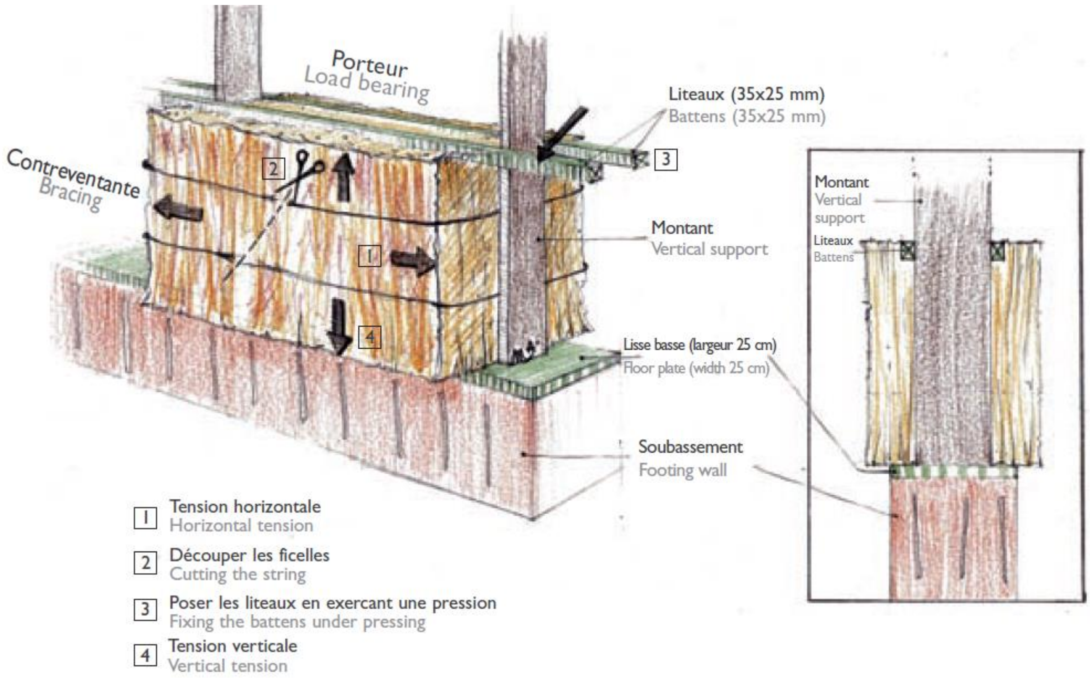


Figure 8: Description of the Original CUT technique by Rijven, (2007)

After the surface of the wall is uniformed, the straw bales surfaces are plastered in two layers, the body coat (also known as an undercoat) with an average thickness of 25 mm and the final coat. The body coat connects the bales, the cells of the wall, together, and thus secures the final structural integrity (Rijven, 2007).

2.6.3 The body coat

The body coat is a specific mixture containing of a thick clay slip, 3/8 of fibres (straw, hay, grass or fern), 1/16 sand, 1/8 of sawdust or wood shavings, and 1/16 of fermenting liquid. The combination of straw and fresh grass as the fibres are recommended, the grass serves as a fermentation starter, and the straw as plaster reinforcement. After thoroughly mixing the ingredients, it is necessary to activate the fermentation process and leave the mix in a humid and warm environment. The bodycoat can be applied on a wet surface of clay-dipped straw by hands and hand tools. Body coat is smoothened with the help of a swimming pool trowel and usage of a body pressure (see Figure 9). Right after that, it is keyed with a notched trowel or nail board to make the surface rougher to ease the application of the final layer. It takes in between two weeks and two months for the body coat to dry out, the walls can be freely exposed to the weather since the coat is weatherproof because of the fermentation process. The body coat will most likely crack, these cracks need to be filled after the plaster is completely dry (Rijven, 2007).

Figure 9: Smoothening the body coat with swimming pool trowel (Rijven, 2024)

2.6.4 Final plaster coat

The final coat mix composition is determined based on the amount of clay that is present in the used earth. To determine the right proportion of clay and sand, on-site tests need to be done. The desired mixture is mixed with fromage blanc (250 gr of fromage blanc for 10 l of clay slip). To increase the waterproof abilities of the final coat, it is mixed with mayonnaise made from linseed oil and egg yolks is added (0,5 l of mayonnaise to 30 l of final plaster) (Rijven, 2007).

2.6.5 Mechanical performance of the Original CUT construction

The Original CUT wall is a combination of wood (base and top plate, horizontal battens, and posts), straw bales, and clay plaster. These materials together create a load-bearing system. The straw bales to insulate, provide stable plaster ground, and transport some of the horizontal loads while also having a small impact on the wall bracing Clay plaster to transfer vertical and horizontal loads and ensure the air tightness and weather protection of the building. Wooden battens to fix the bales in place and prevent the planks from buckling. Lastly, wooden studs, that could be classified as planks due to their low dimensions, to transport vertical loads and allow on edge infill that ensures with better thermal properties (Gruber, 2020a).

Since the plaster has a major impact on the bracing capacity of the walls, it is important to ensure the right connection of the plaster to the straw bale surface. It was proven that shaving the walls has a positive impact on the mechanical performance of straw bale walls. Shaving allows easier and deeper penetration of the plaster material into the straw bales and therefore reinforces this connection (Torregrosa Armendariz, 2020). A deeper connection between the plaster material and straw also increases the horizontal capacity of the wall (Walker, 2004). Moreover, the shaving eliminates the fibres that weren't properly connected to the bale and also increases the flatness of the straw surface (Torregrosa Armendariz, 2020). In the past years, three mechanical studies of the Original CUT technique were performed and are summarized in following chapters.

The first mechanical test

Horizontal load test

This study was performed by Grappaille in year 2008. In total, three different wall assemblies were tested. The first was a stud wall composed of 22 mm HDF, wooden studs 25 mm · 150 mm, and OSB 22 mm without straw infill and plaster. The second test was performed on a straw bale wall without plaster that was composed of vertical posts 25 mm · 150 mm, horizontal battens 38 · 25 mm, and straw bales compressed in between the posts. Lastly, two compressive strength tests were performed on plastered straw bale walls which were composed of vertical posts 25 mm · 150 mm, horizontal battens 25 · 38 mm, straw bales compressed in between the posts, and a 50 mm layer of clay plaster on both sides. All walls had the same length, height, and amount of load-bearing posts (Grappaille, 2008). The description of a plastered straw bale wall is in Figure 10.

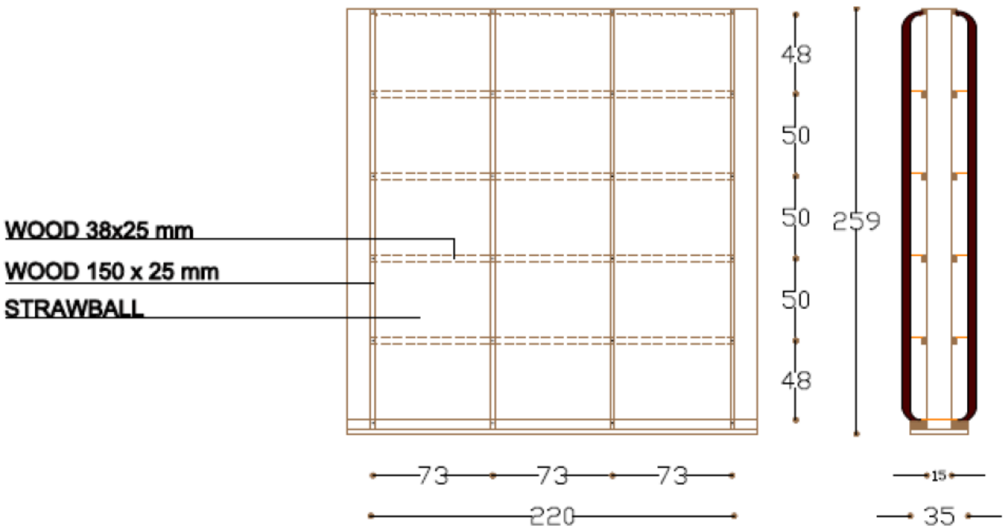


Figure 10: Description of tested walls (Grappaille, 2008)

In Table 1, the results of top-load tests for conventional wall, straw bale wall without plater and two straw bale walls with clay plater are presented.

Table 1: Breaking points of top-load tested walls (Grappaille, 2008)

	Conventional wall	Straw bale wall no plaster	Straw bale wall clay plastered	Straw bale wall clay plastered
Breaking point / t	16,3	8,7	13,8	25,5
Breaking point / (t/lm)	7,4*	3,9*	6,3*	11,6*

*values recalculated by author as ton (t) per length meter (lm) of the wall

The straw bale wall without a clay plaster sustained only 3,9 t/lm while plastered straw bale walls reached 6,3 and 11,6 t/lm until the failure occurred.

Conclusion of the tests

The top-load test showed that a CUT wall can bear 6,3 and 11,6 tons per length meter (if loaded equally) while a wall without plaster can bear only 3,9 tons until the failure. This finding suggests that a significant part of the horizontal load is transported by clay plaster that is connected to the straw bales (Grappaille, 2008).

The straw bales themselves have a minimum impact on the wall bracing capacity, therefore most of the forces are transported through the plaster and wooden construction (Grappaille, 2008).

The ends of the horizontal battens without extensions were determined as a weak part of the construction. Battens should be left with a small overhang of several centimetres behind the corner post (Grappaille, 2008).

The second mechanical test

Another test of the CUT technique was performed in 2010 by Bonnardon et al. Several differently modified CUT walls were built. The walls were firstly tested under horizontal load, until a deflection of L/200 was reached. In the building industry, a deflection that equals to L/200 is considered the admissible limit for timber structures (L being the heigth of the wall). This force is used to assess the effects of wind on the wall. After that, the walls were subjected to a vertically distributed load until failure (Bonnardon et al., 2010).

The wooden construction consisted of four posts 27 mm · 150 mm, battens 27 mm · 38 mm, and all connections were made with screws (Torx 4 · 60). The first three walls were not plastered and differently adjusted. The Wall 4 was plastered. In theory, the posts alone are not sufficient to withstand buckling, but after application of the battens, which are placed every 45 cm, the posts should withstand 30,7 kN and have a load-bearing role (Bonnardon et al., 2010).

In Table 2, results of horizontal force and verticacal force are presented.

Table 2: Results of vertical and horizontal tests (Bonnardon et al., 2010)

Wall type	**Wall description**	**Horizontal force until L/200 was reached /kN**	**Vertical force until collapse /kN**
Wall 1: notches	Five mm deep notch is cut into the battens where it connects with the posts	0,29	97,8
Wall 2: strap	Addition of bracing metal strap	0,46	67,1
Wall 3: basic	Typical CUT wall, no adjustments	0,29	69,7
Wall 4: plastered	Plastered wall type 4	3,3	94,6

Conclusion of the tests

The horizontal load-bearing capacity of an unplastered wall is low, the rendered wall took seven to eleven times more horizontal loads compared to the unplastered walls. This is shown Table 2.

The measurements carried out did not allow to verify the capacity of the posts to support 30.7 kN, therefore the wooden construction is not in accordance with Eurocode 5 (Bonnardon et al., 2010).

It was not proven that plaster increases the vertical load resistance of the walls. Straw bales have a low contribution to the vertical load capacity (Bonnardon et al., 2010).

Latest mechanical test

The aim of the work by Torregrosa Armendariz (2020) was to obtain the bracing capacity of the CUT wall. The tested wall had 45 mm posts spaced 90 cm apart, metal elements and wooden foots were used. The wall was plastered with clay plaster and rendered with hydraulic lime. Two sets of tests were performed – bracing capacity of unplastered and plastered wall (Torregrosa Armendariz, 2020).

Conclusions of the test

It was proven that the plaster has a significant impact on the bracing capacity of the CUT walls. The results showed that plastered wall reached nine times higher bracing performance compared to unplastered walls, therefore the plaster gives the wall its main bracing function. The bracing capacity of the Original CUT walls is sufficient enough for one story buildings and should also be sufficient for two story buildings with efficient shape. The wall was loaded with a force of 8400 N and didn’t show any signs of failure (Torregrosa Armendariz, 2020).

Another finding was that the bales have minimal impact on the bracing capacity of the building and that the penetration of plaster into the straw bales (the plaster-bale connection) is important (Torregrosa Armendariz, 2020).

2.7 Environmental impact of CUT constructions

Straw bale buildings are considered an environmentally friendly way of building, mainly for their low embodied energy and the use of rapidly renewable resources with the possibility to design energy-efficient buildings (Atkinson, 2008). wIn the CUT technique, the potential of all materials is used at its maximum, the amount of wood is minimized, and the straw is a great insulation material with high carbon storage while the environmental impact of clay is minimal in comparison to conventional render systems usually composed of cement. It is also possible to use local products, such as straw bales from nearby farmers, clay from foundation digging, and wood supplied by a nearby sawmill (H. Gruber, personal communication, 3 January 2024).

The CUT wall construction consists of five main components – straw, wood, clay plaster, optionally lime render, and metal elements (nails, screws, and metal angle brackets)(Gruber, 2020a), the environmental impacts of straw and clay are discussed in detail in the following sections.

2.7.1 Environmental impact of straw

Straw bales are a renewable construction material that regrows annually, offering widespread availability and ”natural recyclability” without disposal concerns. Upon demolition, it can be effortlessly segregated and repurposed, for example for garden mulch or soil aeration in agriculture (Minke & Krick, 2020). The insulation properties and higher wall thickness ensure energy efficiency and minimize environmental impact during the use phase as well (Minke & Krick, 2020). For instance, straw bale production requires approximately 14 MJ/m³ of energy, significantly less than the 1077 MJ/m³ needed for mineral wool, making it about 77 times more energy efficient when constructing a 1 m² wall section with a thermal resistance (U-value) of 0,15 W/(m²K) (Krick, 2008).

Figure 11 shows the whole life cycle carbon impact of straw and other insulation materials at thickness resulting in the R-value of 7,13 (m^2K)/W (School of Natural Building [SNaB], 2021).

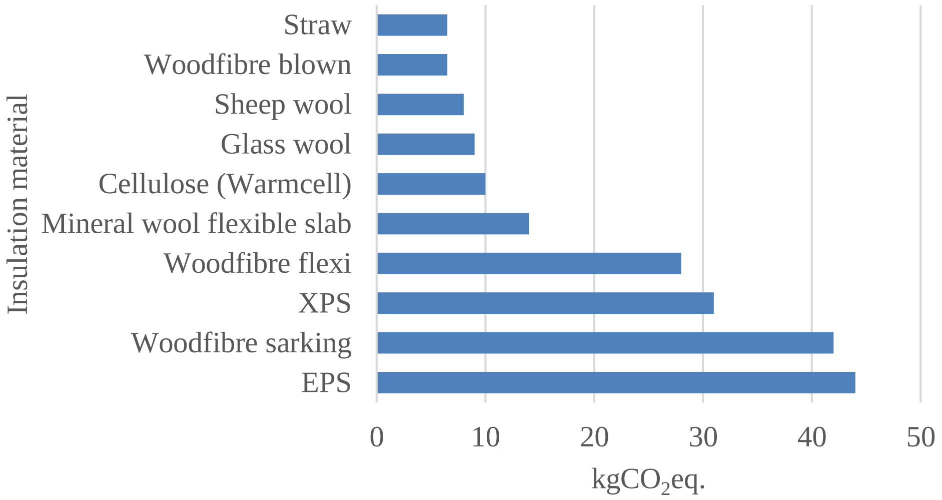


Figure 11: Whole life cycle carbon emmision of 1m^2 of insulation materials with R- value of 7,13 (m^{2}K)/W including biogenic carbon (SNaB, 2021a)

According to ISO 14044:2006, it is allowed to calculate with biogenic carbon, however, some countries might have stricter LCA guidelines. For example in Sweden, calculating with biogenic carbon is not allowed (Boverket, 2021). The biogenic carbon stored in renewable materials is the CO_2 that was removed from the atmosphere by the plant's photosynthesis process, thus lowering the CO_2 proportion in the atmosphere. The environmental benefits are enlarged the longer the CO_2 remains in the material (Stora Enso, 2020). Excluding the biogenic carbon would led to worse results of materials including carbon (SnaB, 2021a). Constructing with straw benefits the environment by capturing CO_2 during its growth phase, while the production of straw bales and their use as thermal insulation in buildings generate minimal CO_2 emissions, further aiding in the reduction of carbon emissions (FASBA, 2019b). The carbon dioxide captured by straw during photosynthesis notably exceeds the emissions from its production and transport, enabling buildings insulated with straw to notably decrease carbon dioxide emissions in the construction sector. Therefore, straw not only fufills but exceeds the criteria for sustainable building material, surpassing even wood in terms of lower energy consumption and carbon dioxide production during its lifecycle (Minke & Krick, 2020). Figure 12 shows the potential of different bio-based materials to store carbon (negative values), compared to cradle-to-gate (phases from extraction to the factory gate) emissions per 1 kg of the building material (possitive values).

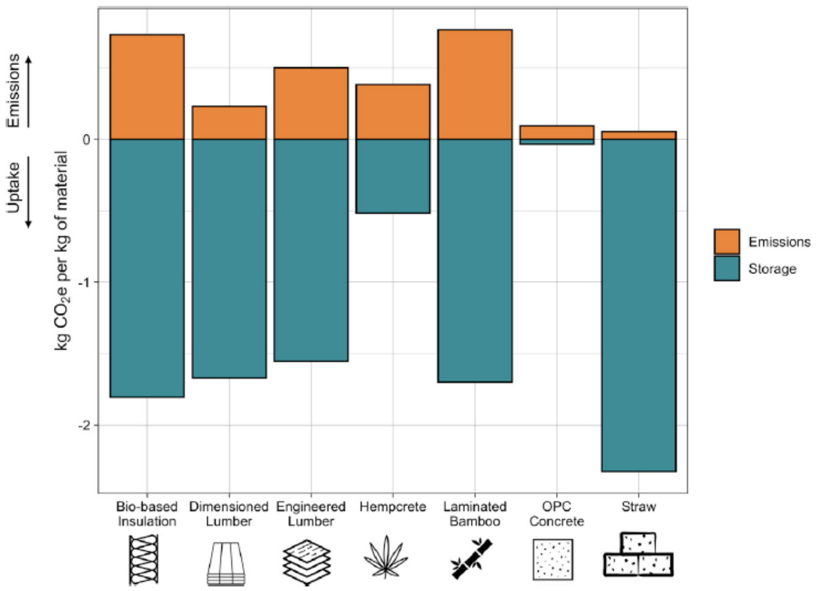


Figure 12: Net carbon storage potential of 1 kg of building materials (Pomponi et al., 2020)

For straw bales as a building material, two EPDs (Environmental Product Declarations) verify the positive environmental impacts of straw bales as a building material (FASBA, 2019b). The first EPD file was created by FASBA (2019a), followed by the second EPD by the SnaB (2021). Since the straw is a by-product of grain such as barley or wheat, a process of allocation should be applied to create an EPD file, and since the revenue from the co-production of straw is fairly low, economic allocation should be applied (SNaB, 2021). The allocation process during EPD creation of straw bales might be a possible motivation for grain producers. The allocation of environmental impacts from grain production is 14 % (SNaB, 2021).

2.7.2 Environmental Impact of Clay Plaster

In general, clay products have substantially lower environmental impact compared to other building materials due to their simple production processes and relatively low energy demand on production compared to conventional plasters (Minke, 2005). Typical clay plaster is composed of clay and sand, and the production involves several steps that can be seen in Figure 13.

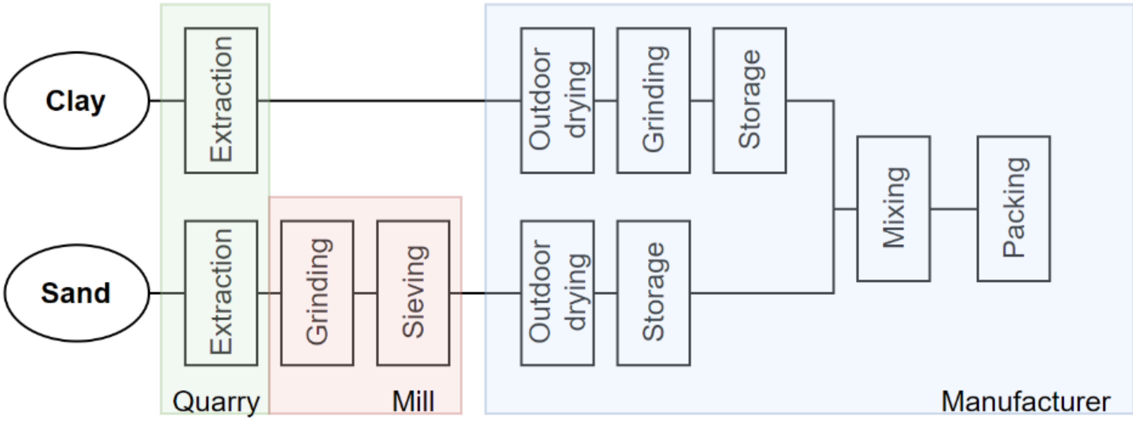


Figure 13: Production process of a commercial clay plaster (A1–A3) (Melià et al., 2014)

The major portion of plasters emissions originates from energy that is derived from fossil sources. For example, the major CO_2 emissions to produce cement plasters primarily arise from the calcination process, and the major emissions to produce clay plaster come from the extraction and processing of material together with transportation (Melià et al., 2014). The comparison of environmental impacts of different plaster materials for cradle-to-gate phases can be seen in Figure 14.

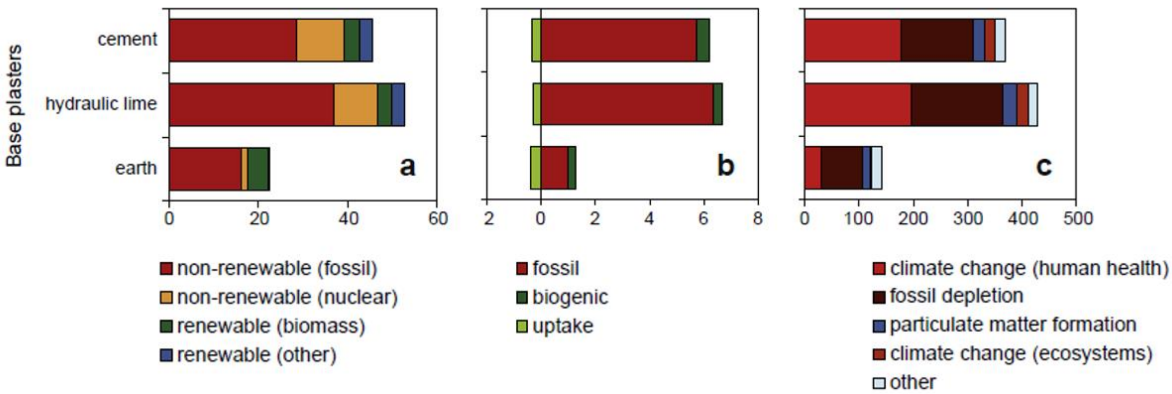


Figure 14: The comparison of environmental impacts of different plasters including cradle-to-gate phases (Melià et al., 2014)

Transportation plays a significant role in determining the overall environmental impact of earthen plasters. This highlights the importance of sourcing raw materials locally to maintain the environmental benefits of using natural building products. A comparison of the three plasters can be seen in Figure 15. The clay for base plaster came from a producer located 14 km from the manufacturing site, the clay for ochre plaster was transported 250 km and the yellow plaster was transported 500km. The rest of the materials like sand and straw had the same transportation distance for all plasters (Melià et al., 2014).

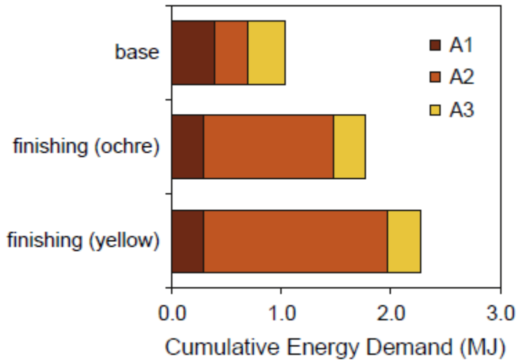


Figure 15: Cumulative energy demand (MJ) for clay plaster production including phases A1 – A3 (Melià et al., 2014)

2.7.3 Environmental impact of wood

The process of drying timber in kilns is the most energy-consuming step in the production of timber products, consuming between six to nine times the amount of energy required for the sawmill process alone (Wengert & Meyer, 1992). The wood drying process takes between 60 and 70 % of the overall timber processing energy (Breiner et al., 1987). For strawbale buildings, using rough sawn fresh, or air-dried timber is often preferred by the builders and architects, therefore the environmental impact of wood in straw bale construction is often lower compared to traditional timber frame houses using kiln dried wood (H. Gruber, personal communication, 3 January 2024).

2.8 Life Cycle Assessment

Life Cycle Assessment (LCA) is a widespread method to evaluate the environmental impacts on the environment over the lifespan, also called cradle-to-grave (Hill, 2012), of the building product or whole building (Hauschild et al., 2012).

LCA helps architects, builders, and authorities make informed decisions about material selection and to be able to compare different products. This approach aims to help cut the building industry emissions. LCA is supported by standards such as ISO 14025 and EN 15804. Those frameworks standardize the procedure of making products EPDs (Del Borghi, 2013).

To conduct an LCA analysis, the following phases need to be carried out according to ISO 14040:2006 standard (Technical Committee ISO/TC 207, 2006):

- Goal and scope phase
    - Including functional unit, the purpose of LCA analysis is defined, and system boundaries such as calculation period, life cycle stages, environmental categories, description of allocations, and assumptions are defined (Farsäter, 2023).
- The Life cycle inventory phase (LCI)
    - Including the collection of required data as stated in the goal and scope phase, Integrating material and energy streams into a single product system, and allocations (Farsäter, 2023).
- The Life cycle impact assessment phase (LCIA)
    - The environmental impacts of the material are evaluated based on the LCI results. This involves linking inventory data with specific environmental impact categories like global warming potential (GWP), ozone depletion (ODP), etc. The goal is to assess the magnitude and significance of the potential environmental impacts deriving from the product system (Farsäter, 2023). The LCIA phase might include normalization and weighting, those steps are not mandatory and are dependent on the goal and scope of the study (Sala et al., 2018).
- The interpretation phase
    - The results of LCA analysis are interpreted and presented (Farsäter, 2023).

2.8.1 Normalization and Weighting

As mentioned above, the Normalisation and weighting are part of the LCIA phase and those two operations are optional in terms of LCA analysis. Normalization and weighting are operations that help to understand and express the results by a single score. Weighting provides the recognition of the most significant environmental categories. At the first step of the weighting, different weight (importance) is given to each environmental impact category. There is no unity on what weighting values should be used for different environmental impacts, the value of the weighting factors might differ based on personal opinion, geographical location, and other factors (Sala et al., 2018). A recommendation on the weighting factor values was done by Sala et al. (2018) based on their extensive study and is recommended for European Union (EU) area. The recommended values can be seen in Table 3.

Table 3: Weighting factors recommendation (Sala et al., 2018)

Impact category	Weighting factors /-
Climate change	21,06
Ozone depletion	6,31
Human toxicity, cancer effects	2,13
Human toxicity, non-cancer effects	1,84
Particulate matter	8,96
Ionizing radiation	5,01
Photochemical ozone formation	4,78
Acidification	6,20
Eutrophication, terrestrial	3,71
Eutrophication, freshwater	2,80
Eutrophication, marine	2,96
Ecotoxicity freshwater	1,92
Land use	7,94
Water use	8,51
Resource use, mineral and metals	7,55
Resource use, fossils	8,32

2.9 Thermal bridges in straw bale constructions

Thermal bridges in straw bale constructions should be avoided, and careful awareness of the location and design of ring beams, thresholds, posts, and floor-to-wall junctions (Minke & Krick, 2020), or junctions between exterior walls and windows or doors (FASBA, 2019b). The presence of thermal bridges will lead to higher heat losses and in some cases can lead to construction damages due to condensation of water vapour. All unheated adjacent structures (balconies, pergolas, etc.) should not interfere with the thermal envelope of the building (Márton et al., 2014). To optimize thermal bridges, suitable actions should be taken, such as ensuring adequate insulation for all building components. This is especially important for junctions between exterior walls and windows or doors, as well as for incorporating constructions into the exterior wall, and for all other interfaces between construction elements.

2.10 Fire safety and fire resistance

Resistance to fire (Fire resistance duration) of straw bale walls is done with REI classification which aims to evaluate the time for which the structure can keep its function such as enclosure of space, structural integrity, and heat transfer, during the fire test (Butler, 2020).

Several fire resistance tests on plastered straw bale walls, compliant with EN 1365-1 standards, were performed over the past years. Both loadbearing and non-loadbearing walls succeeded with results between 120 and 135 minutes without any failure in the test criteria. Although these assemblies haven't been officially classified yet, the outcomes indicate that they could potentially meet a fire resistance classification of REI 120, which is considered as very good rating (Butler, 2020). As for walls without the plaster, an EcoCocon 250 mm thick panel covered with 60 mm wood fibreboard was tested and obtained REI 120 as well. The wood fibreboard withstood a fire for only 55 minutes. For the 65 remaining minutes of the test, the straw protected the construction with fire penetration of only 50 mm (EcoCocon, 2021).

G. Minke and Krick (2020) suggest that the strong fire resistance is caused by the properties of the mineralic renders. Other factors that affect the fire resistance are – straw is composed of Silica (≈4 %) which is a natural fire retardant, the compressed straw doesn't allow air supply and creates a carbonized layer on the surface, straws insulating properties prevent self ignition deeper within the construction (EcoCocon, 2021).

Loose and dry straw is flammable, it is also very slippery when spread on a slick surface, therefore it is necessary to keep the building site clean not only for fire safety reasons (ASBN, 2015b). Unplastered straw bale walls during the construction process always present a fire risk, therefore the body coat should be applied right after the straw works are finished (Minke & Krick, 2020).

2.11 Air tightness

The proper role of ventilation systems depends on a high level of air tightness (Minke & Krick, 2020), where the maximum amount of air passing through the heat recovery unit is desired. To ensure this requirement, it is suggested to place the air tight layer closer to the interior (Hudec et al., 2013), however, there are also different ways to reach air tightness in straw bale houses. In the EcoCocon strawbale prefabricated system the main air tight layer (diffusion open membrane) is located on the exterior side of the straw bale wall (Ecococon, 2023). In traditional straw bale walls, clay plaster as the interior surface material has a function of an air tight layer, since the straw bale itself has very poor values of airflow retardation (Brojan et al., 2015). To reach the passive house standard of infiltration at 50 Pa 0,6 h^{-1} only with a layer of clay plaster is hardly achievable (Hazucha, 2013). When using earth plaster as the air tight layer, it must be sufficiently reinforced to prevent the occurrence of cracks that could penetrate the entire depth of the plaster coat (Minke & Krick, 2020).

In the case of clay plaster, the plaster surface can be considered air tight if it does not contain cracks. However, any connections and passing wooden elements are problematic, where it is often not possible to ensure air tightness permanently or only with perfectly thought out and designed details (Hazucha, 2013). Careful planning is necessary for transitions between clay plaster and different materials (Minke & Krick, 2020). Clay plasters have a higher shrinkage and always crack and form a small gap in the joints. This has to be taken into account, therefore the connection has to be solved by plastering flexible strips and foils with the possibility of plaster expansion (Hazucha, 2013), or connecting plaster to textile tape, as shown in Figure 17 (ASBN, 2021).

To reach lower levels of air tightness in a passive house standard, it is recommended to use building foils, papers, or panel materials with securely sealed joints (Hazucha, 2013). As for prefab systems, one of Europe's biggest producers, the EcoCocon straw bale prefab modular system, ensures air tightness with an air tight, diffusion-open membrane with S_d < 0,2 m on the exterior, balancing heat loss prevention and moisture transfer. This measurement contributes to achieving the Passive House standard in cold climates (Ecococon, 2023). Two examples of straw bale passive houses are described in an article by Ščudla (2018), where air tightness of 0,3 and 0,4 h^{-1} at 50 Pa was reached for the Ecococon house and straw bale house with CLT construction by NOVATOP. Another example of an excellent result of air tightness of 0,21 $h^{-1}$is a load-bearing straw bale house in Dobřejovice, Czech Republic, where OSB boards inside were used as the main air tight layer as seen in Figure 16 (Centrum pasivního domu [CPD], 2017).

Figure 16: Load-bearing construction with OSB boards towards the interior to ensure higher levels of air tightness (CPD, 2017)

2.11.1 Air tightness in buildings with clay plaster as the main air tight layer

Several blower door tests were performed. Brojan et al. (2015) carried out a test in Radomlje in Slovenia with the first test result of 9,99 h^{-1} and after repairing the cracks in the surface of the plaster, the result improved to 7,52 h^{-1}. According to Racusin et al. (2021) the average result of air tightness in straw bale houses in the USA is 5,12 h^{-1}. Pierzchalski (2022) carried out two air tightness tests in Poland, where values of 5,33 h^{-1}were measured before the external plaster was applied. The second test showed an improvement of 1,15 h^{-1} with a result of 4,2 h^{-1}. The results of those tests show that it is difficult to reach sufficient levels of air tightness to reach energy-efficient or passive building standard, which is at 0,6 h^{-1} with only indoor clay plaster as the main air tight layer (Pierzchalski, 2022). However, according to Grmela (2018), the world records of air tightness with clay plaster as the main air tight layer was 0,4 h^{-1} measured in Belgium and Germany, therefore it is possible, but only with highly skilled craftsmanship and professionalism. Figures 17 and 18 displays the proper connection of clay plaster to paper building foil and textile tape to reach higher values of air tightness.

Figure 17: Connection of clay plaster to reinforced craft paper to prevent infiltration in the joist in traditional straw bale construction (ASBN, 2021)

Figure 18: Application of building tape on the plaster - ceiling connection (ASBN, 2021)

2.12 Moisture transport and weather protection in straw bale houses

Straw bales, a natural and biodegradable building material, are susceptible to decay under specific higher conditions of moisture, temperature, and time, therefore the major concern in strawbale exterior walls is emphasized on moisture control (Straube, 2000). The literature on this subject typically offers broad design recommendations to eliminate moisture-related risks, emphasizing on the importance of weather conditions (Mesa & Arenghi, 2019). Several moisture and water sources need to be considered, not only the moisture generated indoors (bathing, cooking, washing, and respiration) but also external sources such as wind-driven rain, humidity, mist, etc. (Ezennia & Alibaba, 2017). As for the source of moisture and its effects on straw bale walls, wind-driven rain was identified as the most serious issue followed by humidity generated indoors (Straube & Schumacher, 2003).

2.12.1 Moisture transport in straw bale constructions

For the outer section of a construction element (wall, roof, elevated base plate) insulated with straw, it is crucial to facilitate moisture movement across the different layers of the envelope components (FASBA, 2019b). Strawbales as a material with low values of diffusion are heavily dependent on the ability of a coating to prevent moisture infiltration (Straube, 2000). To prevent the accumulation of condensate on the exterior side of the straw insulation, the cavities need to be uniformly insulated with no gaps. Instead of directly applying a membrane over the straw surface on the external side, a material that can absorb moisture and is capillary absorbent, such as clay plaster or wood fibre insulation boards is suggested (FASBA, 2019b).

Moisture transfer and air tightness are then regulated with an air tight layer of clay plaster that needs to be carefully connected to other materials, or with the use of board materials such as OSB boards (Gruber, 2021), in detail discussed in chapter *2.11.*

2.12.2 Constructive weather protection of straw bale houses

Construction elements insulated with straw need to be consistently protected from external weather elements. For exterior walls, this protection is achieved through the use of either ventilated façade systems or crack-resistant, weatherproof lime plaster that comes with a breathable, water-repellent coating to guard against driving rain penetration (FASBA, 2019b). Another important principle of constructive protection of straw bale houses are a sufficient roof overhang to eliminate the amount of wind-driven rain and water absorption into the render, elevated foundations at least 300 mm above the ground to prevent splash water, capillary break area in foundations, good detailing of windows, doors, and other openings (ASBN, 2015; FASBA, 2019b). Moisture damage on a CUT Flexagone house due to the higher long-term levels of humidity and exposure to splash water can be seen in Figure 19.

Figure 19: Moisture damage on two year old CUT Flexagone straw bale wall located in Denmark

2.12.3 Common finishes and coatings of straw bale walls

In general, mineral-based materials are applied on the exterior of straw bale walls such as lime, clay, but also cement, and gypsum. The render has several functions such as weather protection, insect and rodent control, and fire protection (Straube, 2000). Wihan (2007) presented answers of 27 straw bale builders, engineers, and architects. Results showed that the preferred type of finishes on straw bale walls is earth plaster (37 %), lime renders – hydraulic lime, and lime putty (31 %), clay plaster stabilized with lime (8 %) and cladding façade (4 %). The results showed that to increase the resistance of plasters against weather conditions following measures are utilized – sufficient overhangs, good design and building details (26 %), limewash (18 %), siloxane (11 %), linseed oil (11 %), silicate paint (11 %) and wheat paste (7 %).

2.12.4 Moisture performance of straw bale walls with lime render

Examples of non-load-bearing double post and load-bearing straw bale wall systems with lime render is shown in Figure 20 and Figure 21 respectively.

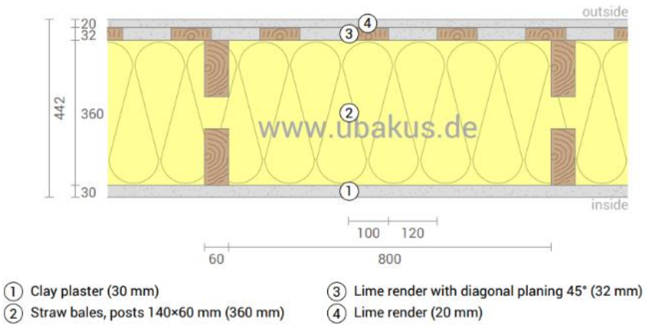


Figure 20: Non-load-bearing straw bale wall with diagonal planking and lime render)

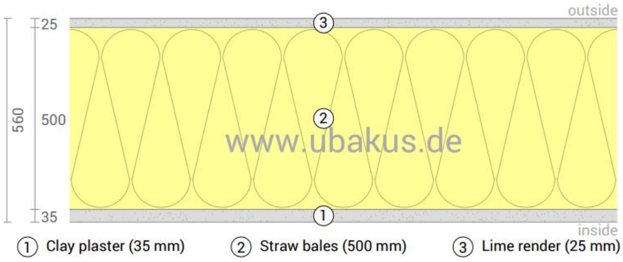


Figure 21: Load-bearing straw bale wall with lime render

Goodhew et al. (2004) investigated levels of moisture in 5 year old straw bale walls in the UK rendered and plastered with lime surrounded by higher levels of vegetation with higher levels of relative humidity. Results showed that probes located on the bottom of the southern façade close to the dewpoint area showed higher levels of humidity exceeding 25 to 30 % and degradation of straw, while probes located on the west and east facades showed levels of RH under 20 %. It was concluded that the cause of higher levels of RH is caused by water absorption into the render on the windward, unprotected side of the building.

Another long-term six year study was done on a straw bale passive house in the UK in a similar climate with sensors located closer to the interior not exceeding critical RH of 75 %, therefore no mould growth in the layers that could affect the indoor environment was detected. Other sensors were inserted into the outer part of the wall (shown in Figure 22) to the dewpoint area, where the RH exceeded the 75 % RH threshold in all facades, therefore VTT Mould Index (MI) was calculated and didn't exceed 3 and gradually decreased under 2 in the eastern wall and close to 0 in the southern, northern and western walls (Marincioni & Bradshaw, 2023).

Figure 22: Location of inner and outer sensor in the straw bale wall (Marincioni & Bradshaw, 2023)

It is suggested to finish the lime plaster with hydrophobic diffusion open paints such as lime-wash or silicate paint, which will reduce the absorption (the w-value) of water during driving rains from 7 kg/m^2h to 0,7 kg/m^2h and thus protect straw bales and wooden structure from higher levels of humidity (Gruber, 2021). Brandhorst (2013) states that the exterior plaster must have a w-value lower than 0,1 $kg/(m^2h)$ in the long term for EcoCocon walls in Vienna, Austria. A comparison of real-time values of moisture content and WuFi simulation was carried out by Mesa and Arenghi (2019), where similar results were obtained.

2.12.5 Moisture performance of straw bale walls with clay render

An extensive study by Straube and Schumacher (2003) was performed on load-bearing houses with clay render in California. It showed that the levels of RH on the outer side of the straw bales reached values lower than 75 %. The rain was the cause of the peaks of the RH and the drying of the wall took a few days. However serious wetting of the wall would require between four to eight weeks of drying time.

Permeability of clay render

Clay is a highly permeable material compared to other products used for renders (Straube, 2000). Clay is a material composed of clay crystals, that are bonded with electromagnetic force, and sand. The electromagnetic force attracts molecules of water with capillary action, leading to the swelling of clay minerals and closing the pores and gaps between clay and sand. The closure of pores at high humidity levels protects the straw from moisture intrusion and after the surrounding humidity decreases, clay starts to release the humidity back into the environment, the crystal shrinks back and the permeability of the render increases again (Warren, 1999), leaving the strawbale layer behind the render to dry out. Therefore clay render can be classified as semi-permeable material (ASBN, 2021). Nevertheless, the particles of sand and clay minerals are neither mechanically nor chemically bonded, and with the growing amount of water in the material, the electromagnetic force weakens and clay render is susceptible to water erosion. There are several different methods how to make clay render surfaces more water resistant and clay plaster itself more stabilized against water erosion:

Hardening the surface with a metal trowel using high pressure

The easiest method to harden the surface of the plaster is to use a trowel and apply high pressure by rubbing it on the surface when it's "leather hard". This will cause the macroscopical pores to close and the surface should appear shiny (Minke, 2005).

Paints

Paints applied on the surface of clay plaster need to be periodically reapplied because they can undergo physical wear due to wind, frost, rain, or chemical degradation from ultraviolet radiation or acid precipitation. It is required to keep the plaster diffusion open, thus latex and dispersion paints are not suitable (Minke, 2005). Table 4 displays the influence of clay plaster coatings and water repellents on the A-value (Water absorption coefficient) and S_d-value (Equivalent air layer thickness) of the clay plaster.

Table 4: Properties of coatings and water repellents (Minke, 2005)

Paint	Required amount / g/m^2	A-value / kg/(m^{2}h^{0,5})	S_d-value /m
Without paint/repellent	0	9,5	–
Linseed oil (1 layer)	400	0	1,45
Lime Casein 1:1	420	0,6	0
Silin-paint (van Baerle)	700/250/310	0,3	0,04
Hydrophob (Herbol)	390	0	0,02

Stabilization against water erosion

It is not necessary to increase the water resistance of earth plasters if they are completely protected from rain and leaning water. Theoretically, above mentioned, weather-resistant coats should be sufficient protection, but due to the formation of cracks and water erosion, it is suggested to use stabilizers in the clay render such as lime, cement, bitumen, water glass, and animal products (blood, urine, manure) (Minke, 2005).

Clay render in CUT technique

In the Original CUT technique by Tom Rijven, horse manure is used in the clay render. This render is optionally mixed with other fermentation starters such as grass or other natural fibres, and is kept aside for at least ten days for the fermentation process to take place. The first houses built with the CUT technique around 20 years ago show that this clay render can sustain weather conditions (T. Rijven, personal communication, 6 February 2024).

2.12.6 Mould Index

In certain conditions of temperature and moisture, different surfaces within buildings can become prone to mould formation. This presents aesthetic and hygienic problems but also poses a considerable health risk (WUFI®, 2024). Exposure to mouldy environments can negatively impact humans, and children more severely, for example can lead to numerous health complications, including nasal congestion, respiratory colds, and allergic reactions like itching of the eyes and skin. Dangerous outcome is Mycotoxicosis, which refers to a condition caused by exposure to mycotoxins, which are toxic substances produced by moulds (Assouline-Dayan et al., 2002).

During the design phase, it is crucial to prevent mould growth on building elements by appropriate design and conducting simulations. Hygrothermal simulation shows the temperature and humidity conditions within and on building structures. With known hygrothermal conditions, the Viitanen model (VTT) model can be applied to overcome mould growth risks early in the design phase. The VTT model uses the term mould index (MI) which refers to a scale derived from the VTT that assesses mould formation based on temperature, humidity, and duration on pine sapwood considered a sensitive lignocellulosic substrate (Viitanen et al., 2015). It was discovered that straw has the capacity to endure relatively high levels of moisture without undergoing significant deterioration in comparison with other ligno-cellulosic materials, especially when straw is located within the construction (Thomson & Walker, 2014). MI can be used to assess the health risk to occupants as well as a conservative proxy to determine material – straw and wood decay (Marincioni & Bradshaw, 2023). MI, which ranges from 0 to 6, is determined by calculating the cumulative rate of mould growth over time, detailed description of MI is shown in Table 5 (Viitanen et al., 2015).

Table 5: Mould index value and description for experiments and modeling (Viitanen et al., 2015)

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, <10 % coverage, or < 50 % coverage of mould (microscope)
4	Visual findings of mould on surface, 10 - 50 % coverage, or > 50 % coverage of mould (microscope)
5	Plenty of growth on surface. > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100 %

For the VTT model, traffic light classification was created by the Fraunhofer Institute (*see Figure 55*). Green signifies that there is no significant risk of permanent mould development. The yellow zone suggests a potential risk of mould growth and particular assessment by the individual should be varied out. Red light gives a level of risk that is not acceptable.

3 Methodology

The methodology is divided into five sections. Firstly, the survey theory and method are described. The second section described how the original CUT technique, modifications, and development were studied and analysed. The third section explains how were the CAD drawings created. In the fourth section, a description of environmental calculation is presented. The fifth section of the methodology describes how the moisture analysis of the CUT technique was conducted. The methodology overview is shown in Figure 23.

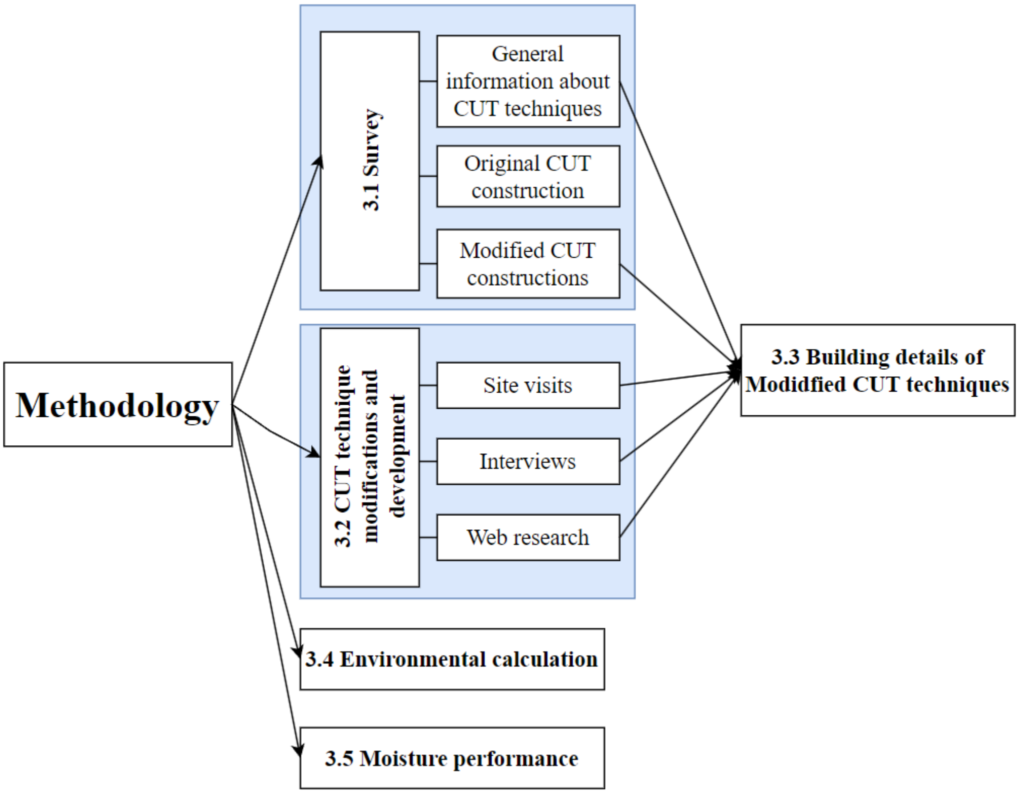


Figure 23: Methodology overview

3.1 Survey

To gather knowledge and insights of builders and architects using the CUT technique, a survey was created. The aim of the survey was to collect data on several topics of the CUT technique.

3.1.1 Survey theory followed in survey design

The survey research primarily aims to gather quantitative data that allows the generalization of results from a set of samples to one population (Fowler Jr, 2013), however, surveys are capable of providing qualitative results as well, if the questions encourages narrative responses (Harlacher, 2016). Surveys might be utilized to gain important information, and surveys conducted online provide outstanding advantages, especially when faced with limitations related to budget, time, or travel. This approach can also help in expanding the total number of participants, thus increasing the sample size (Wagner et al., 2018). Other methods of gathering qualitative data such as interviews may be also appropriate to gain a better understanding (Creswell & Creswell, 2017).

The importance of creating the right and spot-on survey questions is crucial, it should be clear for the researcher what questions he/she seeks to answer (Wagner et al., 2018). Moreover, well-designed questions in the survey ensure that the respondents will understand and answer accurately (Dillman, 2000). Questions can be closed ended or open ended. Close ended questions will provide the researcher with quantitative data, and open ended questions qualitative data (Creswell & Creswell, 2017). Numerous factors, including the method of survey distribution, its design, length, and even the choice of font size and style, can influence the rate at which respondents complete the survey (Wagner et al., 2018). In the development phase, it is a common mistake that researchers may want to cut the survey length or use too simple measurement scales, which can lead to incorrect results (DeVellis, 1991). Ensuring that questions in a survey are logically sequenced is necessary for the correct communication with participants. It was proven that a well-organized survey increases the likelihood of obtaining accurate responses (Schwarz, 2014).

3.1.2 Survey description and data collection

The survey of this study was created in the SUNET survey tool which is a software available for Lund University staff and students. The survey followed several recommendations in the book Exploring Occupant Behavior in Buildings by Wagner et al., (2018) to ensure a higher rate of responses and follow the scientific recommendations on how to build surveys and questions.

The survey aimed to collect knowledge and experience from builders and architects across Europe, therefore it was available in four languages (English, Spanish, French, and Czech) spoken in the countries where the CUT technique or its modifications are used frequently. The translation of survey was done by author and in case of French and Spanish, it was reviewed and corrected by native speakers.

The survey aimed to answer questions in three areas:

1. General information and personal experience about the CUT techniques, moisture, structural and air tightness issues
2. Detailed information about the original CUT construction
3. Detailed information about modified CUT constructions

Most of the respondents were asked to participate in the research by personal communication tools beforehand the distribution to achieve a higher rate of responses. The link to access the survey was sent via email to 47 straw bale builders and architects using CUT techniques. In total, 20 responses were gathered.

The survey used several logic functions and the follow-up questions were differentiated based on the respondent's answers. As an example, out of 20 respondents, 14 stated that they worked with the Post and beam CUT construction, 13 stated that they worked with the Original CUT construction, 10 stated that they worked with Braced CUT construction. Those 14 respondents were asked a follow-up question on the topic of Post and Beam CUT construction, the 13 respondents were asked a follow-up question on Original CUT construction and 10 were asked follow-up question on Braced CUT construction. In the survey, respondents could have shared pictures and other documents.

3.1.3 Result evaluation

The survey report was generated in the SUNET survey tool and the data were evaluated and processed in Excel.

3.2 CUT technique modifications and development

Results of modifications and development of the CUT technique were based on several sources:

- Web research
  - Web pages of companies using CUT techniques were scanned and houses built with the CUT techniques were identified, notes on different CUT methods were saved and noted
- Site visits done by the author
  - Several site visits on the CUT projects were conducted in the past years, prior to the research
  - One site visit of CUT flexagone house in Denmark was conducted during the execution phase
- Interviews
  - Four interviews were conducted with the straw bale builders and architects working with the CUT techniques either in person or through online platforms
- Survey results
  - Some of the survey findings were used to present how builders and architects used and modified the CUT techniques

3.3 Building details of Modified CUT techniques

A list of building details for colder European climates was drawn in AutoCAD 2019. The creation of building details aimed to present some of the suitable solutions or to improve current practices commonly used with CUT techniques. The details were based on the questionnaire results, conducted interviews, and pictures from building sites around Europe, found online or provided by builders and architects using CUT techniques in the survey. Therefore the details are based on a cocmbination of several factors, shown in Figure 23.

Firstly, the execution and function of the details are explained in the text. On the following page, the building details are presented in scale 1:10 in A3 format.

3.4 Environmental calculation of the CUT wall

In the following section, the steps taken to perform an environmental analysis are described. The environmental analysis is divided into two parts, firstly, the environmental impact of the CUT wall is calculated and secondly, the results are compared with a conventional wall system with similar thermal performance.

3.4.1 Goal and scope of environmental analysis

Functional Unit

The functional unit for the environmental analysis was 1 m^2 of the CUT wall with a U-value 0,136 W/(m^2K). Drawing of the wall is shown in Figure 10 – material inputs were taken from the wall that was mechanically tested by Grappaille (2008). The wall consists of four materials (straw bales, wood, clay plaster and metal elements).

Table 6: Life cycle stages declared in the CUT wall environemntal analysis

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	ND	ND	ND	ND	ND	ND	ND	ND	ND	X	X	X	X	X

(X = included, ND = not declared)

Production phase A1 – A3

All relevant steps to extract, transport, and produce the materials obtained in the CUT wall are considered in this analysis, data were collected from the EPD files of each product used in the wall.

Construction process stage A4 – A5

Stage A4 requires a minimum amount of resources since the walls are built with manual labour and minimum use of energy and equipment, the impact of this stage is minimal and in theory, could be stated as 0. For the transparency of the study, it was not included in the analysis. Stage A5 is not considered in the analysis because the transport distance is unknown and varies based on the project distance.

Use stage B1–B7

Stages B1 to B7 are not included in the analysis, during this stage, no emissions to the environment are emitted from the material and no relevant input energy are available. The impact of this stage is minimal and in theory, could be stated as 0 (EcoCocon, 2022; SNaB, 2021a). For the transparency of the study, it was not included in the analysis.

End of life cycle stages C1–C4

When a building reaches its end of life, the process of deconstruction starts. The LCA analysis includes the demolition phase (C1), transport from the side of demolition (C2), necessary recycling activities and incineration (C3), and landfilling of some materials (C4). Those data were collected from separate EPD files of used materials.

Benefits and Loads beyond the system boundary (D)

This phase includes the possible burdens and advantages associated with the recycling and reuse of materials or products (SNaB, 2021), the data were obtained from separate EPD files of used materials within the wall.

Included environmental categories

Table 7: Environmental categories included in the environmental analysis

Environmental category	Unit
Global warming potential (GWP-total)	kg CO_2 eq.
Global warming potential (GWP-excluding biogenic carbon)	kg CO_2 eq.
Ozone depletion (ODP)	kg CFC 11 eq.
Acidification (AP)	mol H+ eq.
Eutrophication, freshwater (EP-fw)	kg $PO4^{3}$- eq.
Eutrophication marine (EP-m)	kg N eq.
Eutrophication, terrestrial (EP-T)	mol N eq.
Photochemical ozone formation - human health (POCP)	kg NMVOC eq.
Resource use, minerals and metals (ADP-mm)	kg Sb eq.
Resource use, fossils (ADP-f)	MJ
Water use (WDP)	m^3

Limitations

The LCA study of the CUT wall used EPD files from different producers, therefore it is calculated with supplied materials. In reality, those materials could be obtained more locally, e.g. using clay for clay plaster from the excavation works, and wood from a local sawmill, therefore the environmental impacts, mainly in stages A1–A3 would be further reduced.

3.4.2 EPD files for the LCA calculation

Table 8: Material input for LCA analysis – The weight of four wall materials included in 1 m^2 of the CUT wall

Material	EPD	Amount /kg in 1 m^2 of the wall
Straw	(SNaB, 2021)	33,5
Wood	(Stora Enso, 2020)	15,5
Clay plaster	(Clayworks, 2020)	77,2
Metal parts	(Borla, 2024)	0,104

Data for the calculation of straw environmental impacts were taken from the EPD file provided by the SNaB (2021), straw with a density of 100 kg/m^3 was used in the EPD calculations. Since the Functional unit of the EPD file was 1m^3 of straw, it was necessary to recalculate the environmental impact values to kilograms, therefore the values of environmental impacts were divided by 100. It was also necessary to recalculate the environmental impact of Eutrophication, freshwater (EP-fw) which was stated in kg P eq. to $PO4^3$ eq to unify the units in all EPDs. According to Ortiz-Reyes and Anex (2018) it is possible to perform this conversion with the Equivalence factor of 3,07 (-) which is based on the substance's molecular atomic weight. The following Equation n. 1 was used:

$$kg\ PO4^3 = kg\ P \cdot 3{,}07 \qquad [kgPO4^3] \qquad (1)$$

Lastly, the environtal impact per 1kg of straw was multiplied by 15,5 kg, which is the amount of wood in 1 m^2 of the CUT wall (shown in Table 8).

Data for the wooden studes were downlaoded from the EPD file created by Stora Enso (2020) for sawn wood. The option of reusing the material at the end of the use phase, for stages C1 to D, was chosen. It was not possible to obtain an EPD file describing construction timber that was not dried, therefore the calculations might not be accurate since the vast majority of strawbale constructions are built using fresh sawn timber. Based on the literature review phases A1 to A3 would require in total 60 % less energy if skipping the kiln drying process. The environmental impacts with FU 1 m^3 in the EPD file were recalculated to 1 kg using the density 460 kg/m^3. To adjust the environmental impacts from a functional unit of 1 cubic meter (m^3) at a density of 460 kg/m^3 to a new functional unit of 1 kg, the fraction of the environmental impacts attributable to 1 kg of the material was calculated, therefore the environmental impacts were divided by 460. The environtal impact per 1kg was multiplied by 15,5 kg, which is the amount of wood in 1 m^2 of the CUT wall, shown in Table 8.

Environmental impact data for clay plaster were taken from the EPD file created by Clayworks (2020) without further modifications since the functional unit was 1 kg. The environtal impact per 1kg was multiplied by 77,2 kg, which is the amount of wood in 1 m^2 of the CUT wall, shown in Table 8.

For the last element of straw bale walls, metal elements, an EPD for an average nail was taken for calculations (Borla, 2024) to simplify the calculation process. The functional unit was 1 ton, therefore the environmental impact values were divided by 1000. The category EP-fw was recalculated with *Equation n. 1*. The environtal impact per 1kg was multiplied by 0,104 kg, which is the amount of wood in 1 m^2 of the CUT wall.

3.4.3 Comparison with conventional wall systems

This subchapter aimed to compare more conventionally used building prefabricated systems with the CUT walls, therefore two other systems with nearly similar U-values were selected. The Functional unit to compare those three systems was set as 1 m^2 of the wall system.

The environmental impact of the CUT wall was compared with the more conventional prefabricated timber wall system from company Biobuilds consisting of a timber-frame structure with cellulose insulation, OSB board, DWD board, weather foil, and timber facade with the U-value of 0,15 W/(m^2K) (Anca, 2022).

Secondly, the environmental impact of the CUT wall was compared with prefabricated concrete panels from German company Heidelberg Materials. This wall consists of inner and outer concrete panels with 200 mm XPS insulation in the middle, with a wall U-value of 0,165 W/(m^2K) (Lidö, 2023). The Functional unit 1 ton which corresponds to 1,85 m^2 of the panel area was recalculated to 1 m^2.

Normalization

The results were normalized by a maximum – the environmental impact for the worst performing wall was set as 100 %, and compared to the wall systems with lower impacts in the examined environmental category. The results are presented in percentages and give a visual comparison between the three wall systems.

Weighting

To understand the results clearly, normalized results were weighted with JRC Technical Report recommendations by Sala et al. (2018), and a single subscore for each environmental category was obtained, those subscores were summed and the final environmental score was obtained.

Limitations

In order to have completely fair comparison, the compared systems should had the same U-values. The compared systems did not have the same U-values because it was not possible to find prefabricated systems with completely same U-values, but walls with slightly worse U-values were chosen. If the U-values were the same, the CUT wals would have reached slightly better values.

3.5 Moisture performance of the CUT walls

A hygrothermal simulation was carried out with the help of WuFi 6.7, results of temperature and relative humidity were exported in ASCII format and were processed in MATLAB to calculate the Mould Index and Critical Relative Humidity (RH_{crit}). The code for calculating RH_{crit} and assessing mould index according to the VTT model was provided by Prof. Vahid M. Nik in the Moisture Safety Design course, version 2022.

3.5.1 Wall assembly and sensor location

The wall consisted of 35 mm of clay render, 360 mm straw bale layer, and 40 mm clay plaster. The exterior surface of the wall was coated with lime casein paint.

To verify that occupants' health is not affected by mould, two sensors were placed on the interior side of the straw bale and the interior surface of the wall. The MI was also used to determine if the wall is not susceptible to decay as a conservative proxy as suggested by Marincioni and Bradshaw (2023), therefore, a third sensor was located on the outer side of the straw bale in the dew point area as done by Mesa and Arenghi (2019).

3.5.2 Climate, Locations, and Simulation Inputs

The Moisture performance was assessed in four different European Climates according to the Köppen climate classification with consideration to the locations where the CUT technique is in use, and also Lund in Sweden. Analysis was performed in the following climates and locations: Humid continental climate – Hradec Králové (Czech Republic) and Lund (Sweden), Temperature oceanic climate – Brussels (Belgium), Cold semiarid climate – Barcelona (Spain/Catalonia). The effect of rain was not considered in the simulations due to the complexity and uncertainty of the simulation. The orientation of the wall was chosen to the northern, since it is the side which receives the least of the solar radiation and have the most suitable conditions for mould growth. All of the simulation inputs are presented in Table 9 below.

Table 9: WUFI simulation inputs

Material inputs	
Clay	Clay rendering, Fraunhofer IBP
Straw bales	Straw bale, Fraunhofer IBP
Exterior coating	Silicate paint
Simulation parameters	
Weather side	North
Adhering fraction of rain	0 (-)
Calculation period	3 years
Indoor climate	EN 15026
Outdoor climate	Corresponding weather file to the examined location from WUFI database
Other inputs	Automatic WUFI preset

3.5.3 Result evaluation

The levels of the Mould Index for different locations were plotted in the graph and discussed. The evaluation was based on traffic light classification provided by Fraunhofer Institute (Fraunhofer Institute, 2024). The levels of Relative Humidity were compared with levels of RH_{crit}, plotted into the graph.

3.5.4 Moisture study limitations

The weather files use data from previous years. With climate change, warmer and more extreme weather conditions such as wind-driven rains and impact rainfalls are expected. Many buildings are built based on available and current weather files, which might not be sufficient in future due to climate change (Robert & Olaf, 2011). The effect of the rain was not included in the simulation, it was assumed that the walls are fully covered with a roof overhang.

4 Results and discussion

The results and discussion chapter is divided into five sections. Firstly, the survey results are presented. In the second section, the modifications and development, of the CUT technique are described and discussed. The third section presents several building details of the CUT technique. In the fourth section, results and a discussion of environmental calculation are shown. The fifth section of the results and discussion presents the mould growth analysis of the CUT technique.

4.1 Survey results

Survey results are divided into 3 parts. The first part describes general information about CUT techniques, the second part presents findings about the Original CUT construction, and the third part presents findings concerning modified CUT constructions.

4.1.1 General information

Overall 20 building professionals and self-builders, mainly from Europe, with various levels of experience with the CUT techniques replied to the survey. Figure 24 represents the results for a single-choice question "*How many CUT buildings have you built/designed?*".

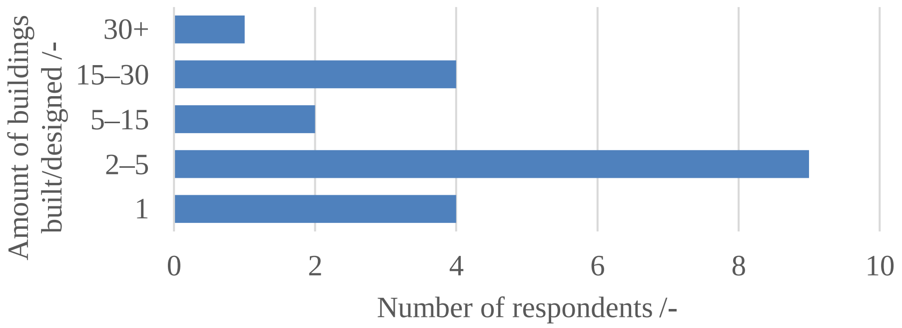


Figure 24: How many CUT buildings have you built/designed?

Questioned builders and architects have built all together between 122 and 250 CUT buildings. The highest number of respondents (45 %) have built between 2 and 5 buildings.

Figure 25 represents the answers to the multiple-choice question "*In what countries have you built CUT buildings?*"

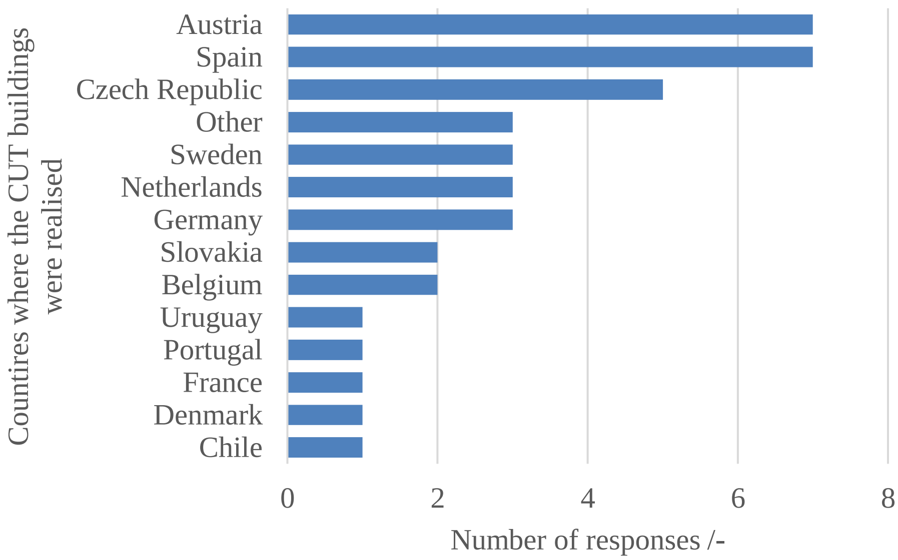


Figure 25: In what countries have you built CUT buildings?

The countries where the CUT techniques seemed to be used the most are Austria, Spain, and the Czech Republic, however, the Original CUT technique is also widely spread in France, mainly among self-builders, which were difficult to track and contact. Another interesting outcome is that 9 out of 20 respondents have built CUT buildings in more than one country.

Figure 26 illustrates the responses to the multiple-choice question, "*How did you learn, or who taught you, to build/design using the CUT techniques?*".

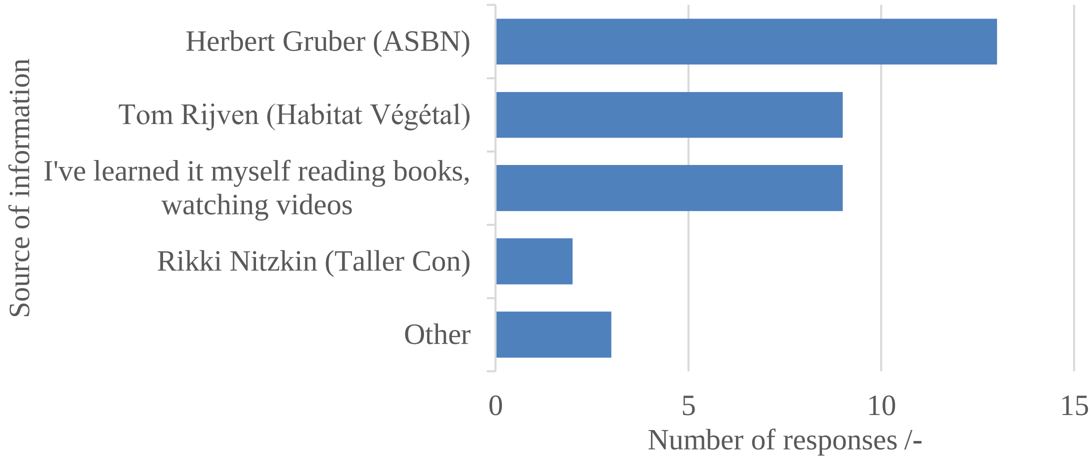


Figure 26: How did you learn, or who taught you, to build/design using the CUT techniques?

Herbert Gruber, Tom Rijven, and Rikki Nitzkin were the most influential individuals spreading the knowledge about the CUT technique. Only three respondents learned how to use CUT constructions solely on their own. Data shows that Tom Rijven's workshops were the source for builders building mostly or only with the Original CUT construction while Herbert Gruber was the source of knowledge mainly for builders using Modified CUT constructions, but the Original CUT construction as well.

Figure 27 shows the responses to the multiple-choice question, "*What kind of CUT technique/techniques did you build/design?*"

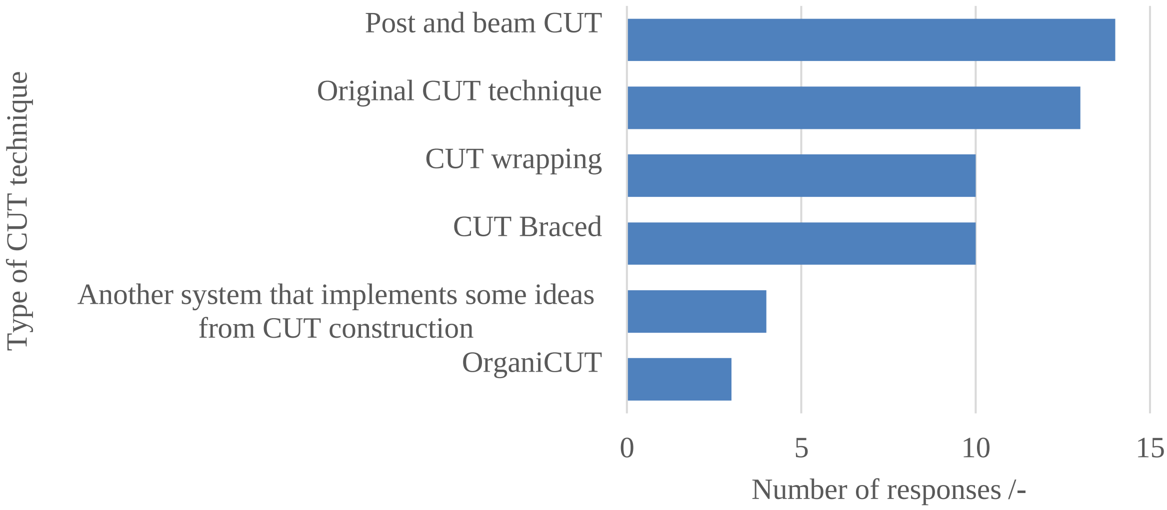


Figure 27: What kind of CUT technique/techniques did you build/design?

The most common types of CUT constructions were CUT walls in combination with post and beam construction (Post and Beam CUT) with 14 responses, followed by the Original CUT technique with 13 responses, CUT wrapping of buildings with 10 responses, CUT walls braced with 10 responses (planks with 8 responses and 2 for board bracing), and OrganiCUT with 3 responses. Other CUT systems that implement some ideas of CUT construction were twice CUT technique with bales laid flat instead of on edge and once using two rows of bales laid on edge with two posts to fix the bales where the inner post was load-bearing.

Cutting the bales on top to insert the battens to eliminate the thermal bridges and stuffing is done by 17 out of 20 respondents. Those 17 respondents were asked a multiple-choice question “*What tools do you use to cut the top side of the bale?*”

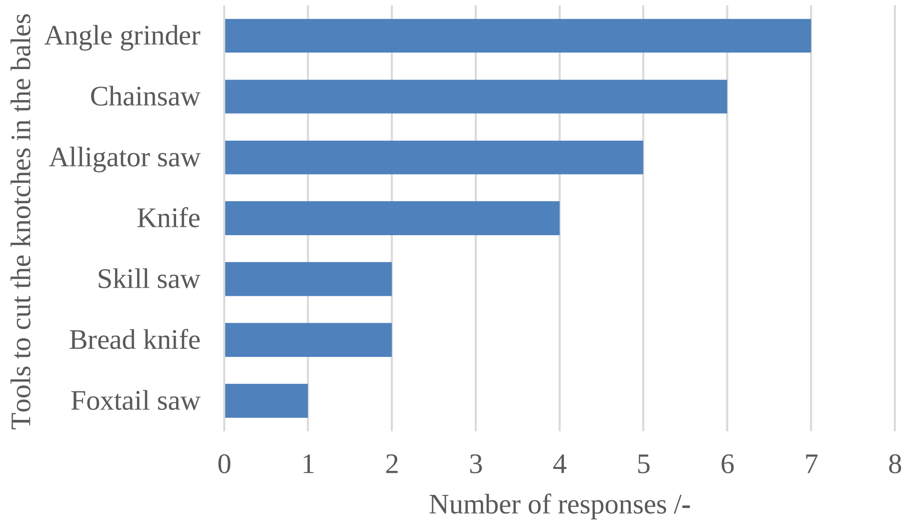


Figure 28: What tools do you use to cut the top side of the bale?

The most commonly used tools to cut the notches into the top side of the bales were an Angle grinder, Chainsaw, and Alligator saw.

As for the finishes on the CUT buildings, respondents were asked multiple-choice question ” W*hat finishes of the outside do you prefer to use on the CUT or CUT system modified walls?*”

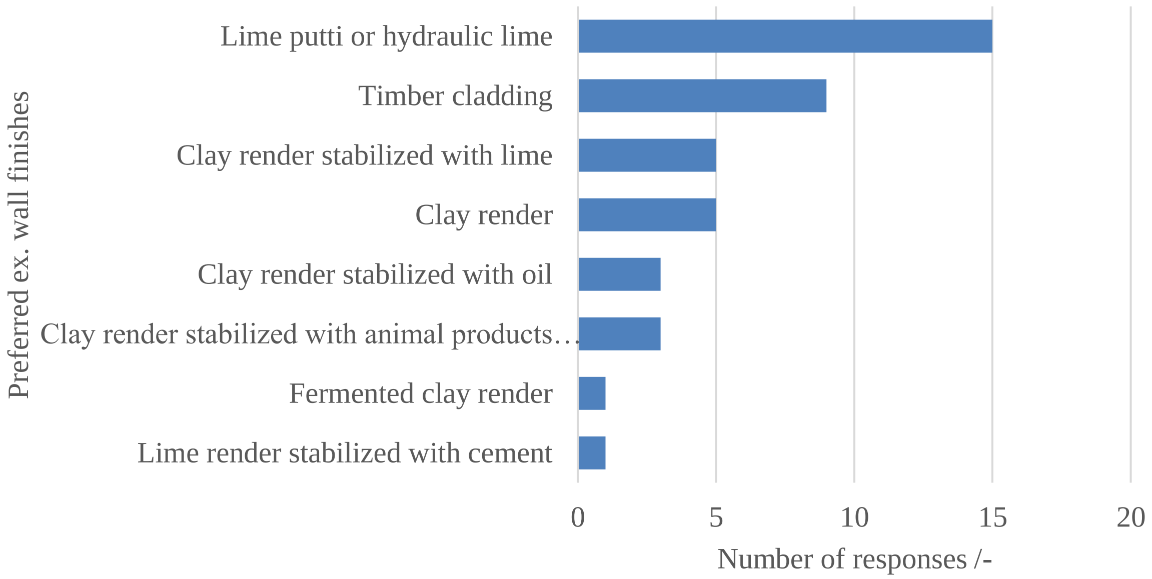


Figure 29: What finishes of the outside do you prefer to use on the CUT or CUT system modified walls?

The results showed that summed variants of clay render are the most preferred wall finishes with 17 responses, followed by lime render with 16 responses and timber cladding with 9 responses. Clay render was preferred by builders working in areas with lower amounts of rain while lime plaster and timber cladding were in general preferred in more rainy areas.

In the following question, builders and architects were asked multiple-choice question " *What surface finish do you prefer to use on the outside render?*"

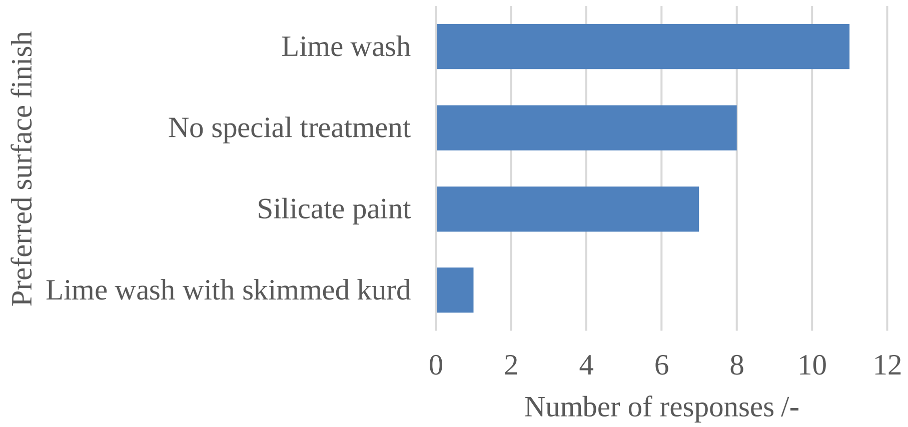


Figure 30: What surface finish do you prefer to use on the outside render?

Lime wash was preferred by respondents who use mostly lime renders and silicate paint by builders who work with clay renders. Around 30 % of responses stated that they do not treat the walls after they are rendered.

Out of the 20 builders, 10 did not experience moisture damages in theirs or other CUT buildings, 5 did experience it and 5 didn't know about any moisture damages. Five builders that experienced moisture damages were asked multiple-choice question "*What was the reason for the moisture damage?*".

The reasons for moisture damage shared by the respondents were insufficient roof overhang with 3 responses, incorrect exterior details with 3 responses, specific climate conditions with 2 responses, and higher levels of splash water with 1 response. One respondent mentioned that moisture damage occurred in northern wall because the humidity in the walls couldn't dry out during the summers.

Air tightness of the CUT buildings can be achieved with several methods, therefore the respondents were asked multiple-choice question "*How do you usually solve air tightness in CUT buildings?*".

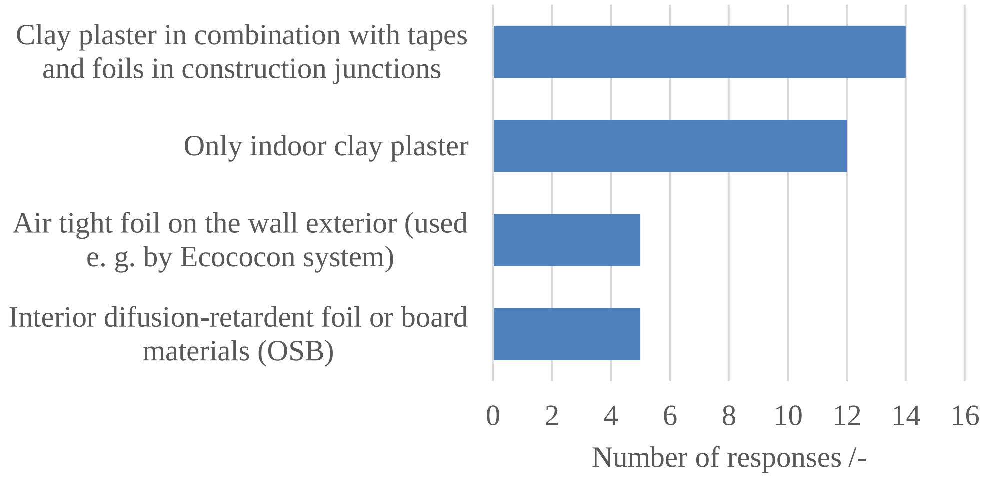


Figure 31: How do you usually solve air tightness in CUT buildings?

The most preferred option was clay plaster in combination with tapes and foils in construction junctions with 14 responses. This option was chosen mainly by the builders building with Modified CUT constructions. The second was only indoor clay plaster with 12 responses. This option was chosen usually by respondents building mainly with the Original CUT construction. Using building foils or board materials as the main air tight layer is not practiced often among CUT builders and architects.

Out of 20 respondents, only one performed a blower door tests on the CUT buildings. The test was done on a house with clay plaster in combination with building tapes and foils as the main air tight layer. The results of those tests varied between 0,6 and 2,5 ACH_{50}.

In the following question, respondents were asked to share tools that they invented to make their work easier. One respondent created a small bale press, shown in Fig 43. Another respondent developed a frame that allows him/her to cut the notches before placing the bales in the wall. “This makes notching much easier as the posts don't get in the way of the saw”.

Figure 32: Small bale press using the tiie down straps ready to use on building site (Respondent, personal communication, 23 March 2024)

The following question was open-ended, allowing builders to share their personal experience. Specifically, it asked ” *What do you like the most about the CUT technique or modified CUT techniques?*”

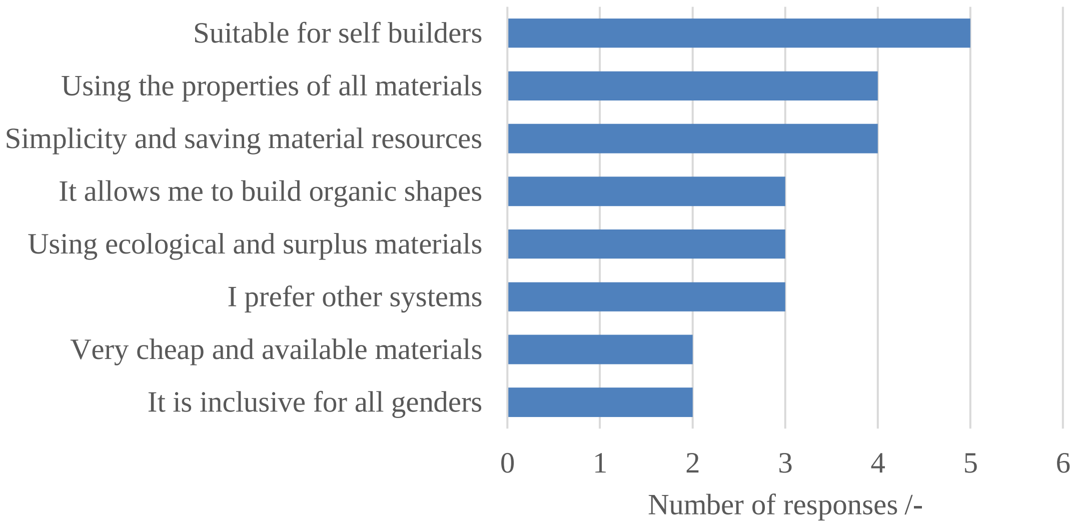


Figure 33: What do you like the most about the CUT technique or modified CUT techniques?

The suitability of the CUT techniques for self-builders was the most favoured aspect, using the properties of all materials together with the techniques simplicity and saving material resources were the next two most appreciated aspects. Some builders also stated that they do not like CUT constructions and prefer to use other straw bale building systems, mainly due to the amount of labour that is required. Factors such as cost effectiveness, the availability of materials, and inclusivity also received positive feedback.

To further illustrate the points mentioned above, below are several citations from building professionals, presenting their points of view on the CUT techniques:

'It's the only way I design straw bale houses, as long as I don't use prefabricated panels. I do not use Nebraska or Original CUT. I always rely structurally on the load-bearing timber structure without taking into account the stresses offered by the straw bales (although I acknowledge them). This is in compliance with the Spanish Technical Building Code.'

'CUT is a smart system using only the necessary ressources for construction (the safety factor is added with the plaster and render); planks (as posts) are available everywhere, easy to transport and to cut, cheap, easy to mount even by beginners; for OrganiCut: the easy way to make organic shaped straw bale walls with overlapping planks'.

4.1.2 Original CUT construction

In the following section, 13 builders and architects who answered that they have been working with the Original CUT technique were asked a set of questions.

Builders and architects that worked with the Original CUT technique were asked multiple-choice question "*What is the most complicated thing about building with the Original CUT technique?*".

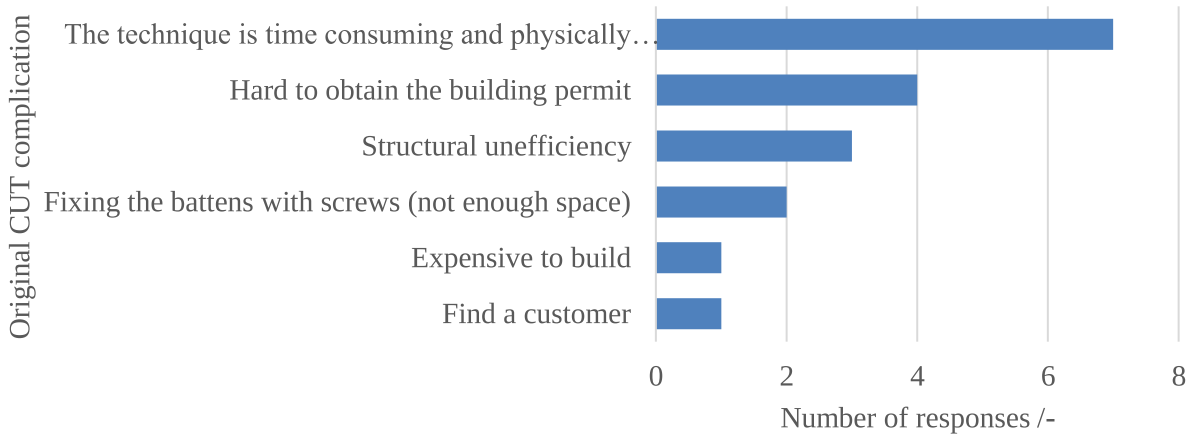


Figure 34: What is the most complicated thing about building with the Original CUT technique?

Time consumption and the amount of labour were seen as the biggest complication, especially cutting the notches into the bales and screwing/nailing the battens as mentioned by several respondents. The difficulty of obtaining the building permit and finding an architect or responsible person who is willing to validate the project was seen as the second most problematic matter. Three respondents mentioned that it is not possible to prove the structural integrity of the Original CUT system according to Eurocode, which is mainly because the Original CUT walls are dependent on the plaster capacity to transport the loads and the thin timber frame structure is not sufficient.

The third question for builders and architects building with the Original CUT construction concerned the sizes of the posts in the wall and was opened, see results in Table 10.

Table 10: The size of posts in the Original CUT walls

Posts dimension / mm · mm	70 · 30; 73 · 38; 80 · 30;	120 · 30; 120 · 40; 140 · 25;	140 · 40; 145 · 45; 150 · 50; 180 · 25

There is no uniform size of the posts between the respondents, the size of the posts is highly variable reaching from 30 mm · 70 mm up to 25 mm · 180 mm. In four cases, it was mentioned that the size of the corner posts is bigger to prevent the corner posts from buckling while infilling the bales, and to reach better structural integrity.

The third question for builders and architects building with the Original CUT construction concerned the distance of the posts. Figure 35 which represents answers on single-choice question "*What is the distance between the posts?*" can be seen below.

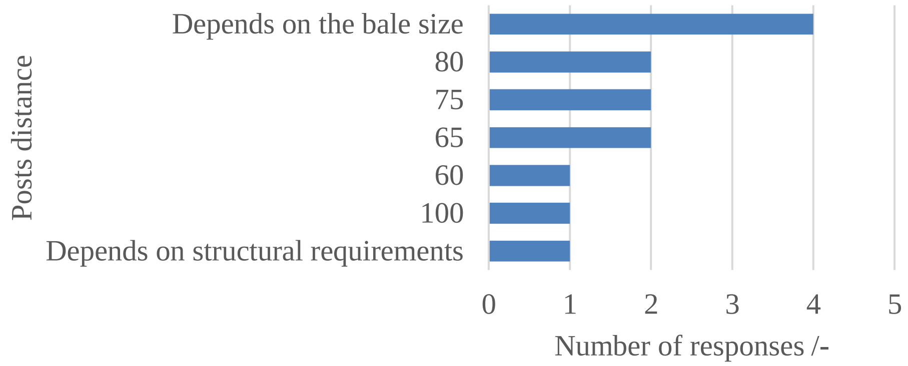


Figure 35: What is the distance between the posts?

In general, the Original CUT construction post distance depends on the bale size and thus varies according to the bales that are available to the builders. In the comment section, it was verified that the bale length was approximately 8 % longer than the distance between the posts.

The fourth question concerning the Original CUT technique was about the thickness of the indoor plaster. Figure 36. represents answers to a single-choice question "*What is usually the thickness of indoor plaster?*"

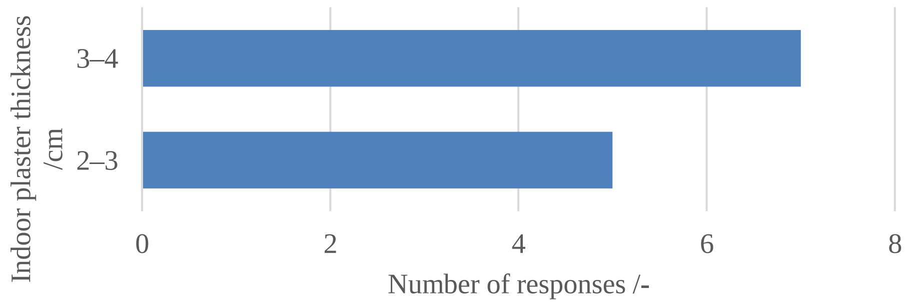


Figure 36: What is usually the thickness of indoor plaster?

Thickness of indoor plaster is most commonly 3–4 cm with 7 responses and 2–3 cm with 5 responses.

The Original CUT construction depends on the plaster capacity to transport vertical loads, therefore, builders and architects were asked "*Can you count on the plaster capacity to transfer horizontal and/or vertical forces in your country? (meaning it is accepted by authorities)"*

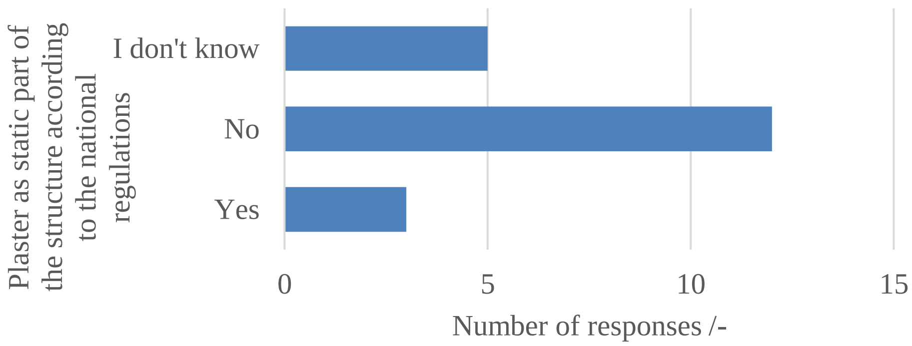


Figure 37: Can you count on the plaster capacity to transfer horizontal and/or vertical forces in your country? (meaning it is accepted by authorities)

4.1.3 Modified CUT constructions

In the following section, builders and architects were asked a set of questions concerning the modified CUT techniques they built with.

Braced CUT

Based on the answers, the dimensions of the posts depends on the type of construction and structural requirements and usually varied between 40 to 60 mm in thickness and 140 to 180 mm in depth. It should be noted that exceeding the post thickness of 40 mm leads to the creation of vertical gaps and thus a lot of stuffing is required (Gruber, 2020a). After cutting the strings, the gaps should close and no larger amount of stuffing is required. The distance of the posts was in general, similar to the post size, dependent on the structural needs of the building, ranging from 80 to 100 cm.

Post and Beam CUT

In total, 11 respondents have built with Post and Beam CUT construction.

In the following single-choice question, builders and architects were asked ”*Do you mostly use one or two battens/lintels to fix the bales?*”

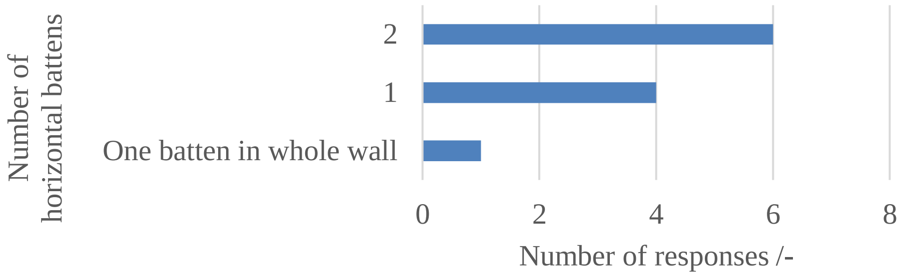


Figure 38: Do you mostly use one or two battens/lintels to fix the bales?

The majority of the builders use 2 battens to fix the bales. Out of the 4 builders using 1 batten, two builders put the batten at the alternate sides of the post in every row.

The following multiple choice question concerned the position of the load-bearing posts and was stated as ”What was the possition of load-bearing posts?”

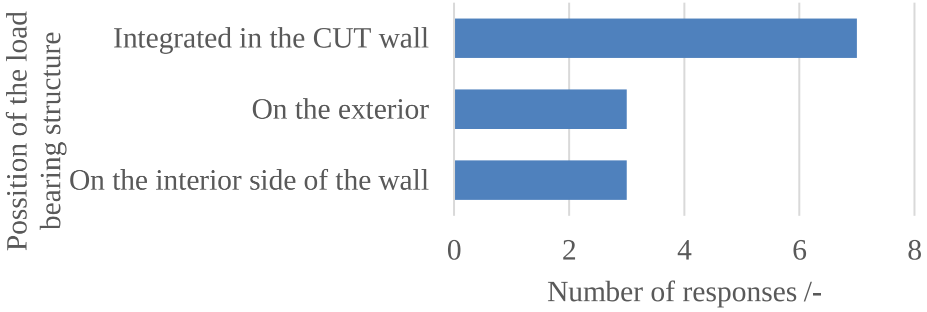


Figure 39: What was the possition of load-bearing posts?

Most of the projects (7) had the post and beam structure integrated within the wall, followed by load-bearing structure in the interior of the wall (3) and the load-bearing structure at the exterior of the wall (3). The number of projects with the wooden structure integrated within the wall, where the CUT wall in this system is load-bearing was not verified.

CUT wrapping

Out of the 10 builders that used the CUT technique to wrap a building, 9 of them used only 1 batten to fix the bale and only one builder used 2 battens for fixing the bales. Based on the answers, it is difficult to add a second batten to the wall because of limited space.

4.2 CUT technique modifications and development

Despite the durability and real examples of the CUT buildings erected since the nineties, the problem of proving the structural capacities of the Original CUT walls seems to be a common challenge that builders and architects encounter. ´The technique itself does not fulfil the load-bearing capacity in conventional Eurocode structural calculations.´ (V. Gach, personal communication 28. March 2024). As mentioned by Tom Rijven, the possible solution to overcome this obstacle could be a certification of the Original CUT wall as a building element/panel, this matter is currently in the planning phase (T. Rijven, personal communication, 6 February 2024). In some countries, for example in France, the builder or homeowner can take on full legal responsibility for the construction method used. In Denmark, it could be possible to build an Original CUT house in ecological villages, that often operate under flexible guidelines (Eeva-Maarja Laur, personal communication, 26 February 2024). In other countries, the local authority can grant exceptions to the standard building codes. It is also worth mentioning that it might be possible to apply to build a CUT house as an experimental building. There are also illegal ways how to build with the Original CUT technique, but they won't be mentioned further. The Original CUT construction is popular among self-builders across Europe but is also offered by several companies, for example, Habitat Végétal, CASETADEPALLA, and Okambuva.

Over time, the Original CUT technique has been modified by builders and architects based on their preferences or to comply with different local building regulations. Several different versions of the CUT techniques have been developed and are in use todays. Apart from the Original CUT construction, several Modified CUT constructions have emerged. These Modified CUT constructions either implement some of the ideas from the Original CUT construction or they were developed from the Original CUT construction.

In countries where the capacity of the plaster to transport vertical and horizontal loads cannot be counted on in structural calculations because of building regulations, the CUT technique had to be modified and the walls had to be braced with planks or boards (Braced CUT). The CUT technique can be also used as non-load-bearing, or load-bearing wall in combination with a post and beam structure (Post and Beam CUT), for wrapping of buildings (CUT Wrapping), or to create organic shapes such as vaults, domes, and curved walls (OrganiCUT).

The division of CUT techniques is shown in Figure 40. Firstly, it is the Original CUT construction and secondly the modified CUT constructions.

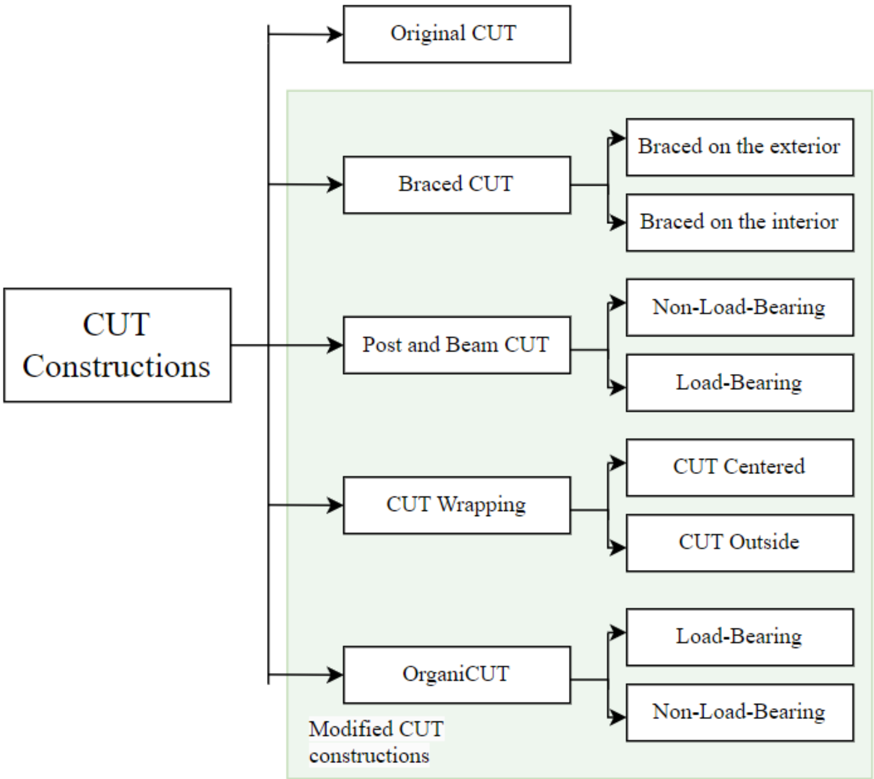


Figure 40: Overview of different CUT construction techniques

4.2.1 Braced CUT

In the Braced CUT construction, the wooden structure that consist of posts and sheathing material sufficiently transport all loads, and the structural calculation is independent of the plaster and straw properties, however, the builders usually acknowledge the straw and plaster additional safety factor, that is not included in the calculations. Braced CUT is commonly used by Austrian company ASBN, Czech company Slamák.info, and other smaller companies. Other projects build with this technique were located in France and Slovakia. The practices of these companies vary, mainly in the execution of building details.

Sheathing material (DWD, OSB boards) or planks in diagonal direction take over the main bracing function instead of the clay plaster, as shown in Figure 41. To fix the bracing material, the posts are no longer located at the centere of the wall, as in the Original CUT construction, but they are placed flush with the exterior or interior side of the straw bales. The board sheathing or planks are fixed to the posts while the batten which holds the bale in place are fixed on the other side of the post. To make the construction more structurally safe, it is possible to use bigger dimensions of posts compared to the Original CUT construction. In this case, the bale infill needs to have high quality (density) – the space between the posts needs to be infilled correctly before the strings are cut. The thickness of the posts higher than 40 mm is not recommended because after the strings are cut, the bale expands in a horizontal direction and fills in the 40 mm gap that was created in front of the posts. Using thicker posts leads to the creation of vertical gaps and a higher amount of straw stuffing (Gruber, 2020a).

Figure 41: Sraw bale house with exterior plank bracing (Grmela, 2019)

In the case of exterior diagonal planking, a gap is left between the planks because wood has a higher water vapour resistance factor (μ-value) over 20 (-), the gap is usually filled with cob, using the hygroscopic abilities of clay to draw out condensed moisture from the straw bales. Reed stucco is stapled directly to the planks because wood is not a good plaster ground. Now, the wall can be plastered. Adding exterior diffusion-open insulation boards to reach a lower U-value is also an option for this technique (*see Detail A.1 on page 43*).

Use of diffusion open boards is optional as bracing for construction with wooden facade. Suitable diffusion open boards with tongue and groove work as bracing, but also as windproof layer of the walls. The battens of the facade can be directly fixed to the boards or to the post behind (Gruber, 2020a). The CUT braced with boards on the interior is described in French Professional Straw Construction Guidelines as Ossature excentrée, see Figure 42 (RFCP, 2012).

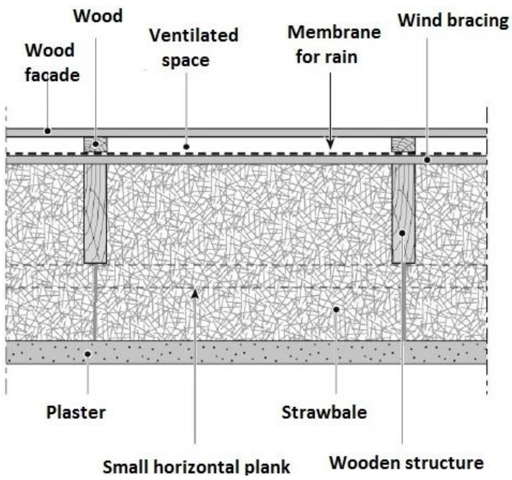


Figure 42: Section view of CUT wall braced with boards (RFCP, 2012), translated into English

4.2.2 Post and Beam CUT

In the Post and beam CUT construction, the structural integrity of the house is secured by the post and beam structure, in the vast majority of cases made out of wood. The most common way how to use this technique is to locate the CUT wall between the load-bearing posts, but location of the CUT wall on the interior or on the exterior of the post and beam wall is also common. Post and beam CUT is used by several companies, for example, Casapasiva. META2020 Architects, ASBN, Habitat Végétal, and others. The history and development of Post and beam CUT were not clarified, however, the first projects found that were built with a CUT wall located behind the post and beam constructions were presented by Rijven (2007). Buildings done with Post and Beam CUT technique were found in Spain, Sweden, Netherlands, France and Austria.

There are two main types of Post and Beam CUT systems depending on a direct impact of the CUT walls on the static of the building – Non-Load-bearing Post and Beam CUT and Load-bearing Post and Beam CUT.

Non-Load-bearing Post and Beam CUT

In the Non-Load-bearing Post and Beam CUT system, the load-bearing element of the building is a post and beam structure of timber, steel, or concrete.The CUT wall does not have a structural function. Non-load-bearing Post and Beam CUT walls are refered to as Ossature légère centrée non porteuse in the French straw building professionals guidelines (RFCP, 2012). These CUT walls are self-supporting and connected to the main structure of the building, as seen in Figure 43.

Figure 43: : OrganiCUT non-load-bearing CUT wall on the exterior side of the post and beam construction, Sweden (StrohNatur CZ, 2016)

The position of the load-bearing post and beam construction can be either:

1. On the interior side of the CUT wall
    - It is suggested to leave enough space between the load-bearing construction and the CUT wall
2. Integrated within the CUT wall
    - Load-bearing posts of the ceiling are weakening the air tightness of the building and the posts within the wall are thermal bridges
3. At the exterior of the CUT wall
    - Structural elements are penetrating the envelope, creating thermal and acoustic bridges and weakening the air tightness of the building (RFCP, 2012)

The other differences from the Original CUT construction are that the plaster can be thinner, and the bales do not need to be compressed from the top due to the fact the the walls are not load-bearing. The horizontal battens are still present, but the function is to hold the bales in place.

The CUT wall might need an elevated foundation, to secure protection from splash water and moisture, as seen in Figure 44. All organic parts of the building need to be elevated at least 300 mm above the surrounding terrain.

Figure 44: Post and Beam CUT wall on the exterior side of the post and beam construction in Kessel, Netherlands, lifted on concrete block foundation (A. Balatsoukas-Stimmin, personal communication, 17 January 2023)

This building technique can be applied to retrofit projects of old post and beam structures. Several thousands of old buildings suitable for CUT renovation can be found in France alone (Rijven, 2007).

Load-bearing Post and Beam CUT

In cases, when the frame structure is integrated within the CUT wall and the properties of the CUT wall are included in the structural calculations, meaning that the structural calculation does not depend only on the post and beam structure, we can classify the technique as Load-bearing Post and Beam CUT. Using this technique allows a broader distance between the posts of the post and beam structure which are usually located only in the corners of the house as shown in Figure 45. This technique is, however, very similar to the Original CUT construction.

Figure 45: Load-bearing Post and Beam CUT (Toledo & Zecchetto, 2024)

4.2.3 CUT wrapping

Another possible use of the CUT technique is CUT Wrapping, where the CUT wall main function is external insulation, the construction is supported by a foundation and usually is not limited by authorities in terms of static.

Kaesberg (2020) states that there are several ways to externally insulate old or new houses with straw, for example with anchoring bales, tethering bales, using retainer holdings for bales, injecting loose straw into cavities, using straw boards, and the CUT technique. Wrapping with the CUT technique requires the building of additional foundations. The weight of the additional CUT construction is transferred to the foundation with posts, that are connected to the top and base plate (Kaesberg, 2020). The specific of this hybrid technique is that the bales are not fixed directly to the wall, as done with most of the other bale wrapping techniques. Fixing bales to the walls can be problematic, especially if the wall is made out of different or unstable materials. In the CUT wrapping, the bales are infilled between the thin posts (e.g. 25 mm ·140 mm). The posts are fixed to the base plate and the top plate or a roof overhang, thus this technique is independent of the properties of the wall (Gruber, 2020c).

There are two ways to use CUT technique for wrapping, dependent on the facade system:

1. CUT centered – the posts are located in the middle of the exterior insulation, bales are fixed in place by one horizontal batten, it is used when clay or lime is applied for rendering the walls (*see Detail C.1 on page 47*).
2. CUT outside – the posts are located on the exterior side of the straw bales, and the connection of DWD boards is possible, there is not enough space to fix the bales with batten from the top, it is used with wooden façade (Gruber, 2020c).

Wrapping renovation in Upper Austria with CUT centered and CUT outside variants is shown in Figure 46. The left and right sides were already rendered with lime while for the middle part, where CUT outside was used, the posts to fix the diffusion open WFB are still visible.

Figure 46: CUT wrapping of existing building using two possible methods in one wall (Gruber, 2020c)

4.2.4 OrganiCUT

The CUT technique has an excellent ability to create organic forms and shapes, like curved walls, chain lines, vaults, domes, etc. For vertically curved CUT (domes, vaults). Depending on the wall radius, the bales must be either angled or the gaps must be stuffed with loose straw. As in other CUT systems, the bales are fixed in place with two horizontal battens. The main advantage of OrganiCUT is that the structures don't require formwork as other conventional techniques and provide good insulation at the same time.

In the case of non-load-bearing structures, 24 mm CLT boards can be used as rafters. In this case, the OrganiCUT structure is self-standing (Gruber, 2020a). One example of Non-load-bearing OrganiCUT construction used in the renovation of a cold attic can be seen in Figure 47 or building a vault extension of a house in Figure 48.

Figure 47: OrganiCUT in cold attic renovation (Gruber, 2020a)

Figure 48: OrganiCUTVault extension (Gruber, 2020a)

In the case of load-bearing OrganiCUT, the walls have to be designed to transport the loads (including wind and snow), therefore, four centimeter offcuts of three layered wood panels or planks screwed together can be used for vaults and domes (Gruber, 2020a). For curved walls, usual posts are used. Figure 49 and Figure 50 show a half-rounded house and geodesic dome built with OrganiCUT respectively.

Figure 49: OrganiCUT house in Czech Republic (Gach & Jirků, 2021)

Figure 50: Geodesic dome (Gruber, 2020a)

4.3 Building details of Modified CUT techniques

4.3.1 Braced CUT

In the following sections, three building details suitable for colder European climates are proposed for the Braced CUT technique.

Detail A.1 – Elevated screw foundation of CUT wall braced with planks

Rafters are fastened to the metal screws. To the top of the rafters, OSB boards are fastened. Diagonally to the rafters, floor trusses are installed (I-joists optional) that are covered with taped OSB on top. Base plate is installed directly on the OSB board. Post dimension 40 – 50 mm · 140 – 160 mm is based on the survey answers. Diagonal planks are fixed to the posts and a roof is built, Straw bales are fastened with one batten that is flushed with the bale surface, the notch is preferably cut with angle grinder. After the wall is infilled, the strings are cut, the gaps within the wall are stuffed, the gaps between the diagonal planks are filled with light clay or cob. Inner surface of the bales is shaved with hedge saw and plastered with interior clay plaster. Clay plaster is the main air tight layer in combination with tapes and foil in construction junctions is applied. WFB is fixed with screws directly to the planks. After this process, the render can be applied.

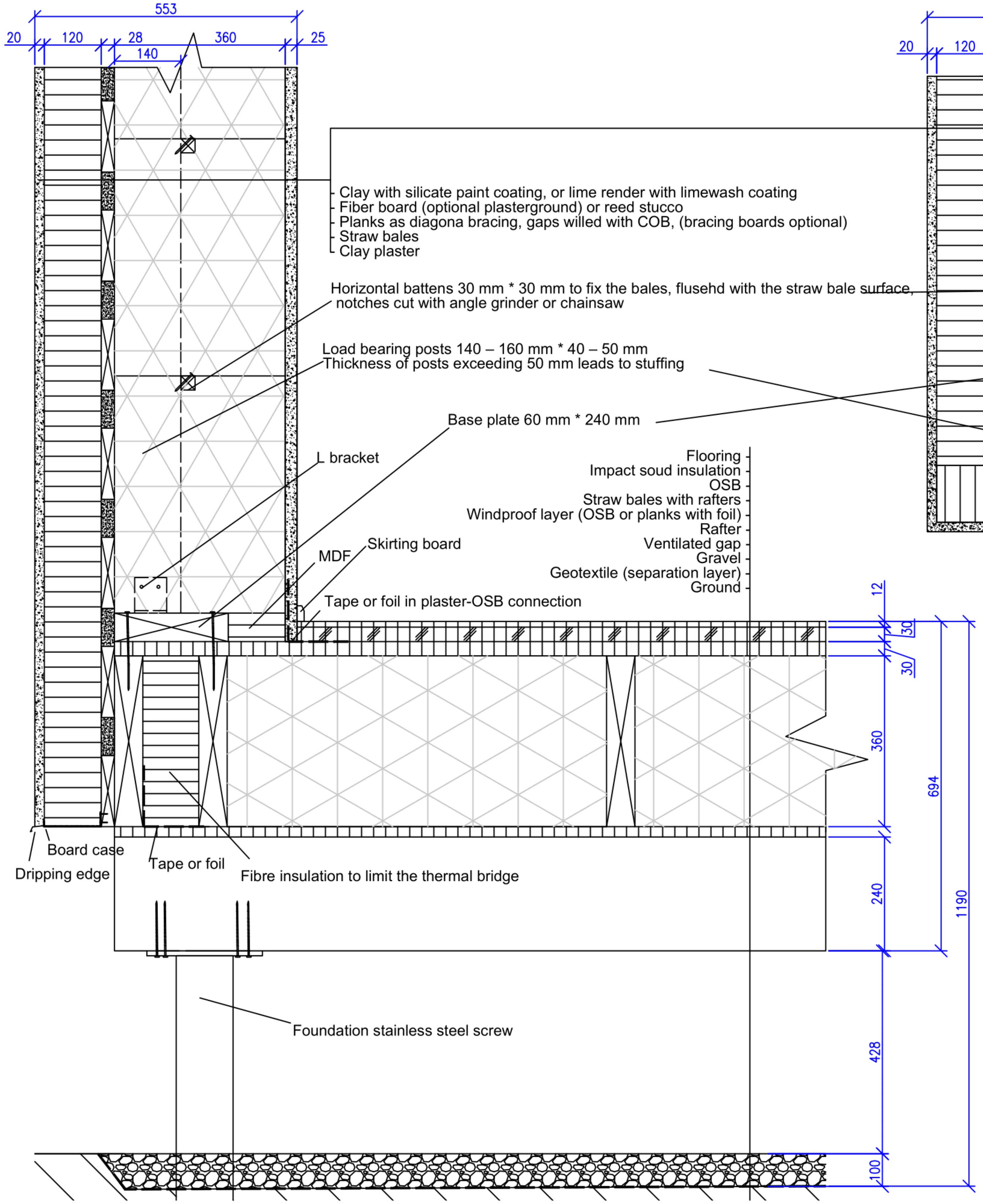
Detail A.2 – Wall corner connection of Braced CUT walls

This corner connection is based on Slamák.info practice, observed on several projects presented by Grmela, (2019) and was chosen because of it's simplicity compared to other possible solutions done by other companies. This corner connection doesn't require any bale customization.

Detail A.3 – Fixed window in window box

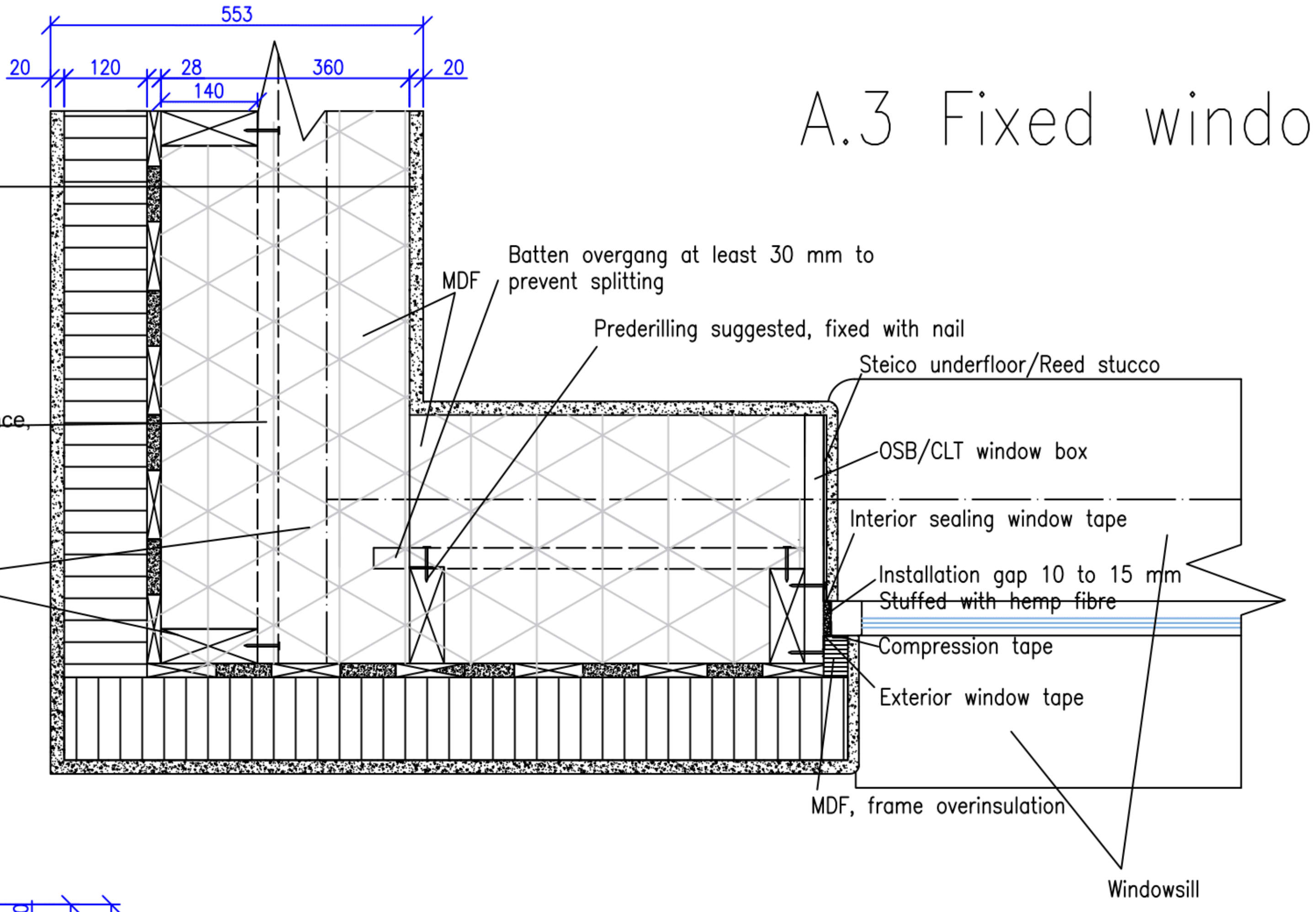
Window box made of plywood or OSB is fixed to the load-bearing posts. The frame is oveinsulated with MDF board, the installation gap is filled with hemp fibre, interior sealing window tape and exterior window tapes are used.

A.1 Elevated foundation



A.2 Wall-wall Corner detail

A.3 Fixed window



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BRACED CUT			
A.1 ELEVATED FOUNDATION			
A.2 WALL–WALL CORNER DETAIL			SCALE: 1:10 / FORMAT: A3
A.3 FIXED WINDOW			DATE: 11.04.2024 / PROGRAMME: EEBD

4.3.2 Post and Beam CUT

In the following sections, three building details suitable for colder European climates are proposed for Post and Beam CUT technique.

Detail B.1 – Over-insulated post and beam CUT foundation on foam glass gravel

Firstly, the foundation is excavated and a drainage pipe together with geotextile is installed. 140 mm layer of gravel comes to the bottom of the foundation. Layers of foam glass gravel, together 500 mm thick are compacted with a plate compactor. Another layer of geotextile is used on the top of the foam glass as a separation layer. Formwork is built, concrete reinforcement is put in place, and concrete is poured between the formwork. As the next step, after the concrete is sufficiently hardened, post and beam construction with water proof roof is raised. The load-bearing posts are fixed to the concrete with a metal profile and threaded rods. The CUT wall has to be elevated (at least 300 mm above the ground), therefore concrete blocks are built on top of the foundation (optionally levelling mortar is used). The blocks are filled with foam glass gravel and concrete mix. A foam glass board is installed to the foundation parameter and a dripping edge is installed on the top of it. The base plate is fixed to the concrete blocks. Hydro insulation under base plate is not necessary. Planks that work as posts are connected with the base plate and roof overhang. Each row of bales is fixed with two horizontal battens that are flushed with the surface, the notch is cut with an angle grinder. The bale strings are cut, the wall is stuffed and shaved with a hedge saw and plaster and render are applied. This detail was inspired by a project of a house in Kessel in the Netherlands done by ASBN.

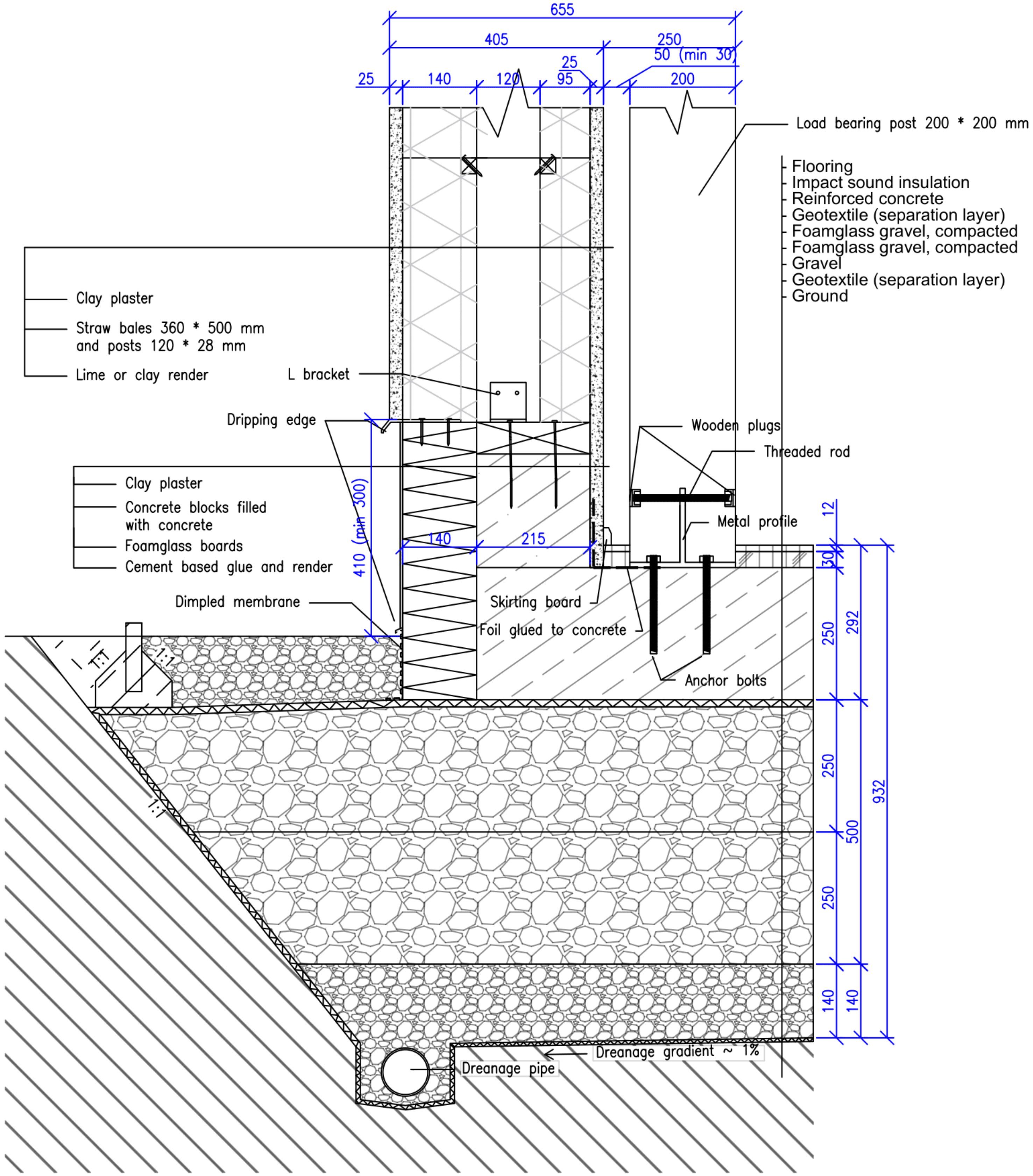
Detail B.2 – Round corner with reed or WFB

Since the foundation is over insulated, it is technically not possible to finish with the posts on the foundation edge. The gap that is created in the corner is filled with reed mats or pieces of WFB. The corner posts are screwed together so the construction is more stable. In this case, the corner bales need to be cut at an angle with an alligator saw.

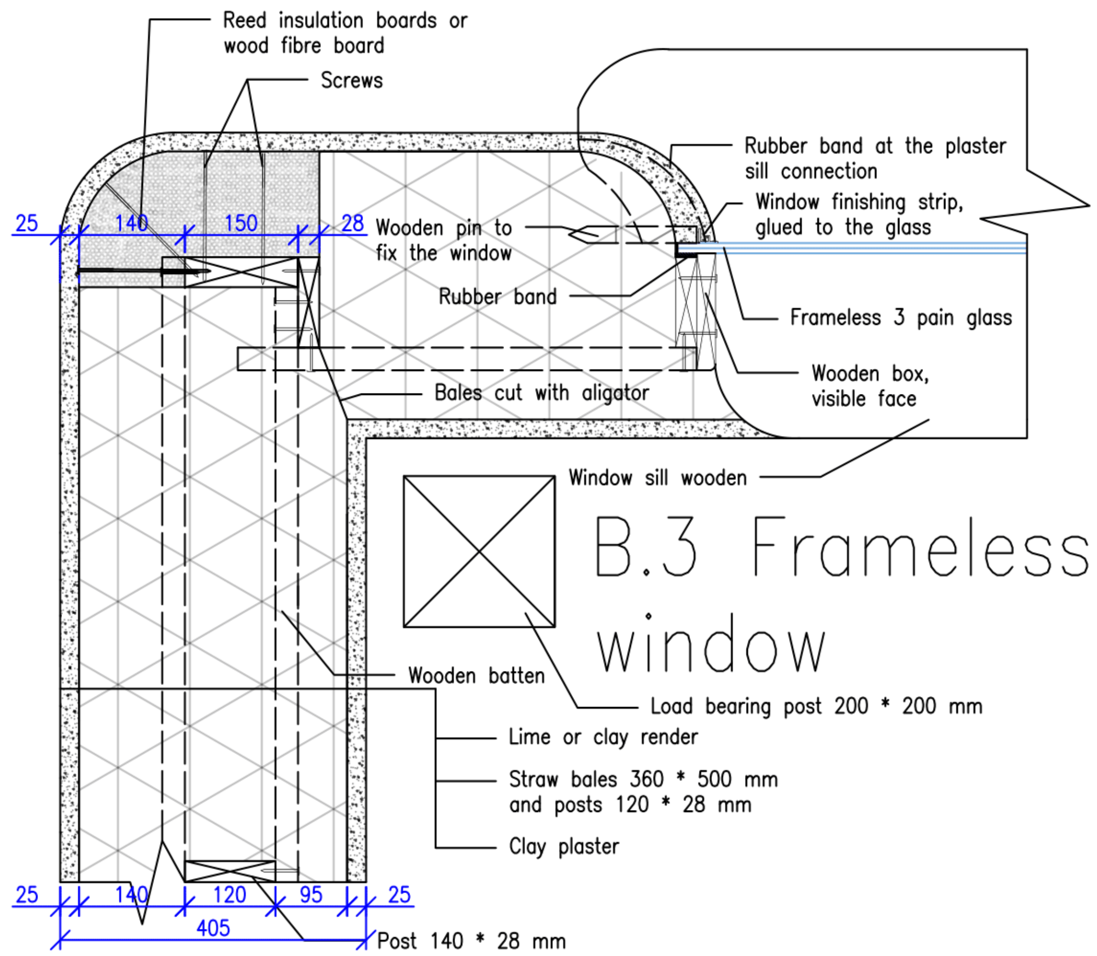
Detail B.3 – Frameless fixed window

This window detail is inspired by Tom Rijven. The main idea is to use only glass, without the expensive frame that limits the daylight and is a thermal bridge. On the exterior side of the posts, the sealing rubber band is glued. The three-pain glass is pushed towards the rubber band and is fixed with wooden pins. To prevent the water and wind penetration into the glass - plaster connection, a window finishing strip is glued to the glass. This strip is taped so it becomes sufficient plaster ground that can be overplastered. Rubber is also glued to the wooden window sill on the plaster-sill connection to prevent water suction.

B.1 Overinsulated Post and beam CUT foundation on foamglass gravel



B.2 Post and beam CUT – round corner with reed or WFB



B.3 Frameless fixed window

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POST AND BEAM CUT			LTH, FACULTY OF ENGINEERING	
B.1 FONDATION, OVERINSULATED ON FOAMGLASS GRAVEL				
B.2 DETAIL WITH REED STUCCO			SCALE	1:10
			FORMAT	A3
B.3 FRAMELESS WINDOW IN CUT WALL			DATE	11.04.2024
			PROGRAMME	EEBD

4.3.3 CUT wrapping

In the following sections, three building details suitable for colder European climates are proposed for CUT wrapping technique.

Detail C.1 – Over-insulated wrapping foundation

To over-insulate the existing foundation, a 30 cm gap is dug around the house. If moisture problems were observed at the building, it is also suggested to install the drainage pipe. Foam glass gravel is filled and compacted in the cavity, levelling concrete is poured on top of the foam glass. The concrete blocks filled with the foam glass-concrete mix are installed on top of the levelling concrete. Foam glass board is fastened to the concrete blocks as perimeter insulation. As a next step, wooden construction of the CUT wall is built. Straw bales are inserted between the posts and fastened with battens. The strings are CUT, gaps stuffed, and the surface shaved with a hedge saw. Lastly, render is applied.

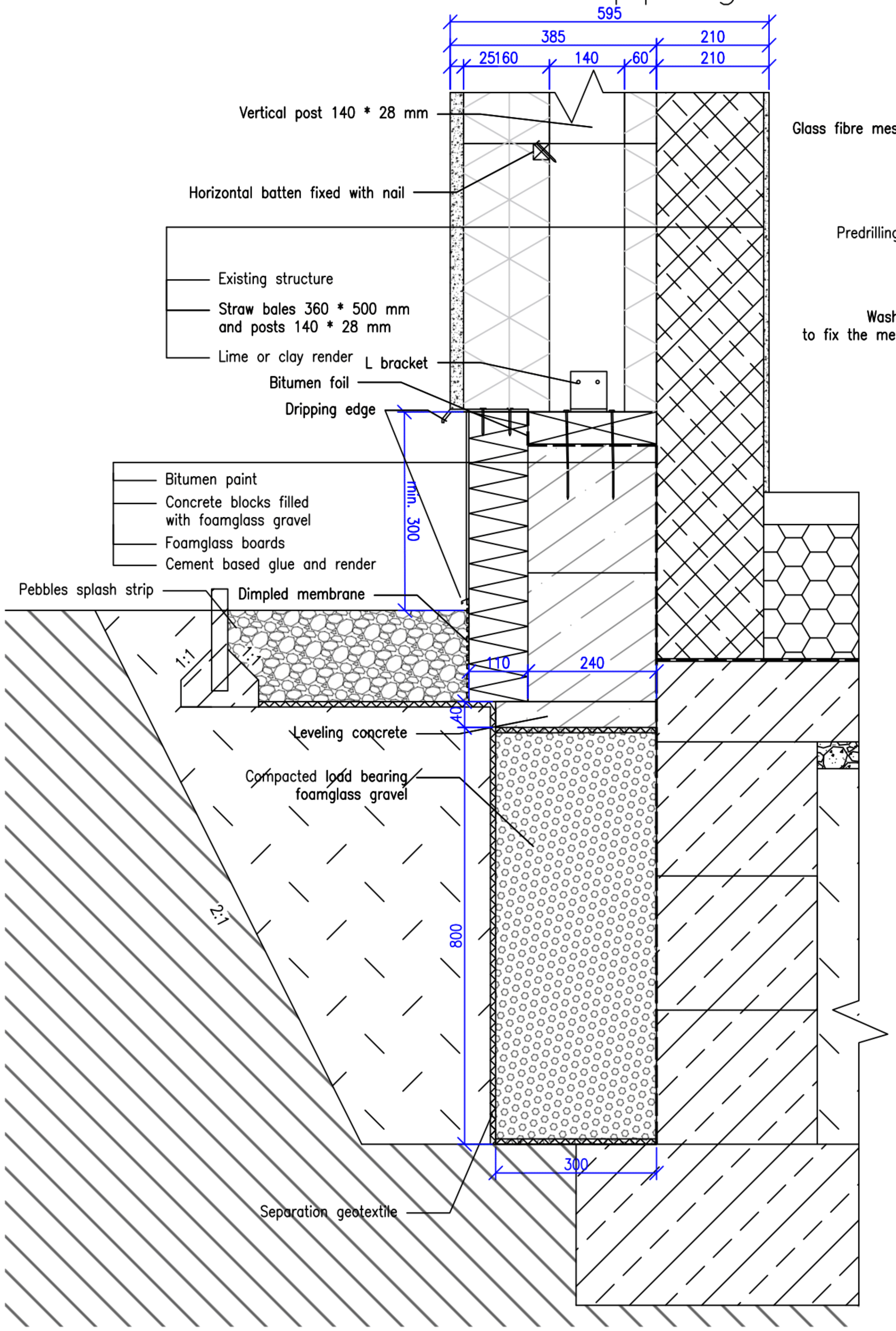
Detail C.2 – Round corner wrapping detail

Glass fibre mesh is used as a cage for the loose straw. Mesh is fixed with either washer head screws or staples with hooks to the straw bales and loose straw is compacted in the cavity. Hard or round corners can be made with this solution.

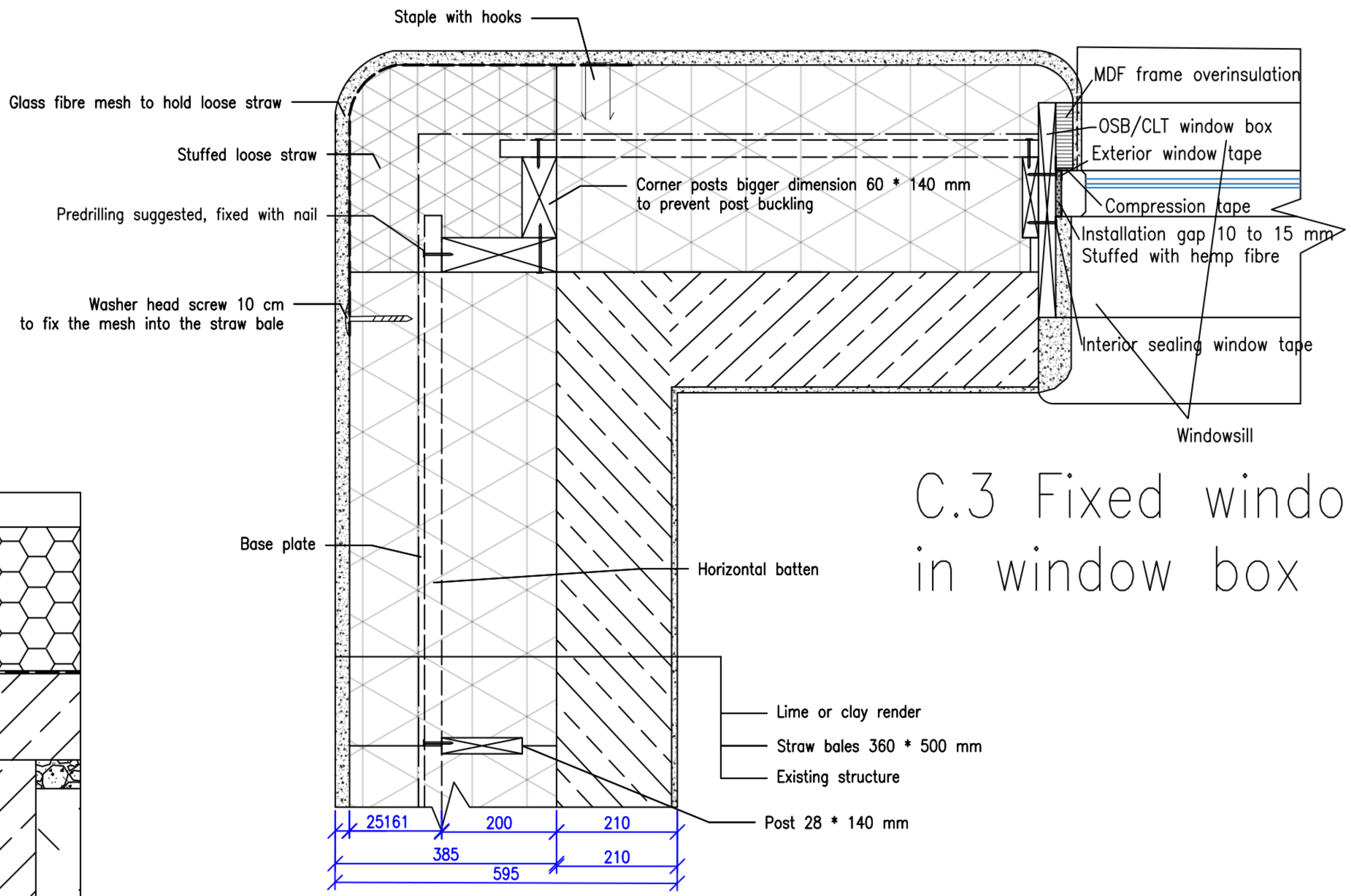
Detail C.3 – Fixed window in window box

In case of window renovation, window boxes are fastened to the existing structure or the posts of the CUT wall. Windows are screwed to the window box, the installation gap is filled with hemp fibre, and the window is taped on both sides. On the exterior, the window frame is over insulated with WFB board.

C.1 Overinsulated wrapping foudation



C.2 Wrapping – round corner detail usi



C.3 Fixed window in window box

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CUT WRAPPING				
C.1 OVERINSULATED WRAPPING FOUNDATION, EXISTING BUILDING				
C.2 WRAPPING CORNER DETAIL			SCALE	1:10
			FORMAT	A3
C.3 fIXED WINDOW			DATE	11.04.2024
			PROGRAMME	EEBD

4.4 Environmental impact of the CUT system

Environmental category	Unit	Phases A1 – A3	C1–C4	D	Total
Global warming potential - Fossil (GWP-f)	kg CO_2 eq.	1,04E+01	1,44E+00	-3,99E+00	**7,84E+00**
Global warming potential - Biogenic (GWP-b)	kg CO_2 eq.	-7,28E+01	7,15E+01	-2,49E+01	**-2,62E+01**
Global warming potential - Land use and land use change (GWP-luluc)	kg CO_2 eq.	3,67E-02	5,00E-04	-4,93E-02	**-1,21E-02**
Global warming potential (GWP-total)	kg CO_2 eq.	-6,23E+01	7,30E+01	-2,90E+01	**-1,83E+01**
GWP-total (ex. Biogenic Carbon)	kg CO_2 eq.	1,04E+01	1,44E+00	-4,04E+00	**7,83E+00**
Ozone depletion (ODP)	kg CFC 11 eq.	1,65E-06	2,72E-07	-1,01E-06	**9,08E-07**
Acidification (AP)	mol H+ eq.	8,08E-02	1,74E-02	-8,55E-02	**1,27E-02**
Eutrophication, freshwater (EP-fw)	kg $PO4^{3}$- eq.	9,81E-03	3,98E-04	-1,99E-03	**8,23E-03**
Eutrophication marine (EP-m)	kg N eq.	4,66E-02	9,65E-03	-2,47E-02	**3,16E-02**
Eutrophication, terrestrial (EP-T)	mol N eq.	2,89E-01	8,37E-02	-3,92E-01	**-2,00E-02**
Photochemical ozone formation - human health (POCP)	kg NMVOC eq.	4,49E-02	2,29E-02	-7,59E-02	**-8,08E-03**
Resource use, minerals and metals (ADP-mm)	kg Sb eq.	2,44E-04	2,75E-05	-1,64E-04	**1,08E-04**
Resource use, fossils (ADP-f)	MJ	1,23E+02	2,14E+01	-5,40E+01	**9,03E+01**
Water use (WDP)	m^3	3,03E+01	1,90E-01	-7,49E-01	**2,97E+01**

The sum of the environmental impacts of investigated phases for each category is calculated in the last column of Table 11. GWP-total was calculated as -18,3 kg of CO_2 eq. meaning that the Original CUT walls are carbon negative. The Environmental study of the CUT wall uses EPD files for supplied materials, however in reality, those materials could be obtained more locally, e.g. using clay from the excavation works, wood from a local sawmill, or straw bales supplied by a local farmer, therefore the environmental impacts, predominantly in stages A1–A3 would be further reduced. Using local materials should be examined in further research.

4.4.1 Building systems comparison

Figure 51 represents the comparison of the three investigated wall systems, where the environmental impacts were normalized by a maximum in each category. The environmental impacts of a timber frame wall from Biobuilds and precast concrete wall from Heidelberg can be found in the Appendix in *Table 12* and *Table 13*.

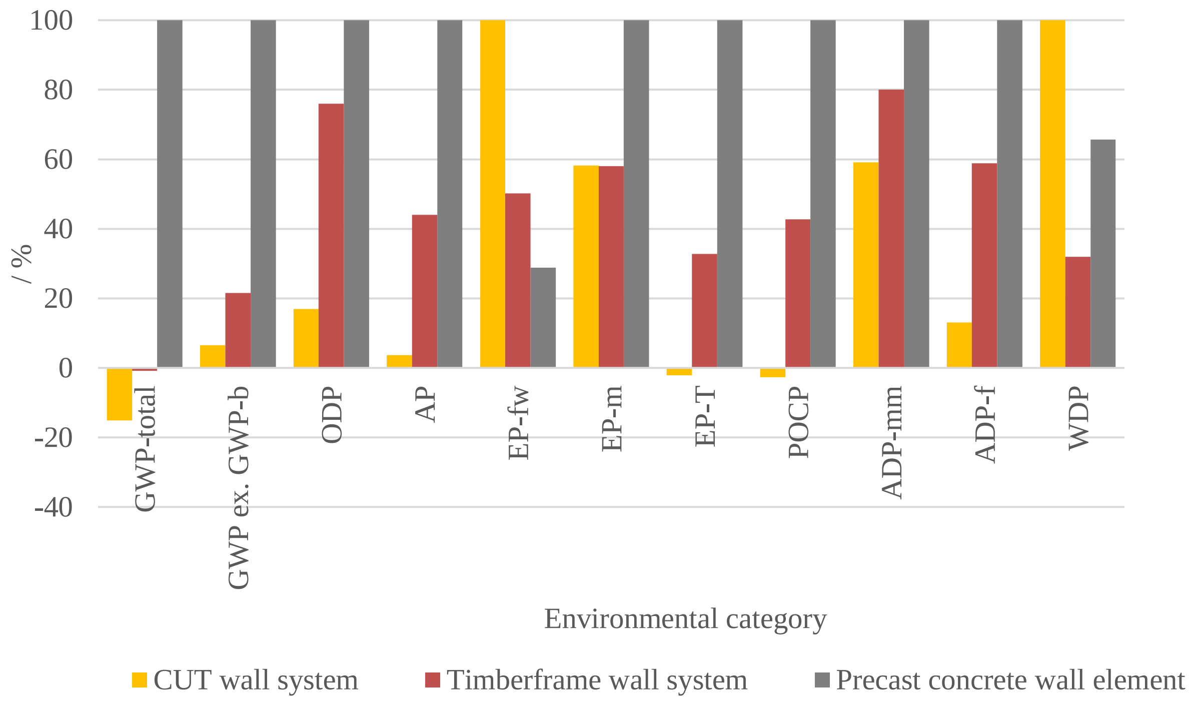

Figure 51: Environmental impacts comparison of three building systems normalized by a maximum in each category

The CUT wall is outperforming the timber frame wall system (Biobuilds) and precast concrete elements (Heidelberg) at 8 out of 10 categories, however in the category Freshwater eutrophication (EP-fw) and Water use (WDP) it reached considerably higher values. The high values of Freshwater eutrophication are caused because the application of fertilizers and pesticides was considered at the phase A1 of straw's EPD. EP-fw refers to the infiltration of nitrogen, phosphorus, and other fertilizers into the freshwater system, which causes excessive growth of algae and cyanobacteria (Tiwari & Pal, 2022).

A comparison of Water use (m^3) between the three building systems is visualized in Figure 52. Straw takes up 95 % of the water use in the CUT system.

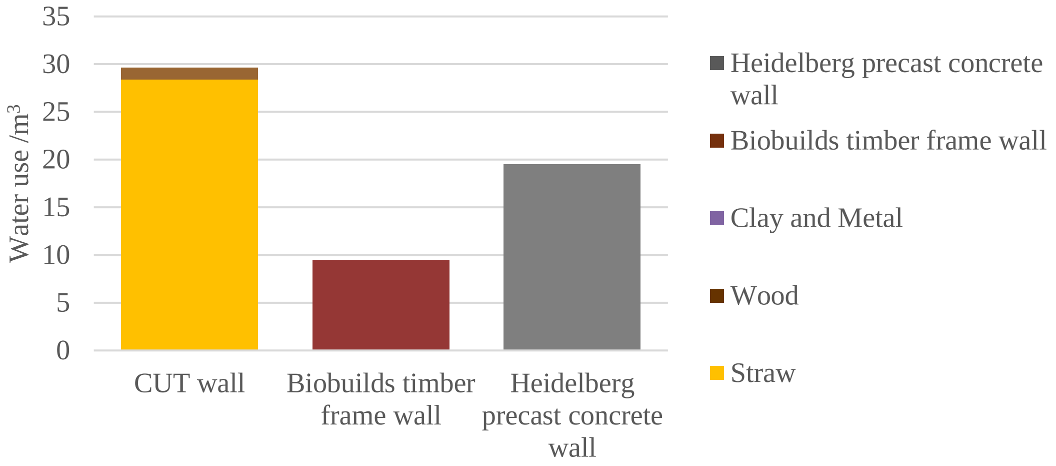

Figure 52: Water use for 1m² of the building system

Straw is a byproduct of agriculture and to produce straw, 77,4 l are needed for 1 m^3 of straw with a density of 100 kg/m^3 (result after allocation, Phase A1) (SNaB, 2021) corresponding to 28,4 l of water in 1m^2 of straw bales within the CUT wall. Regarding Water use, the environmental impact is higher in comparison with traditional building materials, that doesn't necessarily need supply of water for production.

Figure 53 represents the comparison of the wall systems after normalization and weighting, with and without the inclusion of biogenic carbon, the result is represented with an environmental score, which is a sum of subscores for all environmental categories.

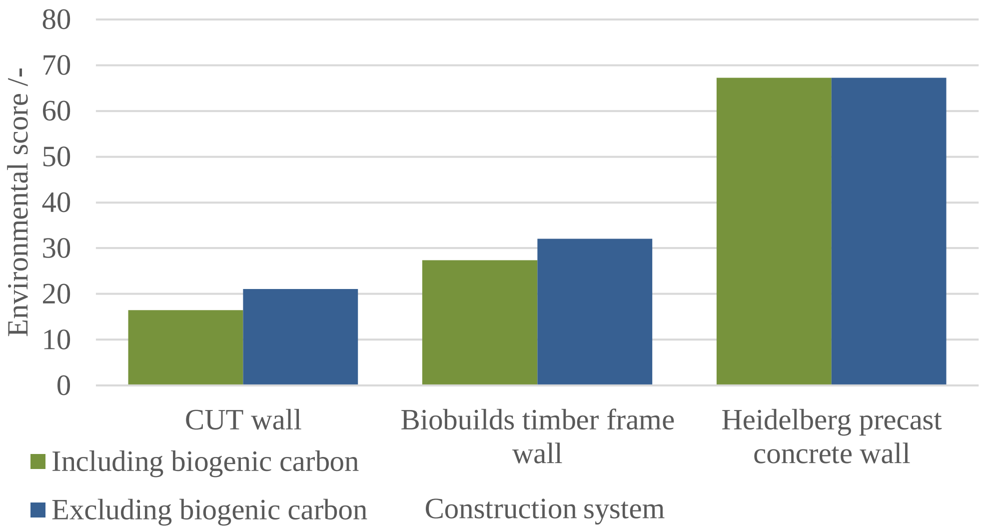

Figure 53: Comparison of environmental scores of three wall systems

The resulting scores including biogenic carbon were 14,5 for a CUT wall, 27,4 for a timber frame wall, and 67,3 for a concrete wall. In the GWP category, the subscores were -3,19; -0,2 and 21,06 for CUT, timber frame and concrete wall respectively, meaning the concrete wall environmental score for GWP category alone exceeded all subscores of the CUT wall combined, the detailed composition of the final score of the building systems can be found in the Appendix in *Figure 56*.

The CUT wall compared to the timber frame wall reached a 40 % lower score. This lower and better result was caused by the following factors:

1. The timber frame wall consists of necessary sheathing with OSB board, DWD board and membrane together with a ventilated façade system. All of those materials are substituted with two layers of clay plaster in the CUT wall – environmental impact of a clay plaster (that has several functions) compared to the several materials mentioned above is significantly lower.
2. Cellulose has worse environmental impact values compared to straw

It should be noted that the EPD files used, were calculated with fairly long transport distances (stage A2) for wood and clay plaster, which in most cases are obtained more locally. On the other hand, building tapes to connect the clay plaster at the junctions and hydrophobic paint are not included in the analysis. The precast concrete wall does not include any biogenic carbon, therefore the results are unchanged.

4.5 Moisture performance and air tightness of CUT walls

4.5.1 Moisture performance of straw bale walls

Experiments and practice have shown that straw bale walls with lime or clay plaster are effective in managing moisture. However, in the case of extreme climate conditions, particularly on the windward side of the building, it is recommended to take extra measures and considerations to ensure proper structural protection. This can be achieved mainly by using larger overhangs and applying water-repellent, diffusion-open coatings on the lime or clay render such as casein paint or lime wash. Wooden ventilated façade is safer from the view of building physics.

4.5.2 Moisture performance of CUT walls

The Original CUT walls

The Original CUT technique depends on a thick layer of clay plaster as the main air tight layer. The posts are located in the centere of the wall, and thus the Original CUT technique does not allow the installation of wallpapers or boards to ensure air tightness of the building, the clay plaster is transporting most of the vertical loads and is directly connected to the strawbales surface. Using building tapes in connection with wooden elements passing through walls, or the connection of plaster to other materials is highly suggested to minimize the effects of infiltration and higher air tightness. The clay render on the exterior provides weather protection for the degradable parts of the assembly.

Figure 54 displays the levels of MI in the exterior side of the straw bale at four different locations – Lund, Brussels, Barcelona, and Hradec Králové over three years period.

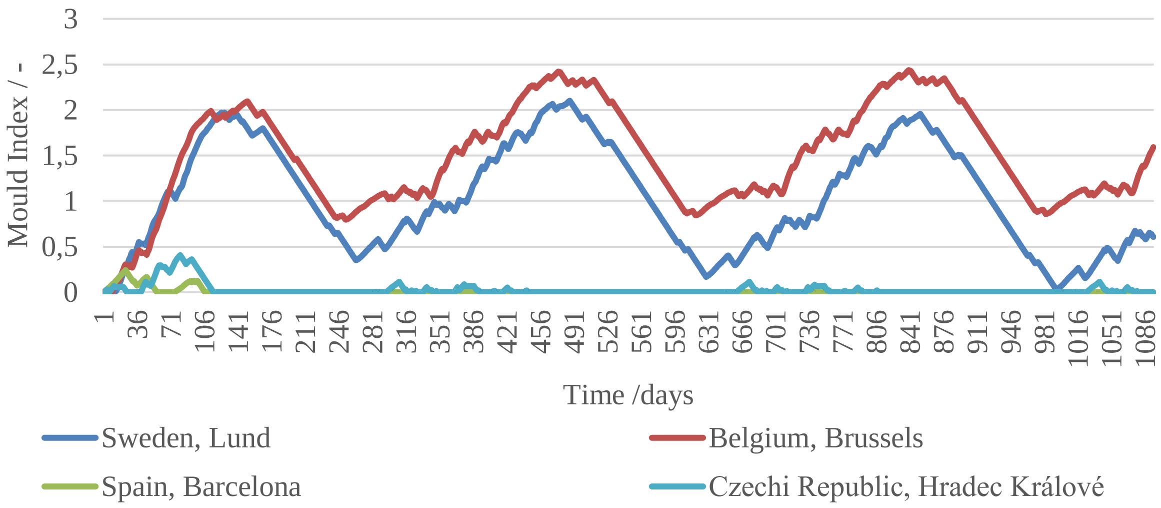

Figure 54: Mould Index at the exterior side of the straw bale in four different European countries

The effect of climate, mainly the higher long term levels of outdoor RH over the year are the reasons for higher MI in Lund and Brussels. The MI between 2 and 3 is acceptable in the areas that are located within the wall assembly, and it does not present any threat to the health of humans, nor to the structural integrity of the walls. The MI in Barcelona and Hradec Králové reaches values close to 0,5 shortly after the construction period and after the build-in moisture dries out, MI is constantly close to 0.

The conducted simulations provided several outcomes. The Original CUT walls are moisture-safe, if not exposed to direct rain, the local climate needs to be carefully considered, it is suggested to use at least a 10mm thinner layer of clay plaster on the exterior side of the wall. No mould growth was detected on the inner side of the bales or the interior plaster surface (MI = 0).

The comparison of RH with RH_{crit} at the exterior side of the straw bale is available in the Appendix for all locations (*see Figure 57, Figure 58, Fig, 59, Figure 60*).

5 Conclusion

The thesis presents complex review of the CUT technique, fulfilling the outlined objectives to gather insight into the modifications and development of the CUT technique. It was was achieved by combination of extensive web research, survey and personal communication with the experts. The technical drawings of the CUT modifications suitable for colder European climates were presented.The thesis provides insight into the performance of the CUT technique, such as environmental performance and mold growth assessment. These findings suggest that the CUT technique is a suitable option for ecological building construction.

The survey provided insight into the CUT technique and its use. The most influential individuals spreading the knowledge about the CUT technique were Herbert Gruber, Tom Rijven, and Rikki Nitzkin. A vast majority of respondents notch the battens into the bales thus preventing thermal bridge creation. Notches are most frequently done with an angle grinder and chain saw. Different variations of clay renders are the most common finishes on the CUT walls followed by lime renders. The factor of the local climate influenced the choice of render used – clay in drier climates and lime in more rainy climates. Limewash is the most common finish on the lime rendered walls while silicate paint is the most common finish on the clay rendered walls.

The Original CUT buildings built in the nineties have been performing well without any structural damages. However, proving the structural capacities of the Original CUT walls seems to be a common challenge that builders and architects encounter. According to building professionals, the biggest challenges using the Original CUT technique are the time consumption and the amount of labour, the difficulty in obtaining a building permit in their country, and the structural inefficiency of the system. The Original CUT technique is practiced by several companies and is favoured by many self-builders, it is the second most common method of CUT techniques.

Due to the insuficient of the Original CUT technique in terms of structural requirements, straw bale building professionals came up with a modification of the Original CUT technique called Braced CUT. In the Braced CUT construction, the wooden structure is sufficient enough to fulfill the structural regulations. The post size and dimension are based on the structural requirements and vary between 40 to 60 mm and 140 mm to 180 mm in depth. This technique is used in Austria, the Czech Republic, Slovakia, and France.

The CUT technique can be also used in combination with post and beam construction for newly built buildings as well as retrofits. The CUT wall can be non-load-bearing, but if the CUT wall is located in between the post and beam construction, it can be included in the structural calculations. The history and development of Post and beam CUT were not clarified, however, the first projects found built with a CUT wall located behind the post and beam construction are presented by Rijven (2007). In the Post and beam CUT construction, most of the building professionals use two battens to fix the bales. One batten and batten at the alternate sides of the post in every row is also less frequently common. Most of the projects had the post and beam structure integrated within the wall, followed by a load-bearing structure in the interior of the wall and a load-bearing structure at the exterior of the wall. Post and Beam CUT construction is the most frequently used CUT technique and is used in Spain, and France, and several projects were found in the Netherlands as well.

The other potential use of the CUT technique is the use of CUT for wrapping of buildings. The main advantage of this system is that the bales are not directly fixed to the wall, which can be problematic and time consuming. The main disadvantage of this system is the need to build an extra foundation that carries the load of the CUT wall. Both rendered or timber cladding façade are possible. In the CUT Wrapping, the majority of building professionals use only one batten to fix the bale, because it is difficult to add a second batten to the inner side of the posts because of limited working space. Several smaller projects were found across Europe.

According to the environmental calculation, the walls are carbon negative with GWPtotal -18,3 / CO_2 eq. in $1m^2$ of the CUT wall. The results of the environmental analysis would be further reduced if using local materials such as clay from excavation works or wood supplied by local sawmill, which is usually a common practice. The CUT wall is overperforming the timber frame wall system and precast concrete elements at 8 out of 10 environmental categories. The resulting environmental scores including biogenic carbon were 14,5 for a CUT wall, 27,4 for a timber frame wall, and 67,3 for a concrete wall. The score comparison underlines the environmental benefits of the CUT technique compared to the traditional building systems.

Based on WuFi simulations, the Original CUT walls are moisture-safe in different European climates. The mould growth was not detected on the interior sides of the straw bales (MI = 0) and thus the health of occupants is not affected. MI in the dewpoint area reached values close to 2,5 in Belgium and 2 in Sweden, which is acceptable in the areas that are located within the wall assembly, and it does not present any threat to the health of humans, nor to the structural integrity of the walls. In Czechia and Spain, MI in the dew point area reached zero after the build in moisture dried out. Based on the literature review and survey responses, the specific climate conditions can cause moisture damage on the CUT walls, especially deterioration of clay render and even straw degradation. In climates with higher long term levels of outdoor RH, it is suggested to conduct WuFi simulations to ensure the safety of the assembly and take extra precautions in constructive protection such as sufficient roof overhang, precise details, and elevated foundation. Using hydrophobic coatings that do not affect the diffusion such as silicate paint, stabilizing the plaster against weather erosion is suggested as well. The majority of the building professionals did not encounter moisture damage on the CUT walls or didn't know about them. The reasons for moisture damage were insufficient roof overhangs, incorrect exterior detailing, and specific climate conditions. As for air tightness, most of the respondents rely on the clay plaster that is connected to tapes and foils in construction junctions followed by only clay plaster. Other air tight layers such as OSB boards or foils in the interior or air tight foils on the exterior are also common solutions. Measuring the air tightness of CUT buildings is not a common practice.

This thesis is suitable foundation to further examine the qualities and prospects of the CUT technique and its modifications.

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Appendix

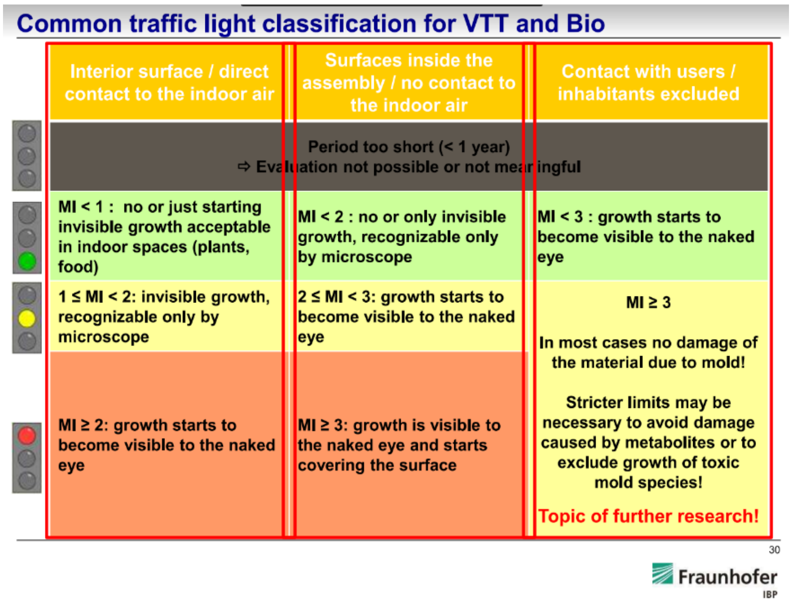

Figure 55: Mould Index traffic light classification (Fraunhofer Institute, 2024)

Table 11: Environmental impacts of Biobuilds prefabricated timber frame system (Anca, 2022)

Environmental category	Unit	Phases: A1 – A3	C1–C4	D	Total
Global warming potential - Fossil (GWP-f)	kg CO2 eq.	3,48E+01	1,58E+00	-1,06E+01	**2,58E+01**
Global warming potential - Biogenic (GWP-b)	kg CO2 eq.	-1,36E+02	1,27E+02	-1,83E+01	**-2,73E+01**
Global warming potential - Land use and land use change (GWP-luluc)	kg CO2 eq.	9,35E-02	1,70E-03	-4,15E-02	**5,37E-02**
Global warming potential (GWP-total)	kg CO2 eq.	-1,01E+02	1,29E+02	-2,89E+01	**-9,70E-01**
GWP-total (ex. Biogenic Carbon)	kg CO2 eq.	3,49E+01	1,58E+00	-1,06E+01	**2,58E+01**
Ozone depletion (ODP)	kg CFC 11 eq	4,78E-06	2,69E-07	-9,70E-07	**4,08E-06**
Acidification (AP)	mol H+ eq.	2,33E-01	9,08E-03	-8,91E-02	**1,53E-01**
Eutrophication, freshwater (EP-fw)	kg PO43- eq.	8,04E-03	2,30E-04	-4,14E-03	**4,13E-03**
Eutrophication marine (EP-m)	kg N eq.	5,45E-02	2,49E-03	-2,55E-02	**3,15E-02**
Eutrophication, terrestrial (EP-T)	mol N eq.	5,73E-01	2,80E-02	-2,94E-01	**3,07E-01**
Photochemical ozone formation - human health (POCP)	kg NMVOC e	1,96E-01	8,06E-03	-7,39E-02	**1,30E-01**
Resource use, minerals and metals (ADP-mm)	kg Sb eq.	4,99E-03	1,45E-05	-1,70E-04	**4,83E-03**
Resource use, fossils (ADP-f)	MJ	5,56E+02	2,72E+01	-1,77E+02	**4,06E+02**
Water use (WDP)	m3	1,18E+01	2,13E-01	-2,53E+00	**9,48E+00**

Table 12: Environmental impacts of Heidelberg prefabrecated cast concrete element (Lidö, 2023)

Environmental category	Unit	Phases: A1 – A3	C1–C4	D	Total
Global warming potential - Fossil (GWP-f)	kg CO2 eq.	1,03E+02	2,09E+01	-4,16E+00	**1,20E+02**
Global warming potential - Biogenic (GWP-b)	kg CO2 eq.	3,94E-01	0,00E+00	-3,77E-02	**3,56E-01**
Global warming potential - Land use and land use change (GWP-luluc)	kg CO2 eq.	1,05E-01	1,55E-03	-4,48E-03	**1,02E-01**
Global warming potential (GWP-total)	kg CO2 eq.	1,04E+02	2,09E+01	-4,20E+00	**1,20E+02**
GWP-total (ex. Biogenic Carbon)	kg CO2 eq.	1,03E+02	2,09E+01	-4,17E+00	**1,20E+02**
Ozone depletion (ODP)	kg CFC 11 eq	4,09E-06	1,61E-06	-3,33E-07	**5,37E-06**
Acidification (AP)	mol H+ eq.	3,19E-01	5,42E-02	-2,54E-02	**3,48E-01**
Eutrophication, freshwater (EP-fw)	kg PO43- eq.	2,95E-03	1,88E-04	-7,68E-04	**2,37E-03**
Eutrophication marine (EP-m)	kg N eq.	3,85E-02	2,11E-02	-5,31E-03	**5,43E-02**
Eutrophication, terrestrial (EP-T)	mol N eq.	7,73E-01	2,32E-01	-6,86E-02	**9,36E-01**
Photochemical ozone formation - human health (POCP)	kg NMVOC e	2,58E-01	6,58E-02	-1,96E-02	**3,05E-01**
Resource use, minerals and metals (ADP-mm)	kg Sb eq.	4,95E-04	7,01E-05	-3,83E-04	**1,82E-04**
Resource use, fossils (ADP-f)	MJ	6,38E+02	1,07E+02	-5,46E+01	**6,90E+02**
Water use (WDP)	m3	2,46E+01	1,11E+00	-6,27E+00	**1,95E+01**

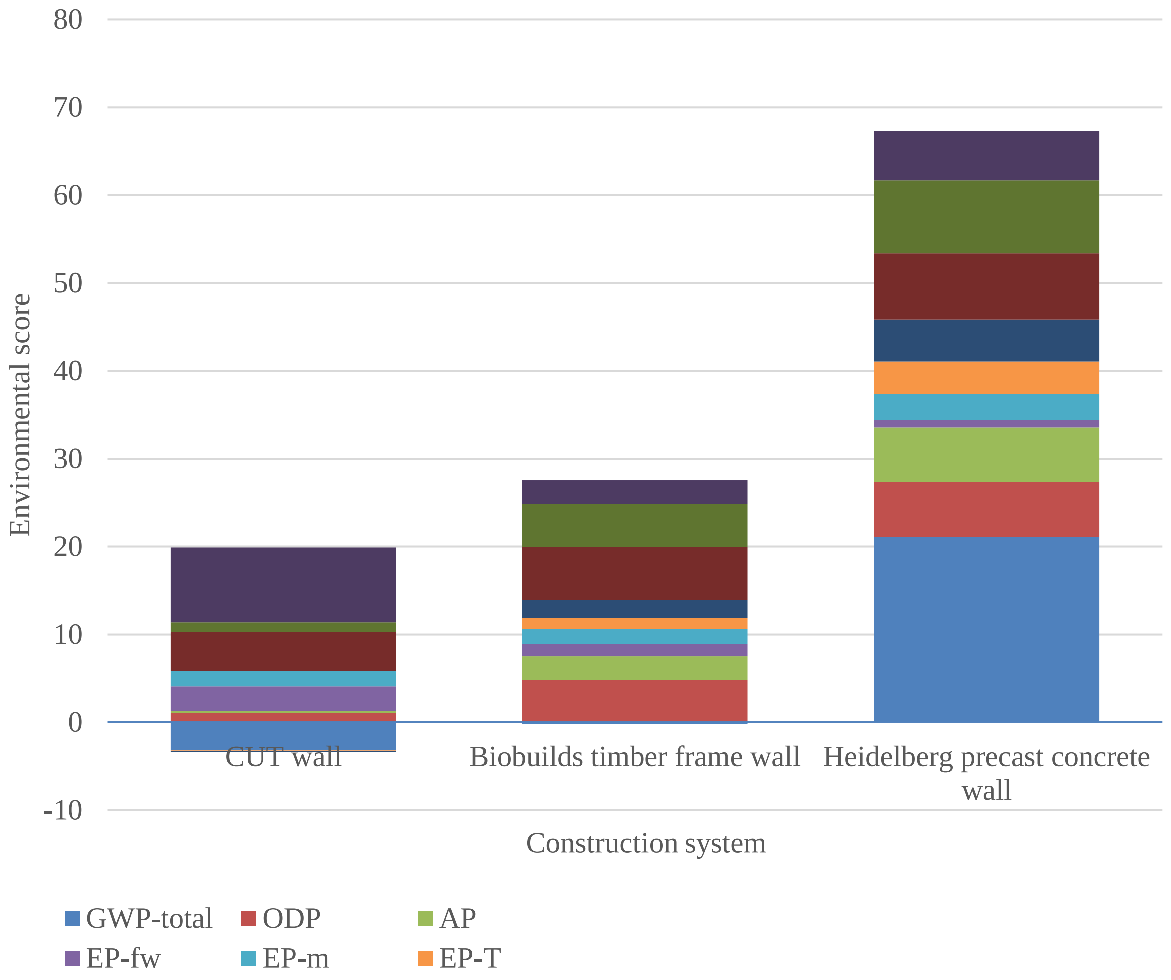

Figure 56: The division of final score by different environmental impacts subscores

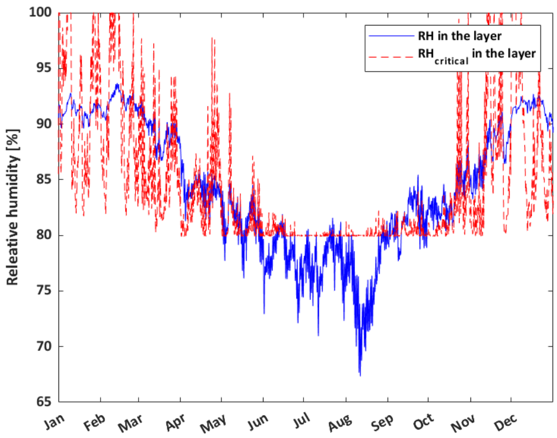

Figure 57: Comparison of Critical Relative Humidity and Relative humidity in the exterior side of the straw bale in Brussels, Belgium

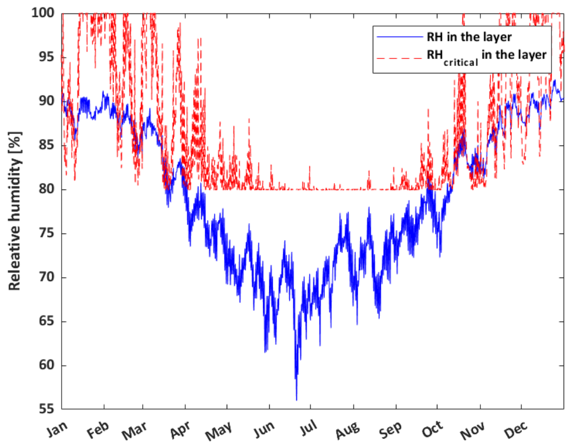

Figure 58: Comparison of Critical Relative Humidity and Relative humidity in the exterior side of the straw bale in Hradec Králové, Czech Republic

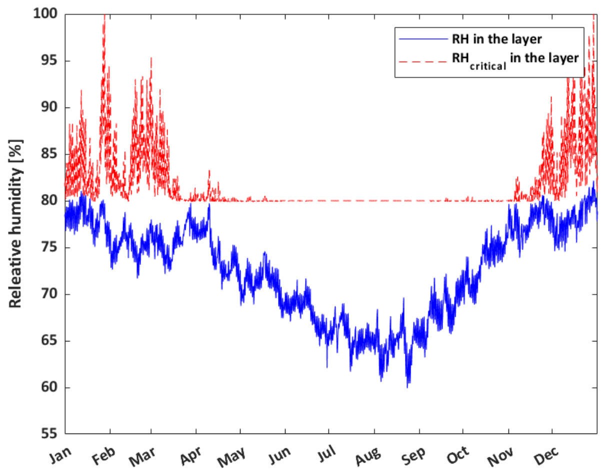

Figure 59: Comparison of Critical Relative Humidity and Relative humidity in the exterior side of the straw bale in Barcelona, Spain

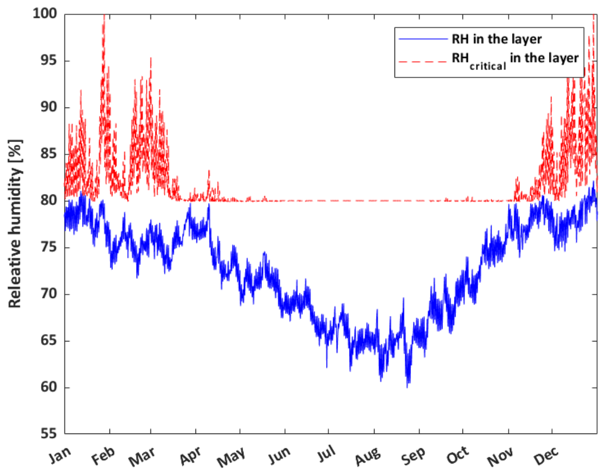

Figure 60: Comparison of Critical Relative Humidity and Relative humidity in the exterior side of the straw bale in Lund, Sweden

Table 13: The use of Generative Artificial Inteligence (GAI)

Question	**Use of GAI YES/NO**	**Description**
I used a Generative AI tool (e.g. ChatGPT or similar) in my report	Yes	GAI was used as an editor (Grammarly) and translator (DeepL pro), in detail described below.
I used a GAI tool as language editor (i.e. to correct grammar mistakes, etc.)	Yes	Use of Grammarly to correct spelling and grammar. This was done in whole document. New structures of the sentences suggested by Grammarly were not used, the original sentences were kept. It was used purely for grammar and spelling mistakes.
I used GAI to retrieve information	No	–
I used GAI to get help in writing code	No	–
I used GAI for translations	Yes	DeepL pro was used to translate documents from German, Spanish and French to understand certain topics. The original PDF was uploaded into the translator, it was translated with AI powered angine. Translated PDF document was downloaded in English. Later, my own text was written based on the findings from the translated documents.
I used GAI to generate graphs/images	No	–
I used GAI to help structuring my content	No	–

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