The Healthy Home

A pilot study on the effect of biobased insulation materials on human wellbeing

By:

Tara van Hoorn

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I would like to extend my gratitude to Chris Benning, who has helped me tremendously by building the virtual reality environment that I used in my experiment. Since I wasn't able to programme it myself, I completely relied on his abilities and kindness to help me.
Additionally, I would like to thank my family, friends, and boyfriend for supporting me and listening to my endless stream of words about insulation materials.

I was inspired to do this research because it seems that we are desperately aiming to improve the sustainability of the built environment, on which we depend so much. Throughout my time at TU Delft and Leiden University, I have learned that pathways towards sustainability and circularity are usually more focused on environmental wellbeing than on human wellbeing. This is of course imperative, but to me, it felt like something was lacking, and it got me wondering whether there is a way to improve environmental wellbeing while also ensuring human wellbeing.

With this research, I hope to inspire you, the reader, to think about the impacts the materials that provide you with shelter, safety, and a place to call home have on your wellbeing, mentally as well as physically.

Enjoy reading my thesis.

Tara van Hoorn
Leiden, 07-12-2023

Abstract

The Dutch government is aiming to transition towards a fully circular economy by 2050 to mitigate climate change. To comply with these standards, a transition team for the construction sector has identified biobased materials as a cornerstone for the sector to become circular, enabling a crucial shift because of the sector's large contribution to carbon emissions and environmental pollution. Principles on which this shift relies are focused on environmental health while neglecting human wellbeing, especially mental health as one of the building blocks of human wellbeing (the other being physical health), albeit of great importance due to the significant amount of time humans spend indoors. Mental health is defined by life satisfaction and happiness and is measured through perception and experience. A two-way path is identified: from mental and physical health to human wellbeing.

This research aims at identifying the effect of biobased insulation materials on the wellbeing of residents through a pilot study in the Netherlands. Individuals' perceptions and experiences of their living environments—specifically, their homes—serve as the basis for measuring wellbeing in this context.

A mixed method is used, combining quantitative and qualitative results from a discrete choice experiment in a virtual reality environment. Participants were presented with three sets of two predetermined configurations. For every set, participants were asked to make a discrete choice between the two alternatives.

The results were analysed using a Cox proportional hazard model in SPSS. The quantitative and qualitative data showed several discrepancies, but both emphasised the importance of indoor comfort. It is concluded that biobased insulation materials that ensure good indoor comfort are preferred over materials that don’t. Additionally, the importance of low maintenance needs and a small wall diameter is emphasised to lead to a preferred living environment and thus increased wellbeing.

Recommendations to move the model beyond a pilot include diversifying the sample population, materials, and attributes that are presented while aligning these with the target audience, including non-expert views throughout the development of the model, and revealing associations with the materials.

Keywords: circular economy, biobased insulation, virtual reality, discrete choice

List of abbreviations

CI – confidence interval

EPS – expanded polystyrene

ESD – environmentally sustainable design

HR – hazard ratio

LCA – life cycle assessment

VOCs – volatile organic compounds

VR – virtual reality

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1. Introduction

Acknowledging the urgency of climate change, there is a pressing need for the building industry to adopt environmentally friendly practices, increase energy efficiency in building systems, and embrace circular economy principles. This transition is particularly critical, as the industry currently accounts for 38% of global carbon dioxide emissions, operating within a linear model (Sobota et al., 2022), thereby generating a substantial environmental footprint. Moreover, the current building system relies heavily on raw materials and energy (Yadav & Agarwal, 2021), and a significant portion of Dutch buildings is energy-inefficient (Zhang et al., 2021). Additionally, there is a current shortfall of adequate houses in the Netherlands. Therefore, the Dutch government has committed to constructing 1.000.000 new houses in the coming years while also renovating obsolete buildings to address this (Sobota et al., 2022), hereby amplifying the depletion of resources and environmental impacts throughout all nodes of the building system.

However, the Dutch government aims to become fully circular by 2050 in the hopes of decoupling its economy from the consumption of raw materials while mitigating climate change and complying with the United Nations' sustainable development goals. The utilisation of biobased materials in the construction sector has been identified as a key factor in realising circularity within the economy (Rijksoverheid, 2020). While current efforts primarily focus on ensuring environmental health, consideration of the potential impacts on human wellbeing resulting from restructuring the building system is of equal significance, as individuals spend ~90% of their time indoors (Visser et al., 2015).

1.1. Environmentally sustainable design

The current focus is aligned with the principles of environmentally sustainable design (ESD), the architectural domain that addresses the environmental impact of construction. It encompasses principles such as energy conservation, efficiency, material selection, waste reduction, and water conservation (Asman et al., 2019). As Lockwood (2006) describes, 'Green buildings […] minimize on-site grading, save natural resources by using alternative building materials, and recycle construction waste rather than sending truck after truck to landfills'.

ESD strategies are widely recognised as effective measures to mitigate the negative consequences of the building industry and play a significant role in promoting the use of alternative building materials, including renewable and biobased materials (Chan & Adabre, 2019). This aligns with the objectives of the transition towards a circular building economy. Moreover, these principles are incorporated in the latest version of the Dutch 'Bouwbesluit' (building code), which stipulates that newly constructed buildings must be nearly energy-neutral and limit the environmental burden of construction materials (Rijksoverheid, 2012).

However considerate of environmental health, ESD has received criticism for its' quantifiable emphasis. It has been accused of relying on checklist-based assessments of building performance while neglecting a human-centred approach (Wijesooriya & Brambilla, 2021). Kellert et al. (2013) also underscore this criticism as they state that this type of 'low environmental impact design' lacks the connection to human wellbeing. More recently, it has also been emphasised by Le et al. (2023), as they show in a review of 97 papers that environmental analyses, analysed through life cycle assessment and economic assessment, are much better represented than social impact research in the context of biobased materials.

1.2. Human wellbeing

Traditionally, the concept of human wellbeing has had a focus on aspects such as jobs, community, education, environment, civic engagement, health, life satisfaction, safety, and work-life balance, and according to the OECD (n.d.), 'living in satisfactory housing conditions is one of the most important aspects of people's lives', as it provides shelter, privacy, a safe space, and a sense of 'home'.' The indicators that measure these aspects primarily address 'material' and quantifiable conditions, focusing more on living standards (general societal standards) than on an individual's wellbeing.

An expert group of the European Commission has tried to expand this limited view by developing sets of indicators to measure an individual's life satisfaction, also including 'satisfaction with accommodation' and broader living environment indicators such as 'perception of pollution, grime, or other environmental problems in the living area' (SpG, 2017). They emphasise that an individual's experience and perception of their environment are vital parts of measuring human life quality, thereby shifting the definition of human wellbeing towards a more elaborate one, including the psychological domain (SpG, 2017). Gaining knowledge on wellbeing through human perception and experience has also been identified by the World Health Organisation: Europe (2012) as a valid measure, thereby moving beyond the traditional measures such as education and income as aforementioned.

When focusing on the built environment as part of the living environment, several studies have delved into the significance of individuals' perception and experience of the building conditions on their wellbeing. For example, Kirillova et al. (2020) examined the influence of workplace design on employees and concluded that interior aesthetics contribute to employees' wellbeing. Al horr et al. (2016) conducted an extensive literature review on wellbeing and indoor environmental quality, finding that thermal comfort, air quality, acoustic comfort, and visual comfort significantly impact occupants' wellbeing.

These findings suggest a one-way path from the characteristics of building materials and design to human wellbeing, wherein wellbeing refers to a person's physical as well as mental health. This pathway has also been identified by Mouratidis (2021), as he states that life satisfaction and happiness are positively related to housing satisfaction, in which residents' preferences and needs play a significant role in improving wellbeing through urban planning: 'Dwelling characteristics that are linked to housing satisfaction are the dwelling's: plan, design, size, adequacy of interior space, construction quality, amenities, and price' (Mouratidis, 2021). However, going even further, research suggests a two-way path from health to wellbeing and wellbeing to health (World Health Organisation: Europe, 2012). A study by Howell et al. (2007) revealed that wellbeing, as defined by 'happiness' or 'life satisfaction', affected pain tolerance and immune system responses, among other health implications.

Thus, it seems as though the focus of research on human wellbeing has seen a slight shift towards an expanded view of the concept of human wellbeing, wherein the concept refers to the building blocks of physical health and mental health. This is an important shift, as there is not a one-way but a two-way relationship between health and wellbeing.

However, when looking at the concept of wellbeing in practice, this building block construct is often disregarded. Especially when focusing on the building sector and the Dutch building code, there is a lack of consideration for mental health, despite its significant influence on human wellbeing (Mouratidis, 2021; SpG, 2017; World Health Organisation: Europe, 2012).

1.3. Biobased building materials

Biobased construction materials are those made of natural and renewable fibres. According to a strategic analysis that the Dutch government commissioned in order to develop a biobased construction industry, biobased alternatives could replace about 86% of construction materials (Studio Marco Vermeulen, 2020). A life cycle assessment (LCA) by Ben-Alon et al. (2021) further emphasises the importance of replacing conventional materials with biobased materials, as they show that several types of natural wall systems can reduce the coupled embodied and operational environmental impacts by 34-57% in temperate climates as compared to conventional wall systems.

Biobased materials show potential for improving both environmental health and human wellbeing, with insulation materials being particularly noteworthy, as these show significant advantages for the indoor climate due to their vapour-permeable and breathable nature (van der Waal, 2023). The environmental advantages of these materials are emphasised by multiple LCAs, not limited to the ones currently cited, that show that the in-use phase of a building has the largest environmental impacts (Chau et al., 2015; Nwodo & Anumba, 2019; X. Zhang et al., 2013). However, the permeability and thermal regulation of biobased walls can decrease energy consumption during the operational phase of a building (Fedorik et al., 2021). Additionally, biobased insulation materials hold promise for renovation as well as new construction and are thus widely applicable in the current building landscape.

The 'Transition Team Circular Building Economy', a team that is challenged with consulting the government on the shift towards the circular building economy, emphasises the importance of the utilisation of biobased construction materials to reduce the sector's negative impact on the environment throughout all nodes in the building system. The team highlights the limited availability of raw and recycled materials to meet the current demands, further increasing the significance of renewable materials (Transitieteam Circulaire Bouweconomie, 2022). Nevertheless, the Dutch building code fails to provide specific guidance on the use of biobased materials, despite its' cornerstone function of the aimed circular economy (Rijksoverheid, 2012; Transitieteam Circulaire Bouweconomie, 2022).

1.4. Research gap and research questions

Research on mental health as one of the building blocks of wellbeing has seen a shift from gaining knowledge through traditional measures such as income and education to the more individual measures of perception and experience. However, this is currently often neglected when put into practise, and there is no specific focus on the field of biobased building materials, even though these have been identified as one of the cornerstones of the circular building economy and are inevitably involved in our future. As there is a two-way path between mental health and wellbeing, the importance of research on this topic in relation to biobased materials is imperative to increase the happiness and healthiness of the human population while moving towards a sustainable economy and mitigating its' effects on climate change (Figure 1).

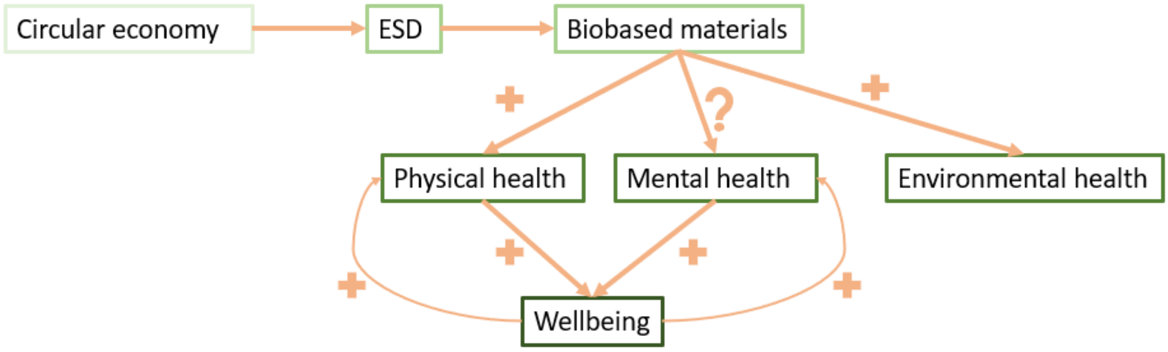

Figure 1: A visual representation of the research gap. The addition sign represents a positive relationship.

Therefore, this research aims at identifying the impact of biobased building materials on human wellbeing. The focus of the study will be on mental health, as this aspect of wellbeing has not been previously researched with regards to biobased building materials. Nevertheless, the current study will summarise several physical health indicators as well, as these will be used for the development and conduct of the research and will add a layer of understanding to the impacts of biobased materials on the construct of wellbeing.

Furthermore, the research is narrowed down to insulation materials, as they are identified as significant materials in improving human as well as environmental health and can be used in new construction as well as renovation, thereby showing significant potential for the current plans of the Dutch government.

Because of limits to the researchers' abilities, time constraints, and availability of tools, the research is conducted as a pilot study and is thereby designed for further development and application to be used in residential settings.

The main research question is:

What is the effect of biobased insulation materials on the wellbeing of residents, as researched in a pilot study in the Dutch context?

To address all aspects of the main research question, it is divided into three sub-questions:

1. What are significant biobased insulation materials, and what are their technical characteristics?
2. What are the advantages and concerns related to these materials?
3. What is the impact of the researched materials on mental health, as measured through the perception and experience of residents?

2. Literature review

First, the current research is connected to the existing body of literature and the Sustainable Development Goals (SDGs). Then, a literature study is done to describe which biobased insulation materials are significant and most common in the Netherlands. Additionally, the technical characteristics of these materials will be determined. Thereafter, the advantages and concerns of biobased insulation are determined (Figure 2). This data is further used to develop a survey (Chapter 3.4).

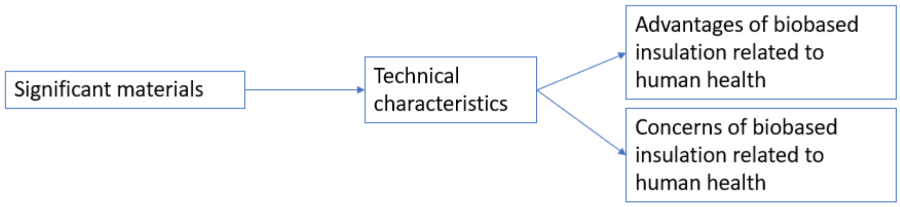

Figure 2: A visual representation of steps undertaken in the literature review.

The literature research is conducted on several search engines: ScienceDirect, Web of Science, and Google (grey literature and other relevant information). Keywords for the search are presented in Appendix A.

2.1. Relating research to the existing landscape

The current research relates to SDG 3: good health and wellbeing, and SDG 11: sustainable cities and communities. The United Nations underscores the utilisation of synergistic methodologies, emphasising collaboration not only among organisations, countries, and regions to achieve the SDGs but also within the goals themselves, integrating economic, environmental, and social dimensions (United Nations (UN), 2023). This study adopts a synergy of SDG 3 and SDG 11, adhering to the United Nations' directives.

Existing literature on biobased building materials predominantly adopts an environmental perspective, employing quantitative strategies to assess the materials' impacts on the environment or economy, often neglecting a social dimension (Le et al., 2023). Contrastingly, research on human wellbeing tends to encompass environmental considerations and living conditions, typically employing quantitative approaches such as cross-sectional or experimental methods (Mcsweeney et al., 2015).

However, both environmental and social perspectives don’t establish direct correlations between specific materials and human wellbeing, often overlooking qualitative design. Consequently, deriving definitive conclusions regarding individual associations and wellbeing from the existing literature is challenging. Nevertheless, this knowledge would be immensely valuable in navigating the collaborative pathways envisioned in the proposed synergies between SDGs 3 and 11 and among various stakeholders, including organisations, governments, and individuals.

2.2. Significant materials

An abundance of information on biobased insulation materials is accessible online, reflecting varying degrees of prominence among these materials. Since some materials have moved past the experimental stage and are now more widely used, economically viable, or have better performance, this is dependent on factors like their accessibility and viability in the Netherlands. Contrastingly, some materials, like mycelium, while identified as an emerging trend in biobased composites, have yet to enter mainstream use (Sandak et al., 2019).

In order to align the research with practical applicability and enhance its relevance, a criterion for material selection has been established. Specifically, materials with five or more references from a total of ten sources (see Appendix B) have been chosen for further investigation. The selected materials are cellulose, wood fibre, flax wool, hemp, cork, sheep's wool, and straw. Additionally, to facilitate a more comprehensive comparison in the subsequent stages of the experiment, one commonly used synthetic material, expanded polystyrene (EPS), has been selected.

2.3. Technical characteristics

There are several indicators to assess the suitability and preference of buildings by residents, particularly concerning the technical attributes of the employed materials. These characteristics impact indicators such as costs, acoustics, indoor climate, and room size (correlated with wall diameter), as well as durability, sustainability, and material origin. These objective factors relate to subjective factors such as the financial health of residents, acoustic experience and perception of indoor climate, room spaciousness, sustainability, durability, and maintenance concerns.

In the current study, the following technical aspects have been considered:

1. **Density:**
   A performance indicator reflecting insulation efficiency indicates the weight of the product.
2. **Thermal conductivity (λ):**
   Indicates the insulation value of the material, with lower values representing better insulation due to reduced heat conduction.
3. **Insulation thickness for thermal resistance (Rc):**
   Reflects the material's thermal resistance (resistance to conduct heat), calculated by dividing the diameter of the material by its thermal conductivity. Thus, a higher value indicates better insulation performance. Compliance with Dutch building code regulations, specifying minimum and target Rc-values (thermal resistance of a construction part), is considered. The minimum Rc-value for a vertical partitioning structure that separates spaces and other structures is 3.7 m2K/W (standard value), and the Rc-target value for vertical partitioning structures is 6 m2K/W (future proof value) (Rijksdienst voor Ondernemend Nederland, 2023). These Rc-values have been used to calculate the insulation thickness in metres: $d = R * \lambda$
4. **Water vapour diffusion resistance:**
   Indicates the material's permeability to water vapour.
5. **Heat capacity:**
   Indicates the energy required to elevate the material's temperature by one degree, highlighting its ability to store energy and contribute to insulation.
6. **Fire class:**
   Characterises the material's reaction to fire based on the European classification system. While synthetic materials typically achieve the highest A1 classification, natural materials range from B to E, although a strong lobby for synthetic materials in the EU exists (van der Waal, 2023). Fire class D is the minimum requirement for the entire construction, achievable with biobased insulation material combined with materials like gypsum.

Acoustic performance is intentionally excluded due to its high variability. The absence of a standardized measure and the dependence on factors like thickness, processing, measurement types, and frequencies make a single-number index, akin to the Rc-value, misleading (Schiavoni et al., 2016). Due to the heterogeneity of the gathered data in the current study, this characteristic is not included.

Appendix C provides values for the technical characteristics of the materials. While density, heat capacity, and fire class are not directly factored into further calculations, acknowledging them contributes indirectly to a more comprehensive understanding of the materials' characteristics.

2.4. Advantages of biobased materials

Biobased insulation materials offer multiple advantages over synthetic or mineral alternatives. Significant benefits are their reduced environmental impact and contribution to climate change mitigation, as materials derived from renewable sources emit less carbon dioxide during production and can act as carbon sinks (van der Waal, 2023). Additionally, they can positively impact the indoor climate and occupants' health while also providing long-term financial benefit as they have good thermal properties (van der Waal, 2023). They are able to effectively regulate indoor temperatures and humidity due to the absorption, storage, and desorption and release of heat and water vapour, which is called ‘hygrothermal performance’ (Raja et al., 2023; Yadav & Agarwal, 2021). This capability not only ensures comfort for occupants but also reduces the need for excessive heating or cooling, thereby lowering energy consumption and utility bills.

Conventional insulation materials often release volatile organic compounds (VOCs) and other harmful chemicals, contributing to the phenomenon known as ‘sick building syndrome’ (Samudro et al., 2022). This was already identified by Visser et al. (2015) in a letter to the Dutch government, informing them of the risks of conventional insulation materials almost a decade ago. In contrast, biobased materials may initially emit VOCs but are overall non-toxic, non-allergenic, and adsorb harmful and toxic substances, ensuring healthier indoor air for occupants (Raja et al., 2023).

In terms of fire safety, the literature shows some conflict. While biobased materials are often considered highly combustible, the literature suggests that these materials may have great fire resistance when treated with fire retardants, while having a reduced emission of toxic fumes and no release of flammable plastic particles when fire occurs (Cosentino et al., 2023; Raja et al., 2023).

Rabbat et al. (2022) concur with these advantages, highlighting the low embodied energy, carbon storage potential, reduced raw material use, minimised carbon footprint, and energy efficiency in buildings associated with biobased insulation materials. Furthermore, they note that biobased insulation materials exhibit excellent thermal performance, regulate temperature and indoor humidity effectively due to their vapour-permeable nature, are recyclable or reusable (when derived from additives), are biodegradable, or can be utilised for energy recovery (Rabbat et al., 2022). The findings of Yadav & Agarwal (2021) further support these statements, stressing the points of air regulation, decrease of energy needs of a building, and carbon sequestration of biobased materials, decreasing the carbon footprint of the building industry.

2.5. Concerns regarding biobased materials

However, Visser et al. (2015) also acknowledge several concerns regarding biobased insulation materials, and Rabbat et al. (2022) state that durability is ‘affected by several factors, such as the nature of the raw material (microstructure), the quality of the material (hygroscopic), the installation technique, rodents, and the in-service conditions (temperature and relative humidity or moisture content). The pH is an important factor affecting the durability of biomaterials since it is related to microbial proliferation.’

Some biobased materials have a higher risk of microbiological contamination, and certain additives used in their treatment to prevent this may lead to the emission of VOCs as well as environmentally harmful substances, particularly those aimed at enhancing fire resistance (Visser et al., 2015). Additives, such as water repellents, flame retardants, and fungicides or biocides, are also used to further increase the durability and lifespan of the materials (Rabbat et al., 2022). These additives concerned with increasing the fire resistance and lifespan of the materials not only affect human and environmental health but may also negatively affect the recyclability and therefore the end-of-life stage of the materials (Rabbat et al., 2022).

Additionally, Rabbat et al. (2022) state that to achieve the same acoustic and thermal performance as mineral or synthetic materials, a larger diameter of biobased material is needed (Appendix C, Table C). They agree with Visser et al. (2015) on the potential risks of additives for human as well as environmental health and state that biomass-based materials may be relatively more expensive due to their lower market share and non-local production (Rabbat et al., 2022). Also, the fire resistance of biobased materials may be questionable in some cases (Sandak et al., 2019).

3. Method

3.1. Approach

Initially, the study was designed using a quantitative approach to measure the relationship between biobased insulation materials and the mental health aspect of human wellbeing. However, while conducting the experiment, it became evident that it could also lead to valuable observations. Therefore, the design was changed to a mixed-methods approach to include the quantitative as well as the qualitative data for triangulation of the results, increasing their validity.

3.2. Survey

To determine the attributes of the materials, an online ranking task was presented to ten experts from Leiden University, TU Delft, and companies or organisations that are concerned with biobased building materials. It was based on the advantages and concerns of biobased insulation as revealed by the literature and aimed to be verified or rejected by experts in the field (Appendix D). Hereafter, Table 1 was constructed to summarise the findings from the literature and the survey.

Table 1: advantages and concerns revealed by the literature and experts.

Disadvantages/concerns	Advantages
Insulation values	Low carbon footprint
Expensive	Renewable
Fire resistance	Good air quality
Maintenance/durability	Durable
Renewability	Non-toxic
Energy costs in-use phase	Moisture regulation
Recyclability (due to additives)	Thermal regulation
Locally produced (EU)	Locally produced
Microbiological contamination	Biodegradable
Human and environmental risks of additives (used to increase durability)	Low energy use in production phase
Emissions of environmentally harmful substances	Low energy costs in-use phase
Emission of VOC’s	Good sound insulation
	Reduced raw material use
	Long-term financial benefits
	Carbon storage potential
	Non-allergenic
	Adsorb harmful substances
	Energy recovery
	Biodegradable
	Reduced need heating/cooling
	Reduction toxic fumes when burned
	Decreased energy consumption

3.3. Discrete choice experiment

The experimental part of this research was less straightforward, as it involved testing human perceptions and experiences, which may be influenced by external variables that are beyond the scope of this research. To minimise the impact of these external factors, the research was conducted using virtual reality (VR), providing a more controlled environment. Participants were immersed in a VR environment where they were exposed to two different types of insulation materials and their characteristics. The participants were then asked to make discrete choices between the alternatives, which was done a total of three times per participant. The alternatives were designed using a statistical design of the configuration of several attributes that could be independently estimated afterwards regarding the effects. This method was identified as more accurate than other choice-based methods such as raking or rating scales (Hensher, Rose, & Greene, 2005) or the two-alternative or referendum questions (Mogas, Riera, & Bennett, 2006). Also, semantic limitations in describing architectural aspects were hereby overcome. The purpose of this experiment was to identify the preferred design model (choice set), in this case related to the insulation material. A more preferred design leads to increased living satisfaction and thus improved wellbeing of residents (see chapter 1.2 for elaboration of the relationship between life satisfaction and wellbeing).

3.3.1. Attributes

After the survey, careful consideration of the significance and feasibility of Table 1 for the experiment led to the following table: a list of attributes and levels of the attributes for the discrete choice experiment (Table 2).

Table 2: Levels per attribute.

	Attributes	**Levels**							
		1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
1	Insulation material	Cellulose	Wood fibre	Flax wool	Hemp	Cork	Sheep wool	Straw	EPS
2	Rc-value (material thickness)	3.7	6						
3	Interior finishes	Wood	Plasterwork	Non-latex paint	Loam				
4	Interior sheathing board	Wood	Gypsum	Loam					
5	Fire resistance	Yes	No						

The Rc-values adhered to the minimum insulation requirements as outlined by the Dutch building code and the requirements of wall insulation indicated by the government as ‘future proof’.

The different layers of a wall were added as attributes, as they were shown in the VR, and can influence participants’ choices. All wall layers were biobased, as this allows the permeable and breathable nature of the insulation materials to be preserved, which is of significance to be able to take advantage of the materials’ hygrothermal properties.

Some aspects were not included in the attribute table: ‘expensive’ as costs for the material do not impact a tenant; aspects related to climate change, specific material knowledge, or technical knowledge, as prior knowledge by participants on these aspects cannot be assumed; ‘non-allergenic’ as this does not influence all participants homogeneously; ‘durability’ as this mainly relates to the use of additives (which is assumed for all materials included); utilization for energy recovery’ as this is part of the end-of-life treatment and does not affect the participants directly; ‘carbon sink’, ‘indoor climate’, ‘reduced raw material use’, ‘biodegradable’, ‘thermal insulation’ and ‘decreased energy consumption’ as these were included in the basics video shown to all participants. ‘Maintenance’ and ‘moisture regulation’ were included in the VR but depend on the material and are therefore not accounting for attributes because they are not able to vary independently.

Design

A full factorial design containing all possible combinations of the attributes and levels was constructed. The model contained one attribute with eight levels, two attributes with two levels, one with three levels, and one with four levels, denoted as 8*2*2*3*4. Without optimisation, this resulted in 384 renders (combinations or ‘choice sets’).

From the full factorial design, a fractional factorial design was developed by constructing orthogonal arrays using R software to optimise the number of choice sets and make the study less overwhelming (Kuhfeld, 2010). Using orthogonal arrays, there were no linear combinations in the matrix, meaning the attributes could be estimated independently. This optimisation of the model resulted in 192 choice sets.

3.3.2. Virtual reality

The attributes were conceptualised and visualised using Unreal Engine, a gaming software. A virtual reality (simulation) was created to conduct the experiment, offering the advantage of a reduced number of disturbing factors and noise (Figure 3). See Appendices E and F for elaboration on the modelling of the VR texture and the representation of the design characteristics.

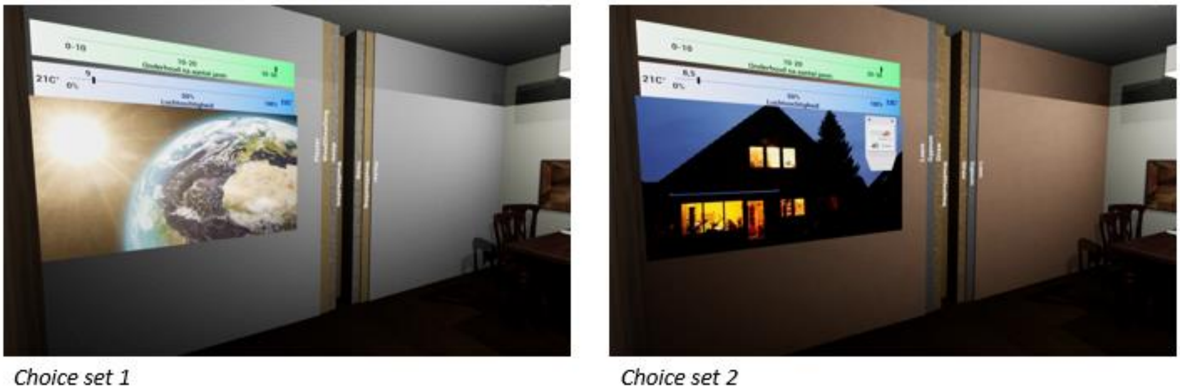

Figure 3: example of a discrete choice with two choice sets in virtual reality (screen capture). Both screen captures show a living room from the point of view of the participant. In the middle, the wall is open to show all three wall layers. On the left, there is a TV screen showing videos with extra information. Above that is a blue slider indicating the humidity and perceived temperature and a green slider indicating the maintenance needs, both related to the insulation material shown in the choice set.

3.4. Procedure

A total of 28 students were selected to participate through snowball sampling. This was done by advertising the research at the Faculty of Architecture and the library of TU Delft. They participated in the study on two consecutive days.

The participants were seated in a chair to ensure their safety during the experiment. Before the VR glasses were put on the participants, they underwent preliminary questioning to identify basic demographic information, including their age, gender, place of residence before their 18th birthday, and education. While the primary dataset was derived from a discrete choice experiment pilot study involving exclusively TU Delft students, rendering their basic information somewhat less pertinent, the comprehensive nature of the experiment was maintained for potential relevance in further development of the model beyond the pilot.

Thereafter, the participants were assisted in putting on the glasses by a researcher, after which the experiment was started on a laptop. The researcher had real-time visibility of the participants' VR perspective on the laptop screen, enabling effective guidance throughout the course of the experiment.

Consideration of wellbeing of the participants

To ensure the wellbeing of participants during the experiment, an experienced researcher was present or nearby to help the participants with the use of the equipment as well as to ensure their safety. Virtual reality can make some people dizzy or nauseous, making this a specifically important aspect of the experiment.

3.5. Data analysis

3.5.1. Quantitative data

Data analysis was done by utilising the SPSS software tool. The fractional factorial design file and the empirical data file were both uploaded into the software, with the empirical data file merged into the fractional factorial design file. Unused choice sets were removed. Subsequently, a nominal regression was done using the Cox proportional hazard model. The analysis utilised a conditional logit model to examine the selection between the two configurations, considering the attributes of the alternatives (Kuhfeld, 2010). This generated hazard ratios (HR) as effect measures, corrected by 95% confidence intervals (CI). The HR quantifies the probability of variables being chosen over their reference (the hazard). While conventional significance is often denoted by p-values < 0.05, the current pilot study, constrained by a limited participant pool, interprets significance as a relative metric. As such, the term 'relative significance' is further used in this research.

For the Cox proportional hazard model, the data is needed to delineate participant choices in comparison to the presented alternatives. A binary variable, named Dchoice, was created: '1' denoting a match between the participant's choice and the presented alternative, and '0' signifying a mismatch. The variable 't' was subsequently derived as 2 - Dchoice, designating the event (t1) and no event (t2). Cox regression analyses were then iteratively conducted for all attributes, varying the hazard to assess the significance of outcomes. Attributes demonstrating the highest significance were selected for 'insulation materials': level 8 = EPS, 'sheathing': level 3 = loam, and 'interior finish': level 3 = white paint. The attributes ‘fire resistance’ and ‘wall thickness’ only had two levels and were inherently relative to each other in the analysis.

3.5.2. Qualitative data

During the experiment, qualitative data was gathered in terms of observations. They were noted down in the form of bullet points by the researcher. They were later organised, written down in full text, and used in an inductive way to help form recommendations to move the study beyond a pilot.

4. Results

4.1. Quantitative data

The Cox regression analysis showed the following results for the attributes ‘insulation material’, ‘interior finish’, and ‘sheathing board’. The results are summarised in Table 3-5 that include the hazard ratio, which holds 95% confidence intervals, and the significance.
Additionally, Figure 4-6 present the cumulative hazard function (the cumulative probability of preference).

Table 3 displays the results of the analysis for the attribute ‘insulation materials’, sorted by significance from largest to smallest, and the other characteristics that were shown for the variables to connect the results to the characteristics and explain the outcomes. The overall significance of the attribute is 0.208, indicating relative significance.

Participants exhibited a preference for hemp, flax wool, cork, and wood fibre over EPS, as evidenced by a significantly larger Hazard Ratio (HR) than 1.0. Specifically, the HR of 5.213 for hemp indicates that participants opted for this material 5.213 – 1 = ~421% more frequently than EPS, while an HR significantly below 1.0 implies a preference for the reference level. In cases where the HR is not significantly different from 1.0, i.e., the 95% CI includes 1.0, no clear preference emerges for either of the two levels.

Notably, the results for hemp, flax wool, and cellulose are significant even with the current number of participants and do not include 1.0 in the 95% CI. Hemp and flax wool are both related to low maintenance, relatively small wall diameters, and low humidity. Cellulose presents an HR below 1, meaning it is not preferred over EPS, and shows medium maintenance needs as the only significant difference between hemp and flax wool.

Straw, sheep wool, and cork have a similar significance, all within the range of 0.241–0.252, but only cork has an HR above one. All present a 95% CI that includes 1.0, implying no specific preference is given for either of the levels.

By far the least significant material is wood fibre, with a significance of 0.708, and its’ HR is not significantly different from 1. The material shows a large wall diameter and high humidity as compared to EPS, which has a small wall diameter and high humidity.

Table 3: results of the analysis on the attribute 'insulation material', matched with the other characteristics as shown in the virtual reality. Results are sorted by significance.

	Characteristics				Significance	Epx(B)=Hazard ratio	95% CI for Exp(B)	
Material	Maintenance	Thickness R=3.7	Thickness R=6	Humidity	0.208		Lower	Upper
Material(4)=Hemp	Low	0.18	0.29	0.3-0.4	0.009	5.213	1.519	17.89
Material(1) =Cellulose	Medium	0.15	0.24	0.3-0.5	0.029	0.247	0.07	0.869
Material(3)=Flax wool	Low	0.17	0.27	0.6-0.9	0.034	3.673	1.102	12.245
Material(7)=Straw	Low	0.17	0.28	0.3-0.4	0.241	0.487	0.146	1.621
Material(6)=Sheep wool	Low	0.21	0.34	0.6-1.0	0.242	0.494	0.151	1.612
Material(5)=Cork	Low	0.17	0.27	1.4-2.2	0.252	1.996	0.611	6.516
Material(2)=Wood fibre	Low	0.23	0.38	1.3-2.1	0.708	1.284	0.346	4.769
Hazard=EPS	Low	0.13	0.22	15.6-26.4				

Figure 4 shows the cumulative hazard function per material level, with a 95% confidence interval error bar. It shows the largest cumulative hazard, but also an especially large uncertainty, for material 2 (wood fibre). The other materials show smaller error bars but also a smaller cumulative hazard. Especially material 1 (cellulose) has a small cumulative hazard and thus a small probability of preference.

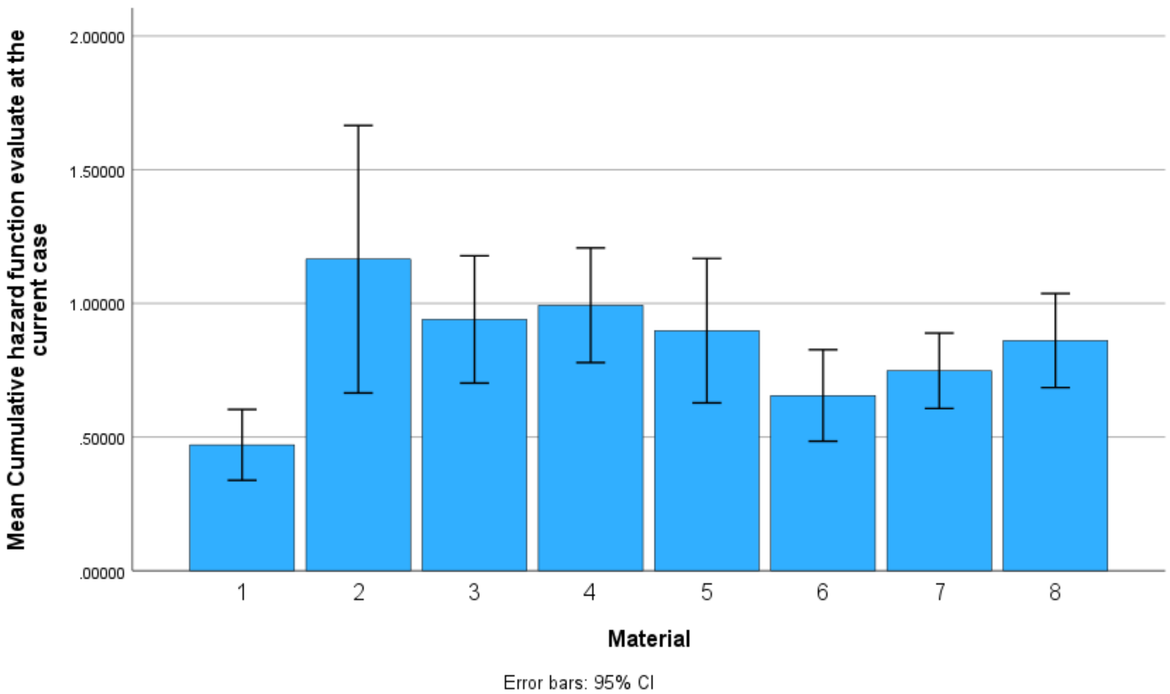

Figure 4: the mean cumulative hazard functions for materials 1 – 8 (1=cellulose, 2=wood fibre, 3=flax wool, 4=hemp, 5=cork, 6= sheep wool, 7=straw, 8=EPS). Error bars with a 95% confidence interval are included to display the uncertainty in results.

Table 4 displays the results of the analysis for the attribute ‘interior finish’, sorted by significance from largest to smallest. The overall significance of the attribute is 0.592, revealing no relative significance.

Participants exhibited a preference for loam and wood over paint, both having an HR over 1. However, wood is not showing relative significance, and the HR is close to 1. Loam does show relative significance, and the HR ratio relates to ~35% preference over paint. Plasterwork is not preferred over paint, as the results show an HR below 1 and the results are relatively significant.

However, all materials show a 95% CI that includes 1.0, implying that there is no preference for any of the variables over the reference with the current participant pool.

Table 4: results of the analysis on the attribute ‘interior finish’. Results are sorted by significance.

	Significance	Exp(B)=Hazard ratio	95% CI for Exp(B)	
Finish	0.592		Lower	Upper
Finish(2)=Plasterwork	0.237	0.692	0.376	1.273
Finish(3)=Loam	0.283	1.356	0.777	2.366
Finish(1)=Wood	0.491	1.252	0.66	2.378
Hazard=paint				

Figure 5 shows the cumulative hazard function per finish level, with a 95% confidence interval error bar. It shows the largest cumulative hazard for finish 4 (loam), but also a relatively large uncertainty. Finish 3 (paint) shows the smallest cumulative hazard and a relatively small uncertainty. Finish 2 shows a small cumulative hazard and a relatively small uncertainty, while Finish 1 (wood) shows a relatively large cumulative hazard but also a larger uncertainty.

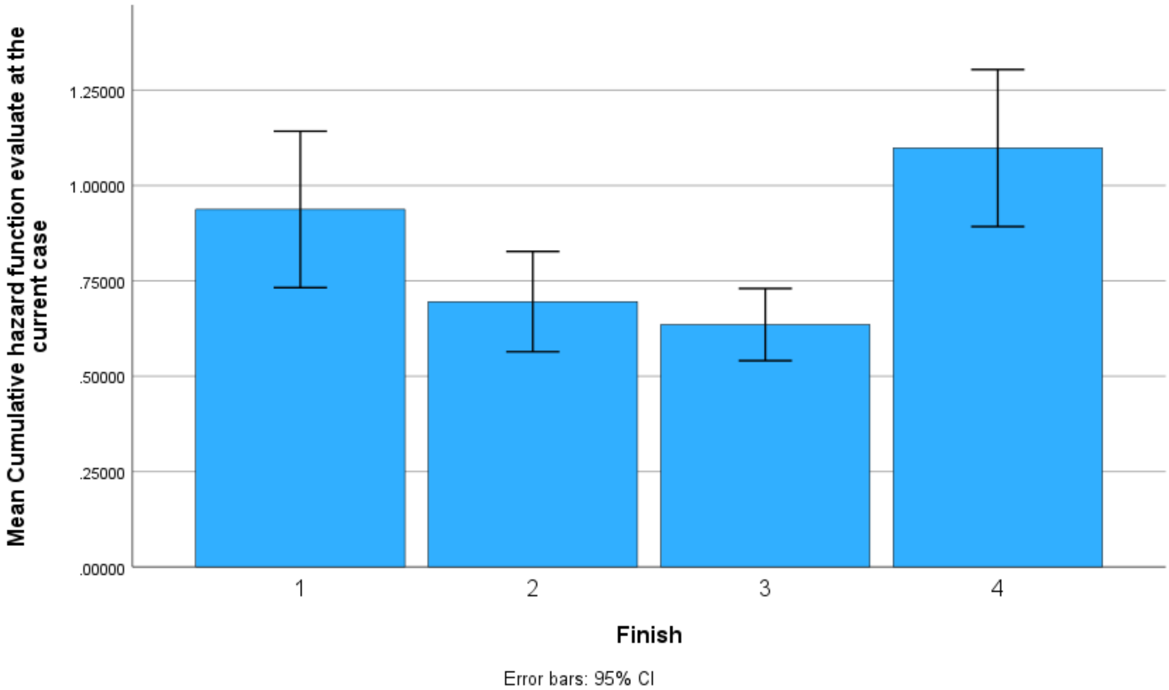

Figure 5: The mean cumulative hazard functions for finishes 1–4 (1=wood, 2=plasterwork, 3=paint, 4=loam). Error bars with a 95% confidence interval are included to display the uncertainty in the results.

Table 5 displays the results of the analysis for the attribute 'sheathing board', sorted by significance from largest to smallest. The overall significance of the attribute is 0.131, showing relative significance.

Participants exhibited a preference for gypsum over loam, as shown by the HR of 1.551, indicating ~55% preference over the reference level. Notably, the material is very close to significance (0.055) even without many participants.

Wood was not preferred over loam, with the HR being below 1 and showing relative significance.

Notably, all variables show a 95% CI that holds 1.0, indicating that there is no preference for the variables, although the intervals are close to excluding 1.0.

Table 5: results of the analysis on the attribute 'sheathing board'. Results are sorted by significance.

	Significance	Exp(B)=Hazard ratio	95% CI for Exp(B)	
Sheathing	0.131		Lower	Upper
Sheathing(2)=Gypsum	0.055	1.551	0.991	2.428
Sheathing(1)=Wood	0.101	0.686	0.437	1.077
Hazard=Loam				

Figure 6 shows the cumulative hazard function per sheathing level, with a 95% confidence interval error bar. It shows the largest cumulative hazard for sheathing 2 (gypsum), the second largest cumulative hazard is shown for sheathing 3 (loam), and the smallest is shown for sheathing 1 (wood). The variables show no exceptionality in error bars, although sheathing 1 has the smallest error and sheathing 2 the largest.

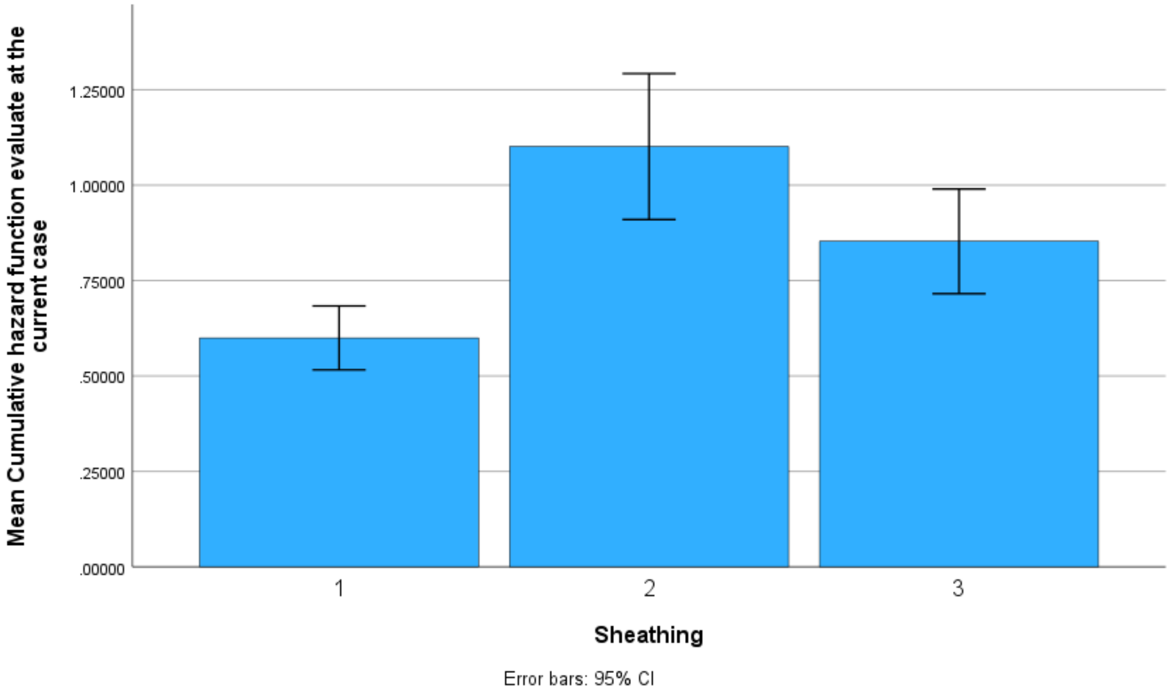

Figure 6: The mean cumulative hazard functions for sheathings 1–3 (1=wood, 2=gypsum, 3=loam). Error bars with a 95% confidence interval are included to display the uncertainty in the results.

4.2. Qualitative data

When in VR, participants engaged in discourse concerning their reasons for making their choices. Interestingly, the majority of the participants did not express their thoughts on the content of the videos they were presented with. Some asked about the specific burning times of the materials as presented in the video, but after reassurance regarding the safety of all materials used in the experiment, they didn’t seem to take the variable into account anymore.

Most participants emphasised the aesthetics of the room, with some individuals declaring that their choices were primarily influenced by the interior finish layer's visual appeal. Participants even expressed a preference for synthetic materials offering aesthetically pleasing interior finish layers over more environmentally sustainable alternatives with less visually appealing interior finishes. The most prevalent finish layer was paint.

Furthermore, participants frequently cited the humidity control slider as a pivotal factor in their decision-making process. Many underscored the importance of indoor air comfort when considering their choices.

Absent from participants' discussions and considerations were observations regarding the thickness of the walls. Although participants were prompted to evaluate the materials' wall thickness as a significant variable, none mentioned this variable.

Participants didn't bring up any of the other concerns that the survey and literature review revealed, such as energy costs or the recyclability of the materials.

5. Discussion and limitations

5.1. Discussion

A pathway towards a circular building economy is the utilisation of biobased materials. However, this pathway is focused on ensuring environmental health, while human wellbeing is of equal importance as humans spend ~90% of their time indoors (Visser et al., 2015). The current research aimed to identify the impacts of biobased insulation materials on human wellbeing, to create a happy and healthy human population and increase environmental health. A notable result from this study is the relationship between humidity regulation of the materials and the preferences of participants. Other characteristics that seem to play a role in the preferences of participants are maintenance and the wall diameter. Insulation materials that stood out were hemp and flax wool, both showing a small wall diameter, low maintenance, and low humidity. Additionally, these materials showed significance of the results and a 95% CI that does not hold 1.0, even with the small number of participants in the current study.

Insulation materials

Noteworthy among the results is the correlation between humidity regulation of materials and participant preferences. Hemp and flax wool emerged as standout materials, exhibiting small wall diameters, low maintenance requirements, and low humidity levels. The statistical significance of these materials, even with a modest sample size, suggests their potential prominence in fostering indoor comfort and wellbeing.

Thus, a preference for materials with low humidity indicators over the synthetic alternative is revealed, emphasising the role of indoor comfort in participants' choices. However, cellulose did not show preference over its synthetic alternative, indicating that maintenance needs also play a pivotal role in individuals' preferences. Other materials, such as straw and wood fibre, underscore the importance of wall diameter and speculate on the importance of aesthetics, as both materials had a rough and unprocessed appearance in the application, which may have invoked associations with insects, lower fire resistance, or untidiness, contributing to their diminished appeal. Additionally, it can be speculated that some participants did consider other, not mentioned aspects, such as the origin of the product and the environmental implications, e.g., for the material wood fibre, as it showed a notable insignificance.

Summarising, the materials hemp, flax wool, and cellulose, exhibiting a 95% confidence interval that deviates from 1.0, emerge as pivotal results, suggesting that considerations of indoor comfort and maintenance play a key role in material selection.

Sheathing board

The unexpected significance of the attribute 'sheathing board,' particularly the preference for gypsum over loam, merits attention. This outcome could be attributed to the smaller number of variables within this attribute group as compared to insulation materials, leading to increased significance. Moreover, it highlights the importance of familiarity and aesthetics in participants' decision-making processes, aligning with the qualitative emphasis on aesthetics.

Discrepancies between qualitative and quantitative results (interior finish)

The divergence between quantitative and qualitative results, notably regarding interior finish, indicates the need for cautious interpretation of observations during virtual reality (VR) experiments. These observations, rather than standing alone, should complement quantitative findings to avoid potential overestimations of certain preferences.

The discrepancies might be due to some participants being more talkative, while others didn’t elaborate as much on their choices, biassing the researcher after the initial participants. Another explanation might be a difference in understanding by the researcher and the participants, e.g., of the term ‘aesthetics’: it might have been that the participants spoke about the aesthetics of all three wall layers and not specifically about the aesthetics of the finish layer as the researcher interpreted.

Translation of theory
A notable qualitative result was the confusion that the video on fire safety created, while it was shown to decrease confusion and show participants that biobased materials are fireproof. After taking away the confusion it led to, participants seemed to disregard this variable, suggesting that safety was not a significant concern for them in their decision-making process. This highlights the disconnect between what might be considered a critical safety factor and the participants' priorities.

Furthermore, the video was initially presented to all participants in the first choice set. While beneficial for studying pre-informed decision impact, alternative timings might unveil shifts in decisions with increased knowledge.

The observations showed that the presented information mostly did not challenge the participants to think about other concerns related to the materials. This raises questions about the translation of theoretical concerns into real-world decision-making. It's possible that participants in the VR environment were only considering short-term, observable factors (like aesthetics and indoor comfort) and were not fully aware of the long-term effects of their decisions in terms of sustainability and energy efficiency.

3.1. Limitations and implications for practice

The current study has several methodological constraints. Foremost is the sample population, composed exclusively of students from TU Delft, who typically possess a higher degree of prior knowledge and have a distinct housing arrangement (particularly not being homeowners). The inherent bias introduced by this homogeneous group poses challenges in generalising the study's results to broader societal contexts. Additionally, the limited number of participants led to statistically insignificant results in certain instances, constraining the robustness of the outcomes. Another constraint pertains to the predetermined selection of materials, limiting the study's exploration to a predefined set. Data availability emerged as an additional limitation, with certain information gaps filled using non-scientific sources, albeit homogeneous, to mitigate potential reliability issues. Furthermore, the chosen attributes within the VR environment were constrained, omitting certain aspects that were revealed by the literature and survey to cater to a broader and potentially less educated audience. Lastly, the timing and geographical location of the research introduce potential confounding factors related to climatic conditions and demographic characteristics.

Nevertheless, the results of the current study can be implemented in practice when taking the limitations into consideration. Governments and municipalities could use the findings to boost support for the use of materials and to establish pathways for the adoption of biobased materials in the building sector in areas with comparable demographic and climatic conditions as in the current study. The sample population in the current research could also be representative of the generation of people that will have to deal with the future implications of these pathways.

Simultaneously, the body of research and knowledge should be increased, improving research on the impacts and application of biobased materials. A first step towards improved research on the impact of biobased materials on human wellbeing is to improve the availability and reliability of background data, such as on the characteristics of the materials, which can lead to substantiation of the pathways to the circular building economy and the development of more practical guidelines on the use of biobased materials that include consideration of human wellbeing. An additional step would be to use a longitudinal and cross-sectional research design to improve the understanding of preferences related to climatic and demographic differences.

The results of the current study don't necessarily root for one material, but the indication of humidity, maintenance, and wall diameter playing a role in the preferences of participants implies that these factors can be considered by manufacturers and project developers, as well as housing associations and homeowners, when renovating and building houses. They can be implemented in the initial building and renovation plans to decrease the chances of residents being dissatisfied with their living environment and having a negative impact on their mental health and wellbeing.

Furthermore, the results can encourage housing associations or project developers to include resident's opinions in the building or renovation plans and to be transparent about the materials that are used, as they show that providing information can influence an individual's preference. This relates to the development and use of different sets of attributes that are more aligned with the target audience, since in the current research a more general approach was taken.

Lastly, the results show the importance of translating expert and academic views into aspects that align with real-world concerns. It implies that in the current research, this translation was sometimes insufficient, e.g., when looking at the responses to the video on fire resistance, and so these results cannot be linearly related to the literature and experts' views, which is an important aspect to consider when using these results. This outcome can be used as an indication of the importance to improve the model to better align with real-world concerns and as a foundation to do so.

6. Conclusions and recommendations

6.1. Conclusion

Aiming to ensure human wellbeing while moving towards the circular economy, the impact of biobased insulation materials on human wellbeing was studied in the current research.

The discrete choice experiment revealed that humidity and maintenance are the most prominent indications of preference for an insulation material, since the results for some materials were significant and showed a 95% CI that doesn't hold 1.0, even with the current modest sample population. Selecting materials with preferred characteristics in construction can be related to a positive experience and perception of one's living environment, thereby increasing mental health and wellbeing.

The results showed that biobased materials create good indoor comfort and that specifically the materials that exhibit the lowest indoor humidity are preferred (e.g., flax wool and hemp). This is an interesting outcome when relating it to the technical characteristics of biobased materials in general, as they have a vapour-open and breathable structure, allowing them to decrease indoor humidity and improve the indoor climate in comparison to conventional materials.

However, from the current results it cannot be concluded that biobased materials in general are preferred and lead to increased living satisfaction, as other indicators seem to play a role as well. These indicators are the wall diameter and appearance of the material, although this last point rests on speculation.

Because of several limitations of the current study, the results don't conclude on the use of a certain material. However, they do imply considerations for governments, municipalities, project developers, housing associations, and homeowners of, in the following order of significance, indoor comfort, maintenance, wall diameter, and appearance of materials.

6.2. Recommendations

The current research has laid the foundation for more extensive exploration. To enhance the depth and applicability of the pilot model, several recommendations are proposed for consideration.

Firstly, it is suggested to diversify the sample population to contribute to a more comprehensive understanding of different demographic segments. This approach aims to understand the demographic influences on individual preferences, facilitate the development of social support strategies, and improve wellbeing across varied regions. Insights derived from such studies may yield region-specific guidelines for the utilisation of biobased materials, enhancing the feasibility of implementation within respective geographic contexts.

In addition, diversifying the array of materials presented is advised. This entails exploring a broader spectrum of both conventional and innovative materials, contributing to the progression of the biobased materials industry. Such diversification has the potential to catalyse the development of enhanced materials while concurrently mitigating the costs associated with biobased materials, making them more economically viable and appealing to the manufacturing and construction sectors. This is particularly pertinent as the manufacturing industry actively integrates innovative materials into its existing landscape.

Furthermore, the customisation of attributes tailored to specific target audiences is proposed. For instance, when focusing on tenants, the study could incorporate the effects of materials on energy bills, which can be complemented by the material costs when targeting homeowners. This recommendation underscores the importance of presenting information in a more nuanced manner, including details on different life cycle stages of materials, to foster a comprehensive understanding of the long-term implications of decisions. Such information can be represented through indicators like carbon footprints, material footprints, or water footprints.

Another suggestion is the inclusion of non-experts in the early stages of research. In doing so, a survey among non-experts could be conducted to gain insights that may differ from those of experts due to varying levels of prior knowledge and involvement. This approach could allow for the enhancement of the translation of academic concerns and advantages into attributes that align more closely with participants' understanding. The outcomes thereof may offer a more realistic portrayal of societal concerns.

Lastly, the literature review has revealed a gap in previous research on the associations of individuals with biobased materials in the current format. Consequently, a recommendation is made for more focused qualitative and quantitative research. This could involve conducting surveys either before or after experiments. A survey beforehand could specifically focus on several materials and characteristics to determine how these should be visualised in the experiment, and a survey afterwards could specifically focus on participants' associations with the materials shown during the experiment. Alternatively, participants could be questioned during the experiment to explain the factors influencing their preferences for certain materials. Such qualitative investigations could be essential for a more nuanced understanding of the subjective associations individuals have with biobased materials and are of great significance to fill this gap in the current body of knowledge.

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Appendices

Appendix A: keywords literature study

Table A.1: used databases.

Science Direct
Web of Science
Scopus

Table A.2: keywords of the literature review of which different combinations are used.

Living quality
Biobased buildings
Human wellbeing
Human health
Biobased insulation materials
Environmentally sustainable design
Technical characteristics/performance
Dutch building code
Concerns
Advantages
Future proof

Appendix B: significant materials

Table B shows the best presented materials in the literature as found by the researcher. Other natural fibres were reviewed but are very diverse and not prominently present in the literature and are therefore not included in the current study.
Materials with five or more references were deemed to be significant and are used in the current study.

Table B: references to the literature, grey literature, and websites used to review the most common biobased insulation materials.

Material	Source
Cellulose	(Visser et al., 2015), (van der Waal, 2023), (Van Dam & Van Den Oever, 2019), (Ouakarrouch et al., 2022), (Biobased Bouwen, n.d.), (van Dijk et al., 2022)
Wood fibre	(Visser et al., 2015), (van der Waal, 2023), (BouwGezond BV, n.d.), (Groene Bouwmaterialen, n.d.), (Van Dam & Van Den Oever, 2019), (Sandak et al., 2019), (van Dijk et al., 2022),
Flax wool	(Visser et al., 2015), (van der Waal, 2023), (BouwGezond BV, n.d.), (Van Dam & Van Den Oever, 2019), (Sandak et al., 2019), (Biobased Bouwen, n.d.), (van Dijk et al., 2022),
Hemp	(Visser et al., 2015), (van der Waal, 2023), (BouwGezond BV, n.d.), (Groene Bouwmaterialen, n.d.), (Sandak et al., 2019), (Biobased Bouwen, n.d.), (van Dijk et al., 2022),
Cotton	(Visser et al., 2015), (Groene Bouwmaterialen, n.d.), (Van Dam & Van Den Oever, 2019), (van Dijk et al., 2022),
Coconut	(Visser et al., 2015), (Van Dam & Van Den Oever, 2019), (Biobased Bouwen, n.d.),
Cork	(Visser et al., 2015), (van der Waal, 2023), (Groene Bouwmaterialen, n.d.), (Van Dam & Van Den Oever, 2019), (Biobased Bouwen, n.d.),
Sheep’s wool	(Visser et al., 2015), (van der Waal, 2023), (Groene Bouwmaterialen, n.d.), (Van Dam & Van Den Oever, 2019), (Sandak et al., 2019), (van Dijk et al., 2022),
Shells	(Visser et al., 2015), (Van Dam & Van Den Oever, 2019), (Biobased Bouwen, n.d.),
Soft board	(Visser et al., 2015),
Grass fibre	(van der Waal, 2023), (Sandak et al., 2019), (Ouakarrouch et al., 2022), (van Dijk et al., 2022),
Hemp lime	(van der Waal, 2023), (Groene Bouwmaterialen, n.d.), (Sandak et al., 2019),
Straw	(van der Waal, 2023), (Van Dam & Van Den Oever, 2019), (Sandak et al., 2019), (Ouakarrouch et al., 2022), (van Dijk et al., 2022),

Reed	(Van Dam & Van Den Oever, 2019), (Sandak et al., 2019), (Ouakarrouch et al., 2022),
Mycelium	(Sandak et al., 2019),

Appendix C: technical characteristics

as shown by the research and companies as referred to in table X. Variations within a materials' characteristics are due to a difference in processing of the material, e.g., cellulose can be in the form of sheets or flakes and straw can be in the form of bales or mats, and variations in the literature. Therefore, averages are shown in the table to be used for further calculations.

Table C: characteristics of materials identified as most significant and one standard material, references as in Appendix B, table B. Sources: [1](Visser et al., 2015), [2](van der Waal, 2023), [3](Van Dam & Van Den Oever, 2019), [4](Ouakarrouch et al., 2022), [5](Biobased Bouwen, n.d.), [6](van Dijk et al., 2022), [7](Groene Bouwmaterialen, n.d.), [8](Sandak et al., 2019)
[1](Visser et al., 2015), [2](van der Waal, 2023), [3](Van Dam & Van Den Oever, 2019), [4](Ouakarrouch et al., 2022), [5](Biobased Bouwen, n.d.), [6](van Dijk et al., 2022), [7](Groene Bouwmaterialen, n.d.), [8](Sandak et al., 2019)

Material	Density ρ (kg/m3)	Thermal conductivity λ (W/m·K)	Insulation thickness for thermal resistance R = 3.7 m^2K/W	Insulation thickness for thermal resistance R = 6 m^2K/W	Water vapour diffusion resistance factor μ	Heat capacity c (J/kg·K)	Fire class
Cellulose	30-70	0.036-0.045 Average: 0.0405	0.15	0.24	1-3 Average: 2	2000-2100	B2
Wood fibre	30-500	0.036-0.090 Average: 0.063	0.23	0.38	1-10 Average: 5.5	2100	B2
Flax wool	15-60	0.036-0.055 Average: 0.0455	0.17	0.27	1-5.7 Average: 3.35	1600	B2
Hemp	24-60	0.040-0.055 Average: 0.0475	0.18	0.29	1-2 Average: 1.5	1600-2300	B2
Cork	70-220	0.040-0.050 Average: 0.045	0.17	0.27	1-15 Average: 8	1750-1800	B2
Sheep's wool	18-90	0.0326-0.080 Average: 0.0563	0.21	0.34	1-5 Average: 3	1700-1750	B2
Straw	90-400	0.012-0.080 Average: 0.046	0.17	0.28	1-2 Average: 1.5	2000-2100	B2
EPS (synthetic)	15-30	0.032- 0.040 Average: 0.036	0.13	0.22	20- 220 Average: 120	~1200	B1

Appendix D: ranking task

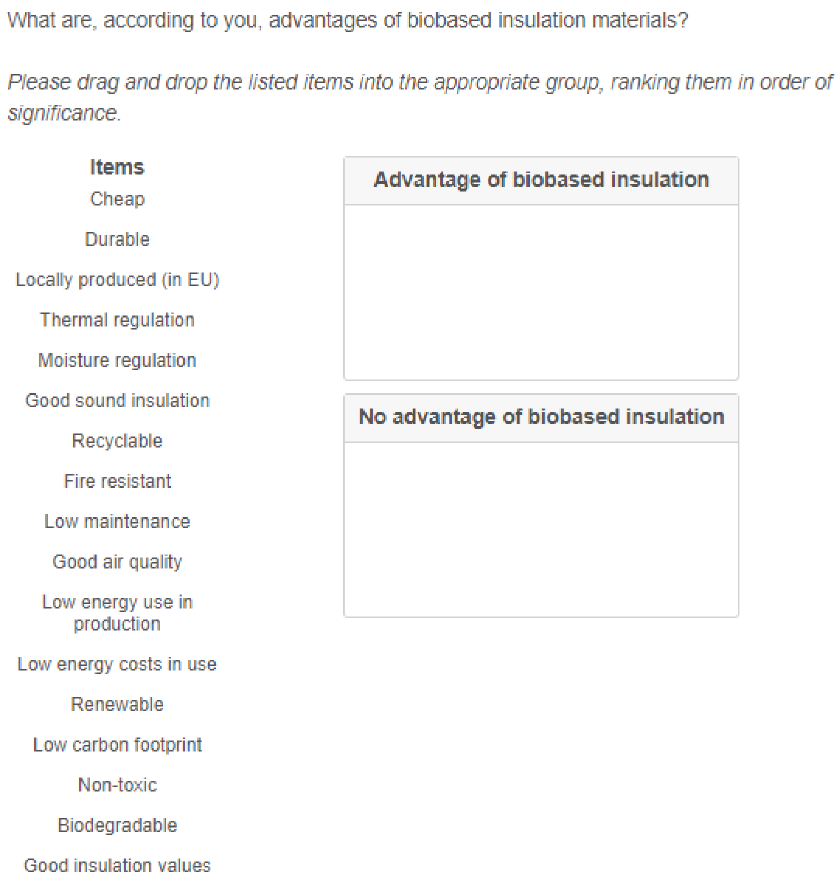

Figure D.1: preview of the ranking task

Results:

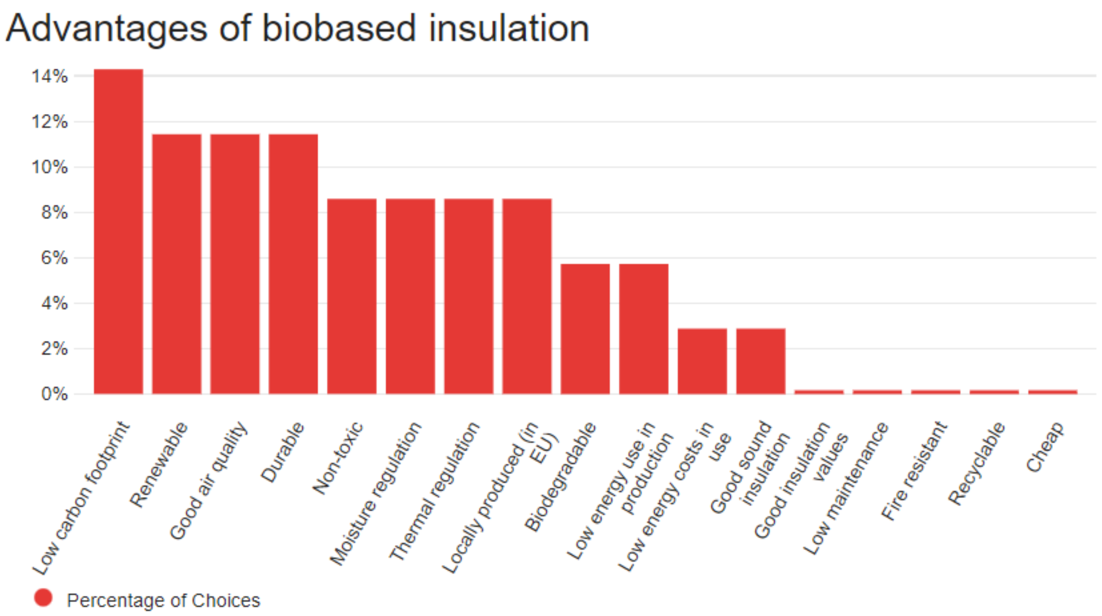

Figure D.2: results from the survey: advantages of biobased insulation materials

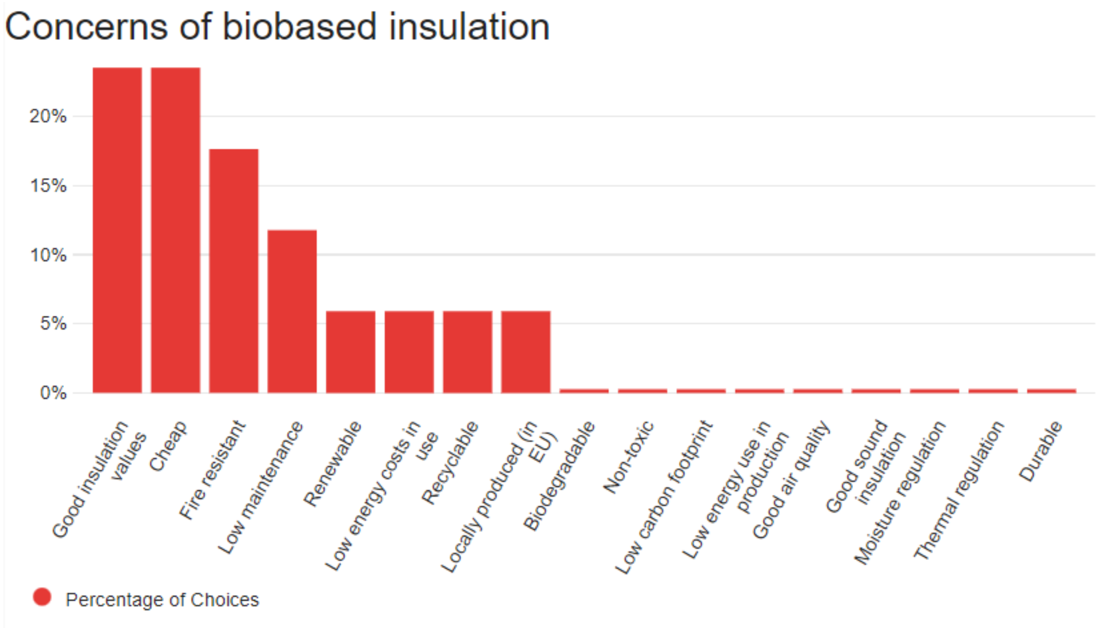

Figure D.3 results from the survey: concerns of biobased insulation materials

Appendix E: Representation in virtual reality

Attributes 1: material

The attribute 'material' has eight levels, which are the significant materials as identified by the literature research. The thickness of the material (attributes 1 and 2) is programmed as the first layer of 'dynamic walls': the thickness of the wall and thus the size of the room varies accordingly as a different material is displayed. It varies randomly between the materials and the Rc-values.

Attribute 2: Rc-value (material thickness)

This attribute has two levels: the current Rc-value (3.7) and the desired future proof value Rc-value (6). The material thickness, or wall diameter, is depended upon the Rc-value.

Attribute 3: Interior finishes

This is the third layer of the dynamic walls and can change randomly.

Attribute 4: interior sheathing board

This is the second layer of the dynamic walls and can change randomly.

Attribute 5: fire resistance video

This attribute is shown as a video on a tv in which the major concern of fire safety is refuted as the video shows that biobased insulation materials can be as fire resistant as mineral or synthetic materials. The video is shown (yes or no) to refute people's concerns and thereby their satisfaction with the chosen materials.

Additionally, all participants are shown a video in which basic knowledge about biobased insulation materials is explained. Also, above the tv screen on which the video is shown, the participants are shown two sliders: one with the perceived temperature and one with a maintenance indicator to give the participants extra information about the differences between biobased and non-biobased insulation.

The perceived temperature is shown as a slider on a relative humidity scale. The humidity scale is a colour gradient from white to blue in which white represents no humidity and blue represents full saturation. On the white end of the scale the base temperature is shown and on the blue end of the scale a higher temperature is shown, representing the increase in perceived temperature as humidity increases. The slider moves along the scale according to which insulation material is displayed. The percentages of humidity for the materials are calculated using material thickness*μ.

Table E.1: vapour barrier of the materials: derived from the diffusion resistance of the material.

Material	Vapour barrier	**R=3.7**	**R=6**
Cellulose	Open	0.3	0.5
Wood fibre	Open	1.3	2.1
Flax wool	Open	0.6	0.9
Hemp	Open	0.3	0.4
Cork	Open	1.4	2.2
Sheep's wool	Open	0.6	1.0
Straw	Open	0.3	0.4
EPS (synthetic)	Closed	15.6	26.4

The maintenance slider is shown as a green slider on a scale divided by three categories: 0-10 years (high maintenance), 10-20 years (medium maintenance), and 20-30 years (low maintenance), representing the time it will take before maintenance needs to happen. The scale is relative, meaning no absolute numbers are used for indication, as these are highly dependent on multiple factors such as installation of the materials, other construction materials, outside and inside temperatures, and residents' behaviours and is therefore a variable parameter when taking the other factors into account. The timescale is based on average maintenance jobs on a home: high maintenance jobs would include e.g., painting (every five years), medium maintenance can involve jobs such as repairing crack in the walls (every 11-20 years), and low maintenance jobs include tasks such as replacing roofs (bitumen or synthetic roofs: every 30 years) (Centraal Beheer, n.d.).

Table E.2: maintenance of the materials.

Material	Maintenance
Cellulose	Medium. Sources: (Eco Spray Insulation, 2021; REenergizeCo, n.d.)
Wood fibre	Low. Sources: (Institut Bauen und Umwelt e.V., 2020; TimberHP, n.d.)
Flax wool	Low. Sources: (Isolina, n.d.)
Hemp	Low. Sources: (Hempitecture, n.d.; IsoHemp, n.d.) *
Cork	Low. Sources: (Orr, 2020; Saxton, 2021)
Sheep's wool	Low. Sources: (Eco Home Essentials, n.d.; Insulation4Less, n.d.)
Straw	Low. Sources: (Downton, 2020; Owens, n.d.)
EPS (synthetic)	Low. Sources: (Kono et al., 2016; Styrene Packaging and Insulation Ltd, 2018)

Figure E.1: visual representation of the application

E.2: Sheep's wool

E.3: Straw

E.4: Cork

E.5: Wood fibre

E.6: Cellulose

E.7: Hemp

E.8: Flax wool

Figures E.2-8: visual representation of the insulation materials in the application

E.9: Plasterwork

E.10: Wood sheathing board

E.11: Loam

E.12: Gypsum

Figures E.9-12: visual representation of the finish and sheathing board materials in the application, only the materials that were imported in Unreal Engine

Appendix F: documentation of VR modelling

Developing suitable material images for unreal engine

- Stock photos
- Making the texture of the stock photo seamless with online tool: ‘imgonlin make seamless texture’
- Making a ‘normal map’ (3d effects) with online tool: ‘NormalMap Online’

Video: biobased basics

- Made with Canva software.
- Images from stock videos Canva.
- Voice over from Canva voice AI tool.

Script:
This is an animation about biobased insulation.
So, what is biobased insulation? It's a special type of material used to keep homes warm. But what makes it so unique is where it comes from.
Unlike standard insulation materials made from oil, biobased insulation materials come from nature, making them renewable! Think of plants, wood fibres, even sheep's wool! These are all natural sources that can be used to create insulation.
Why is this important? Because biobased insulation helps to reduce heat loss from your home, improving energy efficiency. It also reduces your ecological footprint, making it better for the environment!
By using biobased insulation, we release fewer harmful substances into the air. So, with biobased insulation, you create more comfort in your home while having less impact on the environment!

Video: fire resistance

- Made with Canva software.
- Video: downloaded from YouTube (Dijkhuis Bouwteam van Waarde, 2023).
- Voice over from Canva voice AI tool.

Script:
This video is about the fire safety of biobased materials. In the background, you can see 17 types of insulation catching fire and how long it takes. We observe that the duration can vary significantly depending on the material. Some biobased materials ignite quickly, while others take a long time. The same applies to synthetic materials.
So, there are two categories to distinguish: insulation that ignites quickly and insulation that ignites slowly. Both categories include both biobased and synthetic materials.
Many people are concerned about the fire safety of biobased materials because they believe that natural materials catch fire faster than synthetic ones. However, this test demonstrates that biobased materials can perform just as well as synthetic materials in terms of fire safety. Additionally, natural materials burn in a more predictable manner, making them easier to extinguish, and they release fewer toxic fumes when they burn.
Therefore, we can conclude that biobased insulation is just as safe as synthetic insulation. There is no need to worry about the fire safety of your home when it is insulated with biobased materials.

Researcher contributions
The application was built upon an already existing application for a different project, programmed by Chris Benning, PhD. With his help, the application for the current study was built. As learning modelling in VR is an intensive process and would have been too time consuming for the current study while also not part of the curriculum of Industrial Ecology, the application modelling itself was mostly done by Chris Benning, PhD. I developed the ideas that were modelled in the application (the videos, the sliders, and the walls) and was present during the modelling to help with possible bugs etc. and to specify what I wanted the application to look like.