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ARCHITECTURAL TECHNOLOGY TRANSFORMATION

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TENTH INTERNATIONAL CONGRESS
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ATLANTIC TECHNOLOGICAL
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FOREWORD

It is an honour to welcome delegates, participants, and attendees to ICAT 2024. We have the pleasure of hosting on campus this year the tenth International Congress on Architectural Technology Conference at the Atlantic Technological University, Galway, Ireland. This also provides us with an opportunity to mark the transformation of our own Institute into a Technological University in 2022, thereby offering architectural technology educational opportunities in both Galway and Donegal from within the one Technological University. ICAT 2024 is a great way to celebrate both this and the wonderful profession of architectural technology in tandem.

When writing this Foreword, I am reminded of the purpose of the congress, which is to contribute to the progression of research within the discipline of architectural technology worldwide and to publish the results for the benefit of society. We encourage the capture of architectural technology transformation in the built environment on behalf of society through free debate and the presentation of different views and perspectives through research and its dissemination every one to two years. I invite you to review the time immortalised past conference proceedings on our website online if you have not done so already. It is a testament to the transformation of the construction industry in many countries championed through architectural research.

Looking ahead to ICAT 2024, international authors have researched topics across many areas, demonstrating the next evolution of architectural technology transformation. I hope you are all as excited to learn as much as I am about new uses of technology in conservation architecture, building material passports for the circular economy, enhanced fire evacuation opportunities, augmented reality applications for deconstruction surveys, sustainable material choices, as-built monitoring of design choices to reduce service loads, flooding mitigation using blue-green roofs, as-built moisture monitoring and control of building fabrics, fabric first approach options for deep retrofits, EnerPHIT, and Passivhaus projects, and the use of artificial intelligence to do just that, to name just a few research topics showcased this year.

Finally, I wish to sincerely thank Dr Niels Barrett for his contributions to congress over the last fifteen years as one of its founding members, as he steps away from the board this year.

Welcome to ICAT 2024.

Irene Hayden, Conference Chair

Atlantic Technological University, Galway, Ireland

MOVING AWAY FROM A LINEAR ECONOMY TOWARDS A CIRCULAR ECONOMY, MATERIAL PASSPORTS ARE SEEN AS AN ESSENTIAL TOOL TO OPTIMISE DESIGN FOR GREATER CIRCULARITY. HOW CAN BIM SOFTWARE AID THIS PARADIGM SHIFT IN AN IRISH ARCHITECTURAL PROJECT?

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Abstract. Construction is a carbon-emissive heavy industry with approximately 40% of global pollution and waste production being accredited to the industry. This requires a systemic re-evaluation of global material streams from a linear model towards a Circular Economy. The implementation of Material Passports is deemed an integral part of adopting Circular Economy principles into the design, construction, and disassembly of the built environment. As such, designers need to be able to access and utilise Material Passports to optimise the design process and document the material and product use. The Material Passport offers design optimisation, design analysis and documentation parameters hosting both quantitative and qualitative information. The research assesses the current expectations from the Irish Government towards the circular economy in recent publications such as the Circular Economy Act and the National Policy on Architecture, as well as the Office of Public Works position in enabling it. The paper explores what the Circular Economy means to the AEC sector, the roles of the instigators in promoting the adoption of circular economy in design, how it can be implemented through the use of BIM, and what information is required. The paper assesses the various governmental and organisational publications and declarations in their understanding and willingness to implement these principles. Furthermore, the research will examine what a material passport is and how it aids this transition towards a circular economy. This is assessed through three case study projects that discuss integrating the material passport into all stages of an architectural project (both public and private). Ranging from early design stage to construction completion to end-of-life, the case studies offer a comparative of the full lifecycle of a building. The three case studies each offer a workflow that confirm a basic approach to producing the document, while differing in what sustainable parameters are appropriate, indicative of where the studies are situated in the project stage and by what the authors deem valuable.

1. Introduction

There is a pressing need to evolve how the human population uses and consumes materials, lives and does business (Charef and Emmitt, 2020). Current population trajectories predict the global population to reach 10 billion by the year 2050, of which two-thirds (roughly 6.6 billion people) will be concentrated in dense urban areas. Growing alongside this population increase and global acceleration of the urbanisation process, the built environment and by proxy the Architectural, Engineering, and Construction (AEC) sector, has already and will continue to play a vital role in rising to physical infrastructure and service stresses (Lei et al., 2021).

The expected population growth will drive increasing demands for natural resources resulting in concurrent increases in waste production. If left to grow unfettered, future challenges will face issues of waste load and depleting natural resources of land and material (UNEP, 2017). The AEC sector, however, is responsible for approximately one-third of generated waste in Europe. Driven by a high demand for resources, it is estimated that 50% of all extracted materials are used within the AEC sector. These forecasted developments are all associated with high energy demands and associated carbon emissions – both embodied and operational. When considering indirect power generation from building emissions, the AEC sector represents nearly 40% of energy-related carbon (WGBC, 2016). Therefore, the need for concentrated efforts within the EU to transform the construction sector into a Circular Economy (CE) (Roithner et al., 2022).

2. Literature Review

2.1. THE CURRENT PARADIGM

Currently, the global economy is largely composed of a linear model of a 'take-make-waste' format of production and consumption. In this model, great quantities of natural resources are extracted from the earth for the manufacturing of products that have a short lifespan and are designed for failure and relinquishing recyclability. Allowing these resources and products "to go to waste reflects a significant loss of value and increases our dependence on complex global chains" (Government of Ireland, 2022). The pervasive approach of the linear economy model is attributed to the consequential environmental impact in the AEC sector (Benachio et al., 2020). The increasing rate of natural resource extraction paired with the detrimental disposal of waste contributes to the loss of biodiversity and wildlife habitat. The Office of Public Works (OPW) (2022) research shows that "Half of [the] total greenhouse gas (GHG) emissions and more than 90% of biodiversity loss and water stress comes from resource extraction and processing." Key drivers and pressures on biodiversity are classified by the OPW as consumption, economy, infrastructure, institutions, governance, forestry, and mining amongst others. Engagement with biodiversity issues means then, not only looking at the value of the existing biodiversity on a site of construction but also evaluating inputs from governmental and institutional organisations as well as the impact through supply chains and working with suppliers to improve environmental performance (Office of Public Works, 2022).

2.2. THE CIRCULAR PARADIGM

Tackling this paradigm is the Circular Economy (CE), a regenerative by design approach which proposes principles and solutions to move away from the consumption of finite resources. (Royal Institute of Architects of Ireland, 2021). Since 2010, the Ellen MacArthur Foundation has spurred increasing interest in the concept of the CE, defining it with three core principles: "To eliminate waste and pollution; Circulate products and materials (at their highest value); Regenerate nature" (Ellen MacArthur Foundation, 2010). The value these principles retain offers a systematic CE with a transformative and ambitious approach to production and consumption, where the default is to minimise the use of resources and waste by-products. Product and material value is extended through good design with perseverance for durability and an allowance for repair, and at the end-of-life stage, unique materials are retained and readily available for circulation into products of equal or higher value (Government of Ireland, 2022).

The significance of government intervention has the potential of having a great impact on the industry's awareness of the CE, as a large proportion of construction projects tend to be public works projects. Governmental projects within the remit of the Capital Works Management Framework (CWMF) are prescribed with government policies, regulations, and administration systems and are in a position to adopt changes in the systems early to overhaul the current paradigm (Sacks et al., 2018). Design reviews post-completion further allow an assessment of the successfulness of the controls implemented on the project.

In 2022, the Government of Ireland has set the transition to a CE as one of its priorities, expressed through two key publications the 'Circular Economy and Miscellaneous Provisions Act 2022' and the 'Whole of Government Circular Economy Strategy 2022-2023.' The 'Circular Economy and Miscellaneous Provisions Act 2022' gives key definitive language in an Irish context for this economic model, highlighting construction, amongst others, as an imperative industry to target in Section 7 (6) (a). Section 7 (6) (b) of the Act further describes the targets to be set out as appropriate to the industry:

i. Reductions in material resource consumption and the use of non-recyclable materials.
ii. Increases in the use of reusable products and materials.
iii. Increase levels of repair and re-use of products and materials.
iv. Improved maintenance and optimised use of goods, products, and materials.

2.3. IRELAND'S AMBITION AND APPROACH

Section 7 (7) of the 'Circular Economy and Miscellaneous Provisions Act 2022' alludes to the gravity of the Strategy that follows it setting out the actions which will be expected to be governmentally supported to achieve these earnest aims. The 'Whole of Government Circular Economy Strategy 2022-2023' estimates that in economic terms a saving of upwards to €2.3 billion could be achieved with a minimal 5% improvement in Ireland's circularity rate, so there is a financial incentive. Public Procurement has a significant impact on the Irish economy as it is the largest single buyer in Ireland, contributing to 12% of the GDP (Office of Public Works, 2022). Green Public Procurement policies alongside mandatory green criteria for all publicly funded projects will support markets for circular services and products becoming established and expanded. Furthermore, the Irish Government aims to participate and/or lead the initiatives in multinational green procurement to leverage greater economies of scale through collaboration and co-operation. (Government of Ireland, 2022). Through green criteria, public procurement becomes a tool to embed sustainability ideas into practice.

2.4. AREAS FOR FURTHER POLICY DEVELOPMENT

The 'Whole of Government Circular Economy Strategy 2022-2023' admittedly focuses on small-scale and bio-economy operations, falling short of a total policy overhaul with regards to the AEC sector given the scale and the complexity of the industry. It does make an allowance for areas of further policy development in the areas of Construction and Demolition (C&D) and circular design. Annex 4 of the Strategy outlines preliminary actions for the construction industry, including higher rates of offsite design and manufacture; designing modular buildings; existing stocks being refurbished and retrofitted; targeting vacant and derelict properties; higher use of secondary materials from C&D waste as a construction material. Annex 5 also necessitates the relevance of incorporating digital technology to "track and optimise resource use and strengthen connections between supply chain actors through digital, online platforms and technologies" (Government of Ireland, 2022).

2.5. PUBLIC BODIES AND INSTITUTIONS

A stakeholder group composed of representatives from the Department of Housing, Local Government and Heritage (DHLGH), the OPW, and the Royal Institute of Architects of Ireland (RIAI) published a collaborative publication developed through public engagement called the 'National Policy for Architecture: Places for People.' The public body and institutional engagement of the publication are further enhanced when paired with the 'RIAI 2030 Climate Challenge' as both documents overlap key criteria of sustainability through promoting the CE, as explored, the Life Cycle Assessment (LCA), and access to education/knowledge and technology.

2.6. LIFE CYCLE ASSESSMENT

Within a CE, the climatic and environmental impact of the whole building life cycle must be considered. These impacts are relevant to resource and material inputs, the construction process and building operation, and finally the demolition and disposal of material waste. A Life Cycle Assessment (LCA) considers all these stages of a project by calculating the whole life environmental impact of a product/building, including both operational and embodied carbon. EN15978 sets out how the time phases that are relevant to each part of the building lifecycle, establishing how the environmental impacts should be calculated (RIAI, 2021). These requirements demand a collaborative approach to research and innovation into construction methods and materials that are carbon-positive suitable for an Irish CE (DHLGH, 2022).

Environmental Product Declarations (EPDs) provide the necessary data regarding environmental impacts, which the Irish Green Building Council (IGBC) have developed the EPD Ireland programme allowing Irish manufacturers to publish 3rd-party verified data on their material or product (RIAI, 2021). The scope of an EPD displays information on the material or product, the manufacturing process, and the embodied carbon of each time phase. According to the IGBC (2022), the EPD "is the most reliable way to make informed choices when selecting building materials."

2.7. DEVELOPING KNOWLEDGE

Delivery of education methods for the built environment must be in constant flux adapting to the technology-led circular economy. The pace of advancements in social, digital, and environmental landscapes is forcing unprecedented decisions concerning the AEC sector. As part of developing knowledge in the field, there is the impetus to identify a range of essential built environment benchmarks and performance data, frequently collected at all stages of a project and analysed using assured and structured processes. A rigid framework would aid to inspire confidence in policymakers and commercial interests, assessing strengths and weaknesses while forecasting optimum results in the design and delivery of a project. (DHLGH, 2022).

2.8. BIM AND THE OPW

As the governmental authority for public projects, the OPW's duties extend between the delivery of new constructions, refurbishment, conservation, major maintenance, and often occupancy, and is composed of in-house multi-disciplinary professional design teams. The OPW is present throughout the physical life cycle of a building, giving the organisation a prime opportunity to make the most of Building Information Modelling (BIM) (Day et al., 2021).

Concerning alterations of the CWMF, a governmental mandate to use BIM on public projects is currently under review, where it is expected that "opportunities to further deploy digital technologies, such as BIM" (Day et al., 2021) will be included. Ongoing visibility of BIM within the OPW pertains to the use of Autodesk Revit models producing information at all stages of a project, particularly tender and construction stages. However, further adoption and implementation of BIM capabilities are needed to be efficient in design, construction, asset management, and the expectation of adapting to CE principles. A Revit template was developed within the organisation with the expressed intention that the template "enables the transition towards using Revit on projects; simplify and standardise the setup of OPW models; allow changes to be updated centrally in one location, common to all disciplines" (Day et al., 2021).

2.9. MATERIAL PASSPORTS

Documentation is one of the most essential elements for the transition from a linear economy to a circular one. Accurate recording of products and materials allows one to measure the transition progress through indicators. Data naturally is a management precondition for materials flows and stocks within a system, as well as reducing barriers to implementation. The MP records the material composition of a product or a building as a collection of materials and products, documenting tangible measurement qualities such as weight, density, volume, geometric dimensions, and location within the building (Heisel and Rau-Oberhuber, 2020).

A qualitative and quantitative tool for material and product composition, an MP can provide the necessary methodology and data structure for collecting and handling the relevant information. These digital datasets aim to catalogue and disseminate the CE characteristics of building materials, components, and products. Material passports can help to bridge the current information gap and exchange between the relevant actors in the building industry. Standardised information exchange is one of the keys to a successful transition to a circular economy, making the material passport an integral component. Standardisation and central registration of these passports on online material platforms will ideally become a prerequisite for circularity in the built environment, highlighting the need for accessible and accurate data as well as manufacturer transparency. (Rau and Oberhuber, 2017).

The BIM-based MP acts as a design optimisation tool in the early design stages and as a repository of materials at the end-of-life stage of a building. Honic et al. (2019) stress the importance the early design-stages play "on the future recycling potential of buildings, as in this stage the decisions on material composition are met." A study undertaken by Honic et al. (2021) found "the main advantage of using the MP to improve the recycling of construction and demolition (C&D) waste is the comprehensive analysis of the existing building, delivering accurate information not only of the material composition but moreover of the mass, quality, and separability of each material." The capability of separating two entwined materials holds special importance as materials that are glued pose difficulty in recycling and reuse. Atta et al. (2021) conclude that digitisation of the proposed tool is the final phase of the design stage for the MP, "BIM, as a widely used technology in the building industry, is mainly intended to create a digital twin for buildings and their characteristics. Hence, there is an obvious compatibility between the MP's digitising step and the usage of BIM."

3. Methodology

Three case study papers presented here all define a Material Passport, as previously outlined throughout the paper; unique stages of intervention for the material passport; a particular method of production appropriate for the project stage of the intervention; and a tangible project case study with resulting data information. The material passport is relevant to all stages of a project as outlined under the RIAI's Plan of Works, beginning with 'Stage 1 – Inception and General Services' and ending with 'Stage 8 – Operations on Site and Completion,' as well as an additional two stages of an 'Occupation' and a 'End-of-Life' to fully capture the building lifecycle as necessitated by CE principles.

The author will provide a comparative study between each of the papers' MP to investigate how the MP is integrated into the workflow of an architect at all of the outlined stages. Following this, the author will summarise the results of what the data is relevant, both qualitative and quantitative, and recommend a structure for the MP.

3.1 STAGE 01 – INCEPTION AND GENERAL SERVICES

While no apparent design use for the MP is applicable at this early stage of a project, there is an opportunity to write the requirements of MPs into the BIM Execution Plan (BEP), Employer Information Requirements (EIR), Common Data Environment (CDE), as well as the output of MPs at various stages of the project as advised under the Master Information Development Plan (MIDP) and the Technical Information Development Plan (TIDP). Scheduled and consistent use of the MP will ensure adherence to the principles of the CE throughout the project lifecycle.

3.2. STAGE 02 – OUTLINE PROPOSALS; STAGE 03 – SCHEME DESIGN

3.2.1. Scope

Honic et al. (2019) distinguish the Outline Proposal (conceptual) and Scheme Design (preliminary) stages of a project lifecycle with individual MPs – respectively referred to as MPa and MPb within their paper. The scope of MPa serves as a tool for optimisation and analysis and is composed of mono-layer elements allowing for comparative studies on the most suitable construction process – such as concrete versus timber structure – for recycling potential and environmental impact. According to the authors, “this stage has the largest impact on the life-cycle performance regarding recycling and waste as well as the environmental impact” (Honic et al., 2019), hence the imperative for consideration at a very early stage of a project, however, geometric accuracy is vital from this stage moving forward. MPb also acts as an optimisation tool but includes higher-quality information regarding the build-up of the BIM model, requiring multi-layer elements with information on the layer’s volume, thickness, and material. It is important to consistently use building elements provided in the office template for accuracy throughout the project’s lifecycle.

3.2.2. Approach

The paper utilises what they refer to as a ‘Bottom-Up, Top-Down’ approach to modelling and hosting information. The framework is composed of four grades: Building, Component, Element, and Material. Moving through the scales of the levels of the building, any particular component is reached such as the exterior walls, interior walls, and slabs. The component level labels an individual component as ‘Slab 01’ and the elements residing in the component are labelled ‘Slab 01a, Slab 01b,’ etc. Each element is composed of individual materials known as ‘Layer 01, Layer 02’ etc. Each element, or product, is linked to a Globally Unique Identifier (GUID) in a BIM software platform, allowing for parametrisation and allocation within the building.

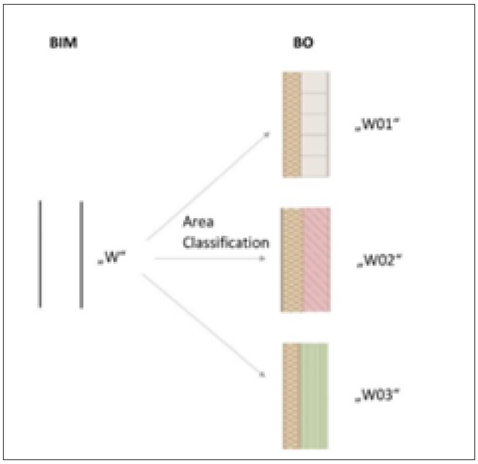

Figure 1. Modelling Method for the MPb

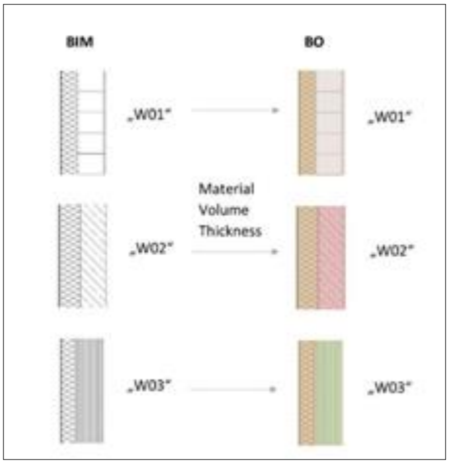

Figure 2. Modelling Method for the MPa (Honic et *et al.)*

3.2.3. Generation

Honic et al.'s (2019) case study was modelled in BIM software, adhering to a template that provided pre-defined building elements and a modelling guide. The established modelling guide dictated the requirement for appropriately classified elements as well as being modelled according to their stage – mono-layered for MPa and Multi-layered for MPb. When the model is generated to an acceptable standard as per the requirements of each MP, the model was exported to a 3rd party database. The workflow utilised the BuildingOne (BO) for analysis and its material inventory and is synchronised with the BIM model. BO linked the relevant data for the MP (such as recycling potential and LCA data) to the materials, and further applies the necessary parameters for assessing the model's circularity. Solibri was used as a control tool to assess any errors present in the model to assure accuracy. The concluding results received from BO display the building's total material composition and mass, the ratio of recyclable material and waste, and environmental impacts expressed as, Acidification Potential (AP), Primary Energy Intensity (PEI), and Global Warming Potential (GWP).

3.2.4. Data

Data obtained for the MP include the Recycling Grade (ranging from 1-5), contrasting quantity and density of recyclable material, and waste likely to be extracted from the building at the end-of-life stage. The material mass is derived from the volume provided by the BIM model, and the density provided by BO to which the BIM model is linked. Honic et al. (2019) define their "material with recycling grade 01 stand[ing] for 75% recycling and 25% waste, grade 05 leads to 0% recycling and 125% waste, [from which] additional waste from auxiliary materials are required for disposal." Another consideration important for their early-stage MP is the separability factor of materials within an element. Separability is vital for recycling materials to their base composition, and any wet connections (i.e., glued) between materials reduce the capability for appropriate recycling of materials into their streams.

3.2.5. Result

The early-design stage building has a total mass of 1338 tons, where 638 tons (48%) of material is recyclable versus 700 (52%) tons of produced waste leading to a recyclable score of 2.5 overall. At these early stages of a project, the geometry and the element/material classification must be accurate to assess the circularity with conviction. The paper concludes with some of the difficulties faced through the process namely a lack of standards and structure existing between data repositories regarding material properties. Naming systems and classifications are not intrinsically linked from one database to the next, making it difficult to replicate the results across platforms and posing difficulty in further confirming their results. Further criticism when considering an early design stage MP intervention from the paper describes that material composition is not yet established in any great detail. An architect would have to rely on pre-determined elements available from their material library, likely hindering creativity. Overall, the MP provides a strong early indicator of the direction the project will lie.

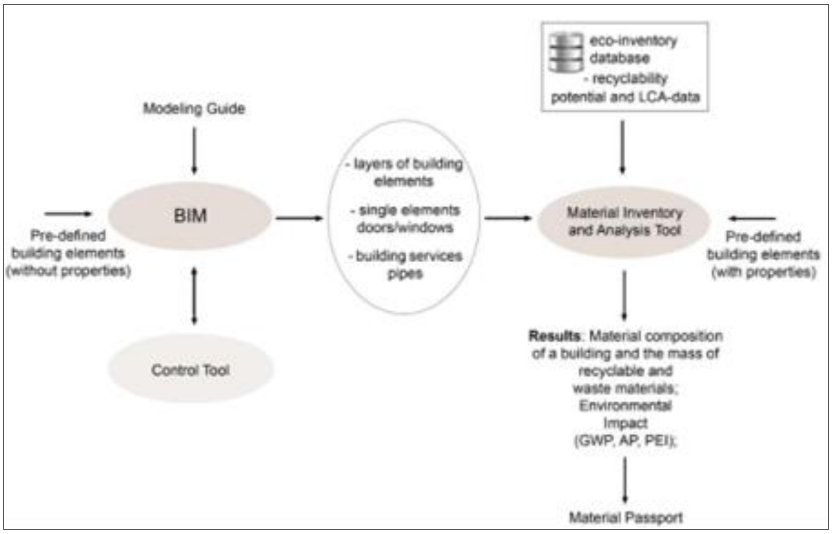

Figure 3. Workflow for the compilation of the MP (Honic et al.)

3.3 STAGE 04 – DETAILED DESIGN/BUILDING REGULATIONS; STAGE 05 – PRODUCTION INFORMATION; STAGE 06 – TENDER ACTION; STAGE 07 PROJECT PLANNING

3.3.1. Scope

The scope that Atta et al.'s (2021) MP takes is relevant to stages 04 through 07, Detailed Design/Building Regulations to Project Planning. Where the previous paper's MP was entirely composed of quantitative data, deriving recyclability from data extracted from the BIM model and the material repository database, this paper goes beyond the exclusively quantitative data to include qualitative data such as sustainability guidelines (i.e., CE principles) and technical information (i.e. compliance with country standards) stating it is required for an effective MP. Aiming to develop a more comprehensive MP than previous tools, the paper defines three objectives:

1. Significance of including all lifecycle stages (i.e. LCA) in the sustainability support tools.
2. Providing both quantitative and qualitative information has a crucial role in achieving circularity.
3. Importance of digitising sustainability supporting tools.

3.3.2. Approach

As stated, the paper aims to make use of both qualitative and quantitative information. They offer an instruction guide method as an effective expression for values and social concerns as well as how to benefit from the building materials during different stages of the lifecycle as qualitative data. The instruction guide disseminates information for managing building materials in a sustainable manner encompassing technical, safety, circularity, and disassembly information. Three categories of developed tools for quantitative data fall within: Building certificate or rating; LCA; and building performance. The paper utilises a case study project where a comparison of a residential building composed of either traditional or modular methods of construction is used to illustrate the features of a developed MP as well as testing the quantitative sustainability factors.

3.3.3. Generation

In terms of the quantitative data outlined in the paper, the assessment of sustainability was based on three concepts. First, assessed indicators should be easy to read and understand for universal accessibility to the requirement for LCA and material recovery indicators for the tools producing the MP. The third concept requires sustainability assessment tools to express both environmental performance and human health to conform to a sustainable development plan. This echoes the aspired goals of the Whole of Government Circular Economy Strategy 2022-2023. The resulting considerations taken in the MP at these mid-project stages are the Deconstructability score, Recovery score, and Environmental Score.

The paper considers the shared parameters function as one of the most vital features of Autodesk’s Revit software, as a method of inputting sustainability information that is not readily available in a product/material already and can be carried through the entirety of a project. Furthermore, once created it can be shared between projects through a product library that similarly supports future projects as the project template. The automation process for sustainability assessment requires two steps. First, the creation of shared parameters that help to calculate and display the outlined scores. Four shared parameters considered the condition of building elements; five shared parameters considered differing connection types; and a shared parameter for prefabricated elements was created for the benefits of offsite production, such as reduced production and delivery time, reduced generated waste, reduced cost, and controlled quality. The second step made use of Dynamo, a visual programming tool to model the sustainability indicators.

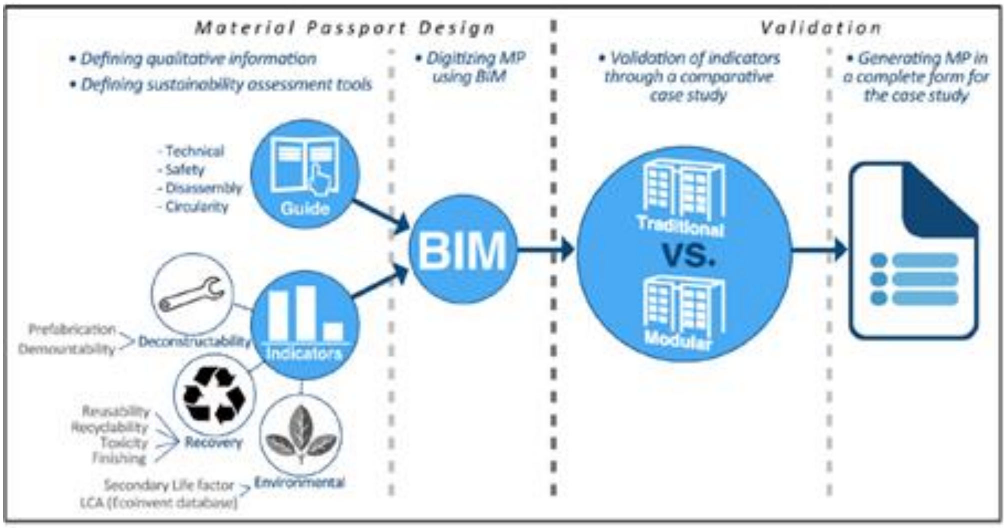

Figure 4. Proposed framework of developing a MP (Atta et al.)

3.3.4. Data

Material quantities are again estimated from the density and volume of each material, data being derived from the BIM model and an external database which helped to shape the shared parameters. The Environmental Product Declaration (EPD) is one such example of providing the required information for the shared parameters. Besides the quantitative data expressed through parameters such as condition, connection, and prefabrication, guidelines on the appropriate handling of construction material are a key factor to avoid on-site waste from human error and should also be recorded as part of the technical data of the MP. Further instructions embedded in the MP are disassembly techniques and correct disposal to encourage the reuse of the material elements as prescribed by local authorities and the initial manufacturer, further adhering to CE principles and aiding material recovery through continuous circulation.

Deconstructability Score: Expresses the dismantling capability of building components and is calculated as a ratio of demountable connections and a ratio of prefabrication elements against the total building. Again, highlighted here is the resulting issue of conventional connections (i.e., wet connections) leading to demolition only.

Recovery Score: Expresses recoverable building elements and is calculated as a ratio of reusable products and recyclable materials. Coated materials, especially when coated with toxic materials, are difficult to return to their base element and negatively affect the recovery score.

Environmental Score: Expressed as an LCA-based indicator tracking both operational and embodied carbon emissions throughout the building lifecycle and promotes normalising LCA as a core tool for assessing environmental impact.

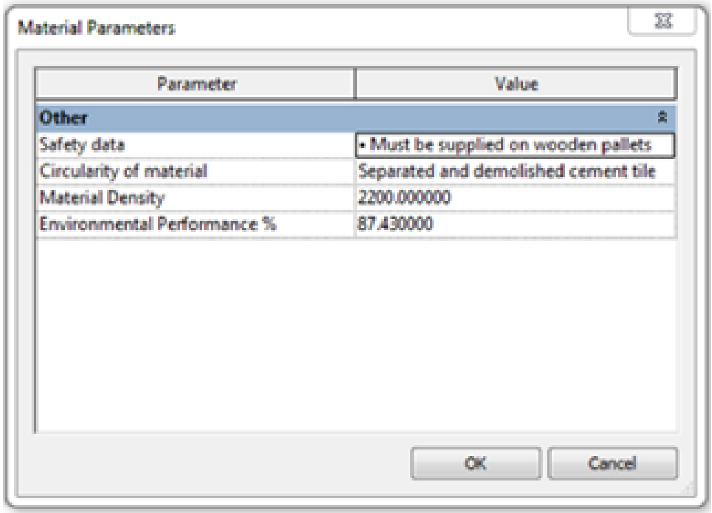

Figure 5. Example of the modelled instructions for a building material (Atta et al.)

3.3.5. Result

Throughout the project stages this case study was situated, it provided guidance on reducing waste at the early stages while targeting high levels of material extraction at the end-of-life stages of a project, prior to any construction. The Material Passport being built up over the stages categorised general information, technical guidelines, and circularity instructions. Each of these categories comprises general descriptions such as building location, structural system, building usage, and sustainability scores. Technical information further displays the amount of material needed for construction, material density, and method of assembly. BIM was a huge factor in automating the various sustainability scores, aiding faster calculation times and avoiding human error. Furthermore, BIM also contributed through its information preservation features of the shared parameters, in which data is available to be extracted as required and exported into programs such as Microsoft Excel.

3.4. STAGE 08 – OPERATIONS ON SITE AND COMPLETION; OCCUPATION AND END-OF-LIFE PERIOD

3.4.1. Scope

The scope that Heisel and Rau-Oberhuber's (2020) MP takes is relevant to stage 08 – Operations on Site and Completion, the Occupation Period, and the End-of-Life Period. The paper discusses the process and results of synchronising a BIM model to an online Material Passport platform called Madaster, showcasing input into the database, data generation, and the subsequent circularity index and MP. Madaster is an online registry that provides a material database, software, and tools for generating information and acting as a data repository. Unlike BuildingOne and shared parameters, Madaster is a specific tool for producing MP rather than doing so serendipitously, however, it lacks the qualitative data format that shared parameters provide. Heisel and Rau-Oberhuber's (2020) circular indicators here examine the three periods and describe them as such:

Construction Phase: Represents the ratio of virgin materials to recycled, reused, or rapidly renewable materials.
Use Phase: Represents the expected lifespan of utilised products, compared to the average lifespan of status-quo products.

End-of-Life Phase: Represents the ratio between waste materials and reusable and/or recyclable materials generated when a building is refurbished or demolished.

3.4.2. Approach

The Madaster Foundation developed its Circularity Indicator (CI) as a method of assessing the circularity level of the highly developed BIM model uploaded to the platform, basing a general circularity score between 0-100%. Within their framework, a circularity of 0% describes a building constructed completely of virgin materials and is expected to be discarded at the End-of-Life stage with no consideration for reuse or recycling, the archetype of the linear economy. Whereas a circularity of 100% describes a building composed of re-used or rapidly renewable materials, designed for disassembly and a planned reuse stream at End-of-Life, the archetype of the circular economy.

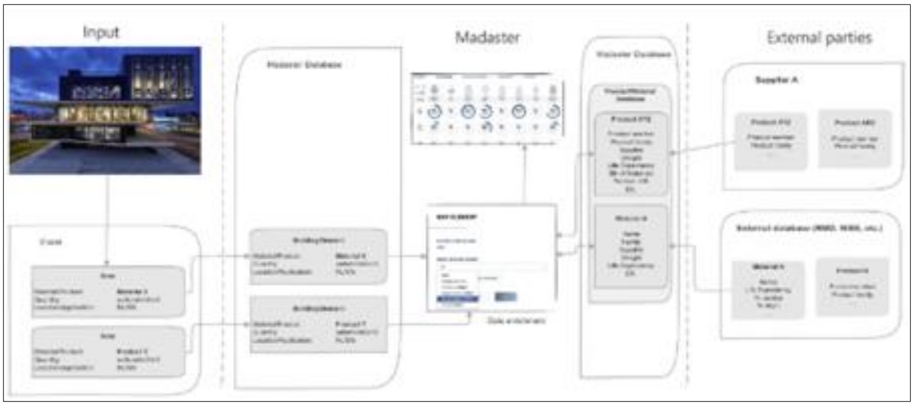

Figure 6. Scheme of data input, hierarchy, calculation, output, and connection to external partners on the Madaster platform. (Heisel and Rau-Oberhuber)

3.4.3. Generation

The case study project known as Urban Mining and Recycling (UMAR) showcases a constructed building located in Stuttgart, Germany. The building was designed and constructed with standardised and prefabricated elements, with easily accessed mountings, and various building elements that can be easily removed and updated without affecting the surrounding elements. Classification codes are linked to reflect a similar process as the ‘Bottom-Up Top-Down’ approach, where building elements are divided by their shearing layers (Site, Structure, Skin, Services, Space, and Stuff) (Brand, 1994) and estimates when certain elements may need maintenance or replacement. Using a heavily detailed BIM model appropriate for the project stage, the following data inputs were required:

1. Collection and verification of necessary building material data and specifications for material and product passports.
2. Data input into the Madaster platform and creation of corresponding material and product data sheets including a step of manual data enrichment on the Madaster platform.
3. Calculation of the Building Circularity Indicator.
4. Evaluation of the results of the available data, the principles of the CE as well as the design parameters of the UMAR unit.

3.4.4. Data

To produce the data requirements for the case study, the first step was to create 32 unique material data sheets which were then connected with 90 unique product data sheets, products beings composed of 32 various materials. Material data sheets contained information such as name, weight, supplier, raw material resource and quality, lifetime, end-of-life disposal, and its recycling efficiency. The product data sheets in turn stored information ranging from brand, product code, supplier, functional and technical lifespan, volume, connection details (again, dry connections are preferred), bill of materials, and a classification code unique to the country.

As detailed, the CI assesses a building during three phases of its life: Construction Phase, Use Phase, and End-of-Life Phase. The accretion of these three indicators results in the overall CI building score, which is then corrected by adjusting for the completeness of the material input data, element classification, and layer attribution. In this case study, like the others, a modular structural timber frame was used and reflects in terms of mass the most heavily used material. Below (figure 7), the material data sheet for the spruce wood used within the project is detailed, with all data provided by the European Wood Initiative (2010):

Material Information		Feedstock Sources	
Material Name	Spruce	% Recycled	0
Specific Weight (kg/m³)	450	% Rapid Renewables	100
Material Family	wood	% Virgin	0
Supplier	Zimmerei Kaufmann	**End of Life Scenario**	
Lifetime (years)	100	% Recycled	*(80)* 100
Description		% Landfill	0
		% Incineration	*(20)* 0
		Efficiency of Recycling Process	
		% Efficiency of Recycling Process Raw Material	100
		% Efficiency of Recycling Process End of Life	100

Figure 7. Material Data sheet

3.4.5. Result

The results obtained from the Madaster platform dictated that the CI scores for the Construction Phase (non-virgin and rapidly renewable materials) as 95%, the Use Phase (utility rate of building elements) as 98%, and the End-of-Life Phase (rate of materials being restored to their pure cycles) as 92%. The overall CI score received was a circularity of 96% for the UMAR case study project. Naturally, this is indicative of a best-case scenario as unplanned circumstances may affect the building throughout its lifetime as well as unforeseen issues at disassembly, but this is mitigated with thorough qualitative data guiding the disassembly as specified by Atta et al. (2021).

As was the situation for the previous case studies, the Madaster database has proved to be a vital tool in evaluating design decisions and implementing the principles of the CE. The platform's indicators express the various implications design choices impact the overall circularity of a project while providing an impression of the quality and durability of the proposed design. Accuracy of CI increases as the project progress from design - construction - occupation - disassembly, and this information will be vital to all stakeholders within the AEC industry during the transition towards a circular economy.

4. Results

In all three case studies, the utilisation of the MP improved the circularity of the building project, highlighting how the MP is a conclusive method for transitioning from a linear to a circular economy. At every stage of an architectural project, these three examples all relied on commonalities, hinting at their importance for the economic transition. Five headings of interest (Scope, Approach, Generation, Data, and Results) allowed a semblance of comparison and contrast between the three papers. Firstly, the 3D BIM model was the primary requirement, which is confirmed through the other papers referenced in this research. AutoDesk Revit being the most referenced programme, but others do include SketchUp, Rhino, ArchiCAD, Vectorworks etc. These programmes all possess the capability of acting as data repositories for key material and product information.

The data repository feature is then further enhanced by another necessity as highlighted from the case studies, a 3rd party database that provided either material/product data or calculated the sustainability rate of the building through various indicators. A lot of intensive groundwork was involved to systematically map parameters of materials/products to the BIM model and then calculated by the database/software, however, this is then offset when recorded and carried into the next project. The Life Cycle Assessment (LCA) was a key criterion in all examples, and understandably so as it calculates a product's operational and embodied carbon emissions throughout its lifetime, a vital component in all sustainable parameters when selecting and tendering materials.

Syncing the BIM model that provided geometric information to a database that calculated the information was typical, however, databases were unique and provided differing sustainability parameters. As a result, comparing one to another is not straightforward, nor is verifying the accuracy of the databases. That said, all the parameters that were outlined in the case studies are relevant and appropriate to any ambition for a sustainable construction industry. As a project moves through the RIAI's Plan of Work stages (or the CWMF stages for public projects), the MP's purpose alternates and expands from a tool for analysis and design optimisation, providing qualitative data as well as the expected quantitative, and providing an accessible Circularity Index that could potentially act as Circularity Certification for the building composition moving forward into the Occupation and End-of-Life periods.

When the quality and condition of the materials are available and accurately tracked to an extent over a building's lifetime, the supply and demand for the materials and products reuse or recycling stream can be matched. Continuous documentation of materials throughout the lifetime provides essential data to lower financial barriers for the direct and continuous reuse of materials and products. This is further enhanced by a subscription business model where manufacturers loan out their products and reclaim them at the End-of-Life stage, promoting circular design by the manufacturers and reasonable care by the consumers. Documentation, therefore, can be considered a cornerstone of the transition toward a circular economy.

Over the stages of an architectural project, either the RIAI or the CWMF plan of works, opportunities arise for the integration of a MP into regular praxis. Using BIM as an enabling tool for the production of the MP, optimising design through the analysis of sustainability parameters becomes assimilated into an architect's workflow. Adhering to ISO 19650 throughout the lifecycle of a built asset and guided by the Level of Detail appropriate to the stage, the three case studies each reflect a section of a project stage, from Inception & General Services to Operations on Site and Completion to the End-of-life period where the end also mirrors the beginning stage of another project. Essential BIM tasks tie into each stage of the project, with greater relevance for the MP in the 'Tendering' and 'Documentation' stages. Asides from BIM implications, the scope of the MP encompasses the Life Cycle Assessment (LCA) for the tendered materials, hosting the qualitative and quantitative data provided by the Environmental Product Declaration (EPD) and manufacturer. Documentation of these materials stretch from the initial extraction to the use stage to the disposal, feeding into the scope of the MP.

5. Conclusion

This paper has provided a general overview of Ireland's transitional goals from a linear economy into a circular economy. Arguing the necessity of the transition and providing an overview of the relevance of a Material Passport in a Circular Economy, and its applicability in the project stages of an architectural project. Inevitably, the scale of such an economic transition towards a circular economy will include adapting consumption patterns and business models to suit. With that challenge comes an opportunity to support and lead the transition to a Net Zero Carbon built environment. If appropriate framework, criteria, and procedures are in place, public spending can accelerate the green transition. An opportunity for sustainable, inclusive, and balanced development relies on the expansion of digital technologies like BIM, which are supported by strong circular policies.

Implementation and integration of the circular economy in the AEC sector will heavily depend on the core enabling feature of BIM which is collaboration between the various professional disciplines. The Material Passport reflects a vital milestone towards a BIM-generated and standardised approach for producing the MP, as well as its relevance to each stage of the project, from conception to completion to disassembly, providing documentation at every stage. It should further become a standard process for the certification of buildings as a vital contribution to the transition towards a circular economy in the AEC sector.

6. Recommendations

This paper strictly provided an overview of each project stage, and further research recommendations proceeding the research would be to individually examine each stage in hyper-focus to critique an appropriate integration method for the MP as an essential tool for construction projects moving forward. The future role an architect may play in a disassembly process at the end-of-life stage is also of great interest. Within the OPW, further development of the Revit template as well as a Building Object Model library with the relevant information linked into products and materials to satisfy the automation of a BIM-generated MP. A built environment knowledge exchange that is well structured and accessible for all stakeholders in the industry, including product manufacturers, will help encourage interdisciplinary collaboration opportunities as well as improving connections between design and delivery interests, matching circular ambitions with solutions.

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CIRCULAR ECONOMY DESIGN STRATEGIES TO ACHIEVE ENERPHIT AND PASSIVE HOUSE STANDARDS

An Investigation into Circular Economy Design Strategies to Achieve EnerPHIT / Passive House Standards for a Protected Structure External Wall and the Proposed Extension

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Abstract. Ireland's 2050 target of net zero emissions requires the elimination of fossil fuels as a heat source, deep retrofit of existing buildings, and the enforcement of low-carbon construction. This study outlines viable options for two types of external walls, first the retrofit of external walls of a protected structure to EnerPHIT standard and secondly, external extension walls to Passive House standard. This study investigated thermal resistance, breathability, cost, and buildability of wall typologies. Currently only a small proportion of construction projects use renewable and recyclable materials. This study investigated the benefits in using sustainable materials, with a focus on aiming to lower the embodied carbon and creating a more circular approach to the design process. Thermal resistance was analysed in the context of insulation options, comparing suitable and sustainable assemblies. Secondary research consisted of reviewing academic reports, articles, and publications. Primary research was conducted using software analysis and a questionnaire survey. A case study was carried out comparing insulations in terms of thermal resistance, condensation risk assessment, and sustainability, limited to internal insulation wall typologies alone for the retrofit wall. Findings concluded a variety of areas for further research, limited options for retrofit of an existing protected structure wall and suitable sustainable options for an energy efficient extension wall.

1. Introduction

In Ireland, the construction sector currently accounts for around 37% of Ireland's carbon emissions. This is also set to increase in the coming years, with over 400,000 new homes and upgrade of existing housing stock to align with the National Development Plan 2021-2030 (Government of Ireland, 2021). A significant reduction is required in order to achieve the targets set out in Climate Action and Low Carbon Development (Amendment) Act 2021 (Iris Oifigiúil, 2021). Ireland has committed to net zero carbon by 2050 and a 51% reduction in carbon emissions by 2030 (Government of Ireland, 2023)

With a 90% reduction in energy requirements compared to typical building stock, EnerPHIT and Passive House Standards are at the forefront of energy efficiency. Complying to these standards could aid in a country's energy consumption and emissions reduction (International Passive House Association, 2023).

In 2017, almost 5 million tonnes of construction and demolition waste was collected in Ireland. This waste was the largest waste stream in the EU representing approximately one third of all waste produced. For Ireland to meet the requirements of National Development Plan 2021-2030 (Government of Ireland, 2021) regarding construction waste it is vital that a circular approach is taken in all upcoming construction activities (Government of Ireland, 2020)

While efforts are being made to mitigate both problems, these areas are often not looked at simultaneously during the design process. This is largely due to energy efficient insulations being that of man-made insulations which have large embodied carbon and may not be suitable for recycling or reuse. This results in most designers having to choose between either energy efficiency or design for circularity.

This research looks at suitable insulation options that would allow for design circularity, while achieving energy efficiency desired for the project.

1.1AIM

The aim of this study is to analyse and compare sustainable wall typologies which achieve EnerPHIT or Passive House Standard for a protected structure external wall and proposed extension.

1.2 OBJECTIVES

1. To identify the EnerPHIT and Passive House Standards in place today.
2. To investigate sustainable insulating materials which achieve circular design.
3. To investigate various internal insulation options on a solid stone wall of architectural importance and asses the viability of meeting EnerPHIT Standard.
4. To compare and analyse sustainable external wall typologies that achieves Passive House Standard and conclude which is a more viable option.

1.3SCOPE AND LIMITATIONS

This study considered the existing external wall of a protected structure and proposed extension wall and investigated typologies that incorporated circular economy design to achieve EnerPHIT/Passive House Standards. Protected structure status of the chosen case study restricts options for the retrofit of the external wall. External insulation would detract from the architectural significance of the building. Due to this, this study focused on internal insulating options only.

2. Research

2.1 SECONDARY RESEARCH

2.1.1 EnerPHIT

In 2011, the Passive House Institute (PHI) created the 'EnerPHIT Standard' for the retrofit of existing buildings. This new standard was an important step in reducing the energy consumption generated by older buildings, thereby aiding countries to meet their CO2 emission targets.

This standard allowed more flexibility in some areas compared to Passive House Standard such as the original building may not have the optimal orientation to avail of solar gains or due to air leakages in the building fabric.

For a building to meet EnerPHIT standard the following criteria listed in TABLE 1 must be meet:

TABLE 1. EnerPHIT Criteria (Passive House Institute, 2015)

Criteria	Limit Value
Space Heating Demand	≤25kWh/m².yr
Primary Energy Demand	≤120kWh/m².yr
Airtightness	Maximum of 1.0 air changes per hour at 50 Pascal pressure (onsite pressure test in both pressurised and depressurised states)

2.1.2. Passive House

These Passive House is a standard which is increasing in popularity over the last number of years, being successfully incorporated into various climates across the world. According to The Passive House Institute (2015) there are five key elements to consider when achieving Passive House Standard, these include:

1. Insulation continuity
2. High performance windows and doors
3. Heat recovery ventilation
4. Draught free construction (airtightness)
5. Absence of thermal bridges

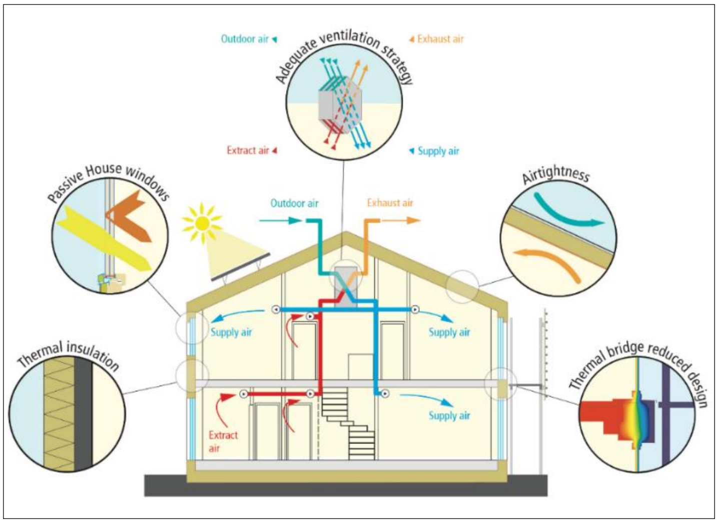


Figure 1. Passive House Requirements (Passive House Institute, 2015)

A Passive House needs 10% of the energy used by typical central European buildings, resulting in up to 90% energy savings (International Passive House Association, 2023). Passive Houses aim to optimize natural solar gains and other internal heat sources. Good insulation continuity for the building envelope increases heat retention thus lowering the need of space heating. By designing a draught free construction, it lowers the air changes per hour resulting in the need of ventilation systems to achieve the required air changes per hour needed for good indoor air quality. Ventilation systems help reduce air contaminates, controlling humidity and can aid in heating the building if heat recovery is incorporated into the system (Passive House Institute, 2015). For a building to be Passive House certified the following criteria listed in TABLE 2 must be met:

TABLE 2. Passive House Criteria (Passive House Institute, 2015)

Criteria	Limit Value
Space Heating Demand	not to exceed 15kWh annually OR 10W (peak demand) per square metre of usable living space
Space Cooling Demand	Similar to the heat demand with an additional, climate dependent allowance for dehumidification
Primary Energy Demand	Not to exceed 120kWh annually for all domestic appliances (heating, cooling, hot water and domestic electricity)
Airtightness	Maximum of 0.6 air changes per hour at 50 Pascal pressure (onsite pressure test in both pressurised and depressurised states)
Thermal Comfort	Thermal comfort must be for all living areas year- round with not more than 10% of the hours in any given year over 25˚C

2.1.3. Thermal resistance

U-value is the thermal transmittance through a material. It is the rate of transfer of heat through a material divided by the difference in temperature across that material. The units of measurement are Watts per meters squared Kelvin (W/m^2K) (NBS, 2015). Each building component has a U-value, lower U-values results in a lower level of thermal transmittance through the building fabric.

TABLE 3. Exterior wall minimum U-value requirements
(International Passive House Association, 2023)(Government of Ireland, 2021)

Standard	Passive House	EnerPHIT	Part L
U-Value	$\leq 0.15 W/(m^2K)$	$\leq 0.15 W/(m^2K)$	$\leq 0.21 W/(m^2K)$

2.1.4. Circular Economy

The term ‘circular economy’ in its simplest form describes how products and materials can continue to be used again once they have reached the end of their ‘first’ life; as such they are no longer viewed as a waste but as a resource. Materials therefore move in loops within the activities of reuse, remanufacture and recycling. The circular economy is the opposite of the 'take-make- dispose' linear economy model (Irish Green Building Council, 2018)

Three key goals of circular economy are as follows:

1. To design out waste and pollution
2. Keep products and materials in use
3. Regeneration of natural systems.

2.1.5. Embodied Carbon

Emissions produced during the activities of retrieving raw materials, manufacturing these materials into products, transportation to site, use, maintaining, replacing, removing, and disposing or recycling is referred to as upfront embodied carbon. The unit of measurement for embodied carbon is kilograms of CO2 equivalent per kilogram (CO2e/kg) of product or material (Irish Green Building Council, 2023). With buildings currently responsible for 39% of global carbon emissions, decarbonising the sector is one of the most cost-effective ways to mitigate the worst effects of climate breakdown. Embodied carbon contributes to around 11% of all global carbon emissions. As operational carbon is reduced it is important to tackle embodied energy as it will continue to grow and increase total emission. World Green Building Council (2019) aims that all new buildings will have a 40% reduction in embodied carbon and must be net zero operational carbon by 2030.

EN15978 describes the calculation of full life cycle, setting out the elements appropriate to each part of the building. There currently is no regulation on embodied carbon emissions in Ireland. This may change in the coming years as other countries such as France and Holland have introduced regulations. EU Construction Products Directive (89/106/EEC) amendments may outline the necessity for use of ecological tracing of products through either Environmental Product Declaration (EPD) or other declarations in the future (Irish Green Building Council, 2023).

Embodied carbon emissions are affected by many factors, so reducing embodied carbon can vary greatly. In most projects the biggest saving can be made at the start of the design process. It becomes more costly and time consuming to make changes during the project in order to reduce embodied carbon (World Green Building Council, 2019).

2.1.6. Reduce, Reuse, Recycling and Disassembly

Given the global need to aim towards a more circular approach to the construction of buildings, the reduction, reuse, recycling and disassembly of building materials is a key part in achieving this. Not only to help in the reduction of waste but to lower costs of the materials. Figure 2 Waste hierarchy for Europe (Zero Waste Europe, 2019) Figure 2 illustrates Europe's waste hierarchy.

Reduction: Design out the need for the component or material (e.g., inherent finishes avoiding the need for paint, etc.) during the design stage selecting materials that can be recycled or reused at end of life leads to the reduction of waste.

Reuse: Incorporating materials that can be reused once the building has reached it end-life helps lower waste. Also, by specifying reused materials in the design of the building lowers the embodied carbon, minimises waste and may lead to cost savings on the project.

Recycle: By specifying recycled materials in a project, it helps lower the embodied energy of the project while reducing the amount of waste. This helps towards countries meeting their emission targets.

Disassembly: Using materials suitable for disassembly, helps reduce material loss and pollution as it is less energy intensive. Ensure materials have the option to be taken apart through mechanical and reversable fixings to allow for future reuse enables disassembly for the project (United Kingdom Green Building Council, 2019)

Figure 2. Waste hierarchy for Europe (Zero Waste Europe, 2019)

2.1.7. Insulating Materials

Lime insulating plaster is a breathable form of insulated plaster typically composed of water, cork and clay. Due to its breathability, it is suitable for the use on old historic buildings such as Columban Hall.

TABLE 4. Lime insulating plaster properties (Green Spec, 2023)

Property	Value
Thermal conductivity	0.037- 0.045 W/m^{2}K
Fire class	A1
Vapour diffusion	4
Reusable/ Recyclable	Yes

Calcium Silicate insulation is made from a mixture of lime and sand. It has good capillary properties and regulates moisture helping prevent mould growth. Due to the board’s strong durability, it has the ability to be reused if retrieved correctly after end of first life.

TABLE 5. Calcium Silicate properties (Green Spec, 2023)

Property	Value
Thermal conductivity	0.059 W/m2K
Fire class	A1
Vapour diffusion	3
Reusable/ Recyclable	Yes

Wood fibre has a range of different uses such as rigid insulation, sheathing and flexible insulation between studs. Wood fibre is a renewable source of insulation due to its composition of mainly wood. Wood is a renewable material and sequesters carbon during its growth creating for a carbon negative insulation. Wood fibre can regulate moisture due to its breathability which allows this type of insulation to be suitable for various applications.

Wood fibre has the ability to be reused for the same purpose as long as it is undamaged and uncontaminated during its first use. Wood fibre can be recycled back into the production process to form part of new insulation.

TABLE 6. Wood fibre properties (Green Spec, 2023)

Property	Value
Thermal conductivity	0.038 – 0.043 W/m2K
Fire class	A1
Vapour diffusion	2-3
Embodied energy	10.8 MJ/kg
Reusable/ Recyclable	Yes

Cellulose insulation is made from recycled newspaper. There are two forms blown in or damped sprayed depending on the location and application of the insulation. Inorganic salts are added to the shredded paper to improve fire resistance and to aid in the prevention of mould growth.

Cellulose insulation is made from up to 85% of recycled material and has a less energy intensive manufacturing process than other insulation products. Cellulose insulation has the ability to be reused once the right measures are taken onsite during removal.

TABLE 7. Cellulose properties (Green Spec, 2023)

Property	Value
Thermal conductivity	0.035 - 0.040 W/m2K
Fire class	A1
Vapour diffusion	1-2
Embodied energy	0.45 MJ/kg
Reusable/ Recyclable	Yes

Hemp fibres are produced from the hemp plant. Hemp insulation is typically made of 85% hemp fibres with the remaining containing polyester binding and 3-5% soda added for fireproofing. Hemp insulation can be reused if no damage has occurred and is easily recyclable (Green Spec, 2023).

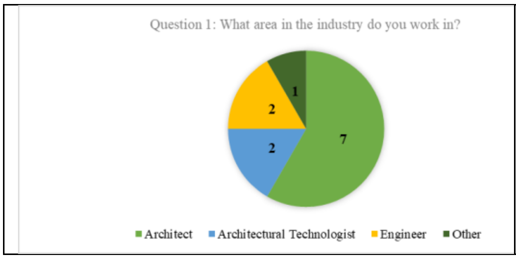
TABLE 8. Hemp properties (Green Spec, 2023)

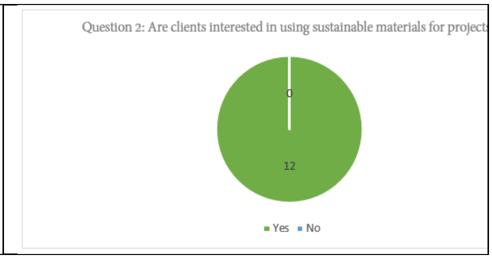
Property	Value
Thermal conductivity	0.037 - 0.040 W/m2K
Fire class	E
Vapour diffusion	1-2
Embodied energy	10 MJ/kg
Reusable/ Recyclable	Yes

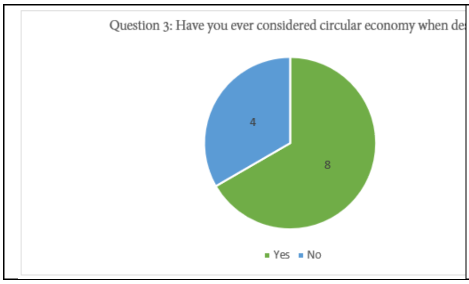
2.2. PRIMARY RESEARCH

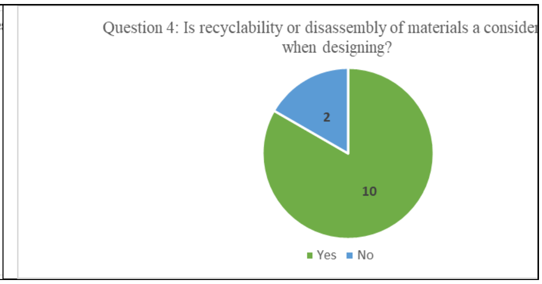
2.2.1. Questionnaire Survey

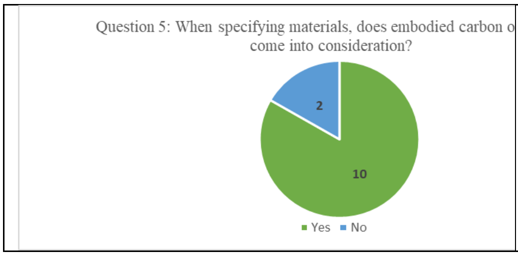
The population for the questionnaire survey was taken from the Royal Institute of Architects Ireland Practice directory. A sample size of 40 was selected and 12 people responded.

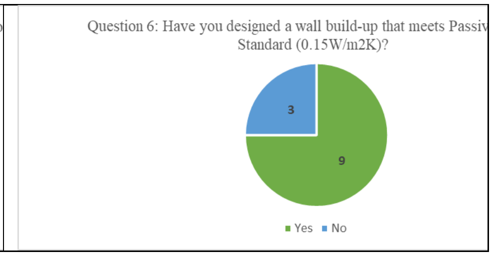












Question 7: Is sustainability a consideration when designing a building and is it becoming more prevalent?

In general, most respondents agreed that sustainability is a consideration when designing. Many also stated that it is becoming more prevalent for the need to be able to comply with current regulations such a TGD Part L. However, one response stated that cost, speed of construction and performance of the materials still play a major consideration, more so than sustainability.

Question 8: Is there a need for more legislation in place for designers to choose the more sustainable option?

There were varying responses to this question with many strong opinions on the matter. 60% of participants agreed that more legislation is needed. One respondent stated that instead of more legislation more support and a practical approach would aid the construction sector to choose a more sustainable option.

Question 9: How would you design a sustainable external wall that meets Passive House Standard?

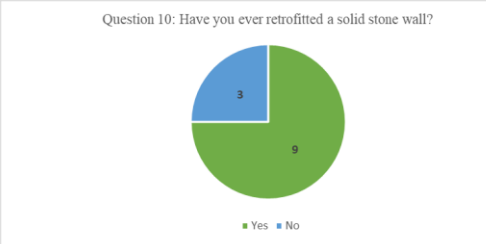
Structure: Numerous responses advised using timber frame as the main structure of the external wall. With the vast options of configurations for an external wall, not surprisingly there were various timber frame options suggested such as twin wall timber frame (thermally broken), timber frame wall systems such as 'Kingspan Ultima Timber Frame wall' and renewable timber from regulated growers for a standard timber frame wall. Other responses included structure options such as CLT and blockwork.

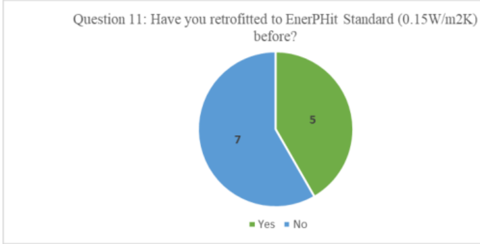
Insulation: Several responses stated natural insulations as the preferred option such as wood fibre, cellulose and hemp.

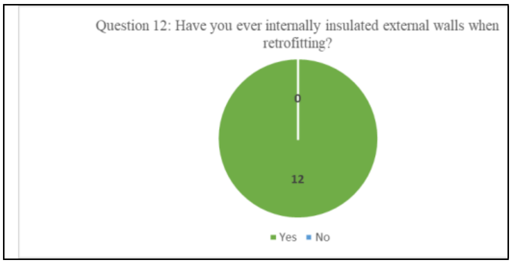
Membranes: Due to most opting for natural insulations many stated the need for a breather membrane to the cold side of the insulation to control the moisture in the wall.

Regarding airtightness, membranes will be needed to the warm side of the insulations with the need for joints to be taped to achieve good airtightness. One response had an alternative to using an airtight membrane.

'Internally a timber-based vapour tight P5 racking support is used and also doubles as the main airtight VCL when adequately taped' – Response 08 Cladding: Surprisingly only one response stated cladding when discussing the wall buildup. This participant's favoured option was timber cladding.







Question 13: How would you design the retrofit of a solid stone wall using internal insulation only, aiming to achieve EnerPHIT Standard?

From the responses there were three options suggested to internally insulate a solid stone wall. These consisted of an independent insulated stud wall, a breathable insulating plaster such as Diathonite and the final option was a levelling lime plaster on the stone wall with insulations boards that have good capillary properties finished with a lime skin finish such as Lime Green Solo.

Some responses stated that this Standard may not be achievable or practicable in regard to this project. As other problems may occur such as risk of condensation.

A hygrothermal risk analysis via WUFI was suggested in order to ascertain an appropriate level of insulation.

Question 14: How would you achieve vapour permeability/breathability of the stone wall?

As a whole, most responses stated the use of breathable materials such as lime plaster compared to most modern-day cementitious renders systems and to use similar materials of the existing wall. Other responses suggested the use of propriety chemical spray systems. One response also stated that once suitable materials have been chosen to carry out a risk analysis using hygrothermal software such as WUFI previously stated in the above question to assess the moisture risk and the compare the results.

Question 15: If rising damp or condensation occurred, how would you solve the problem?

A number of participants stated to fully assess the problem of the moisture in the wall before assuming rising damp or condensation. As it could be caused by poor drainage around the building. It was suggested to use non- invasive solutions such as ventilation and heating before remedial works are carried out. Some responses proposed the use of an injection process such as a chemical DPC.

‘A DPC can be injected into the wall, and this has been known to work in the case of rising damp, an electric current based system can also be installed to remove damp from walls. However ultimately, it is the due diligence beforehand, and the calculations used at detail design stage that should prevent this from happening rather than fixing it when it does.’– response 03.

2.2.2. Case Study

This section of the report carried out a practical case study on a protected structure. The building used was the Columban Hall, Co. Galway. The aim of this case study was to execute a comparative analysis on different suitable strategies for the retrofit of existing solid stones walls to EnerPHIT Standard and suitable options for the extension wall to Passive House Standard. The two properties that will be looked at include thermal resistance and condensation risk.

2.2.2.1. Thermal Resistance

This section of this study looks at the thermal resistance of the three options for the retrofit existing wall.

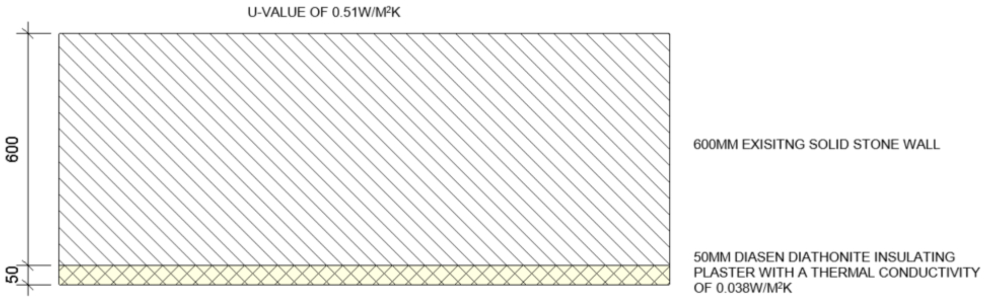


Figure 3. Option 01 used insulating (Mooney, 2023)

Option 01 used insulating plaster as the insulation type which created a U- value of 0.51W/m²K.

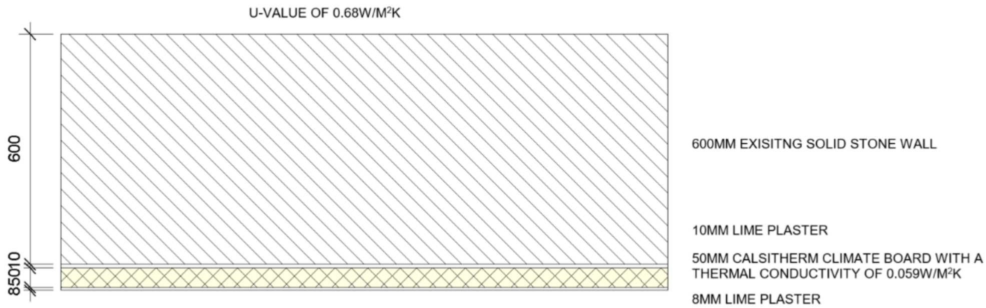


Figure 4. Option 02 Calcium silicate (Mooney, 2023)

Option 02 used calcium silicate boards as the insulation type which created a U- value of 0.68W/m2K.

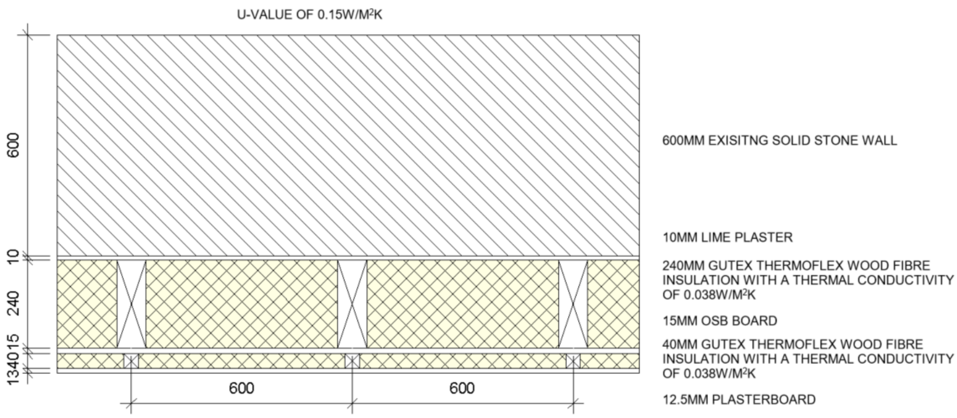


Figure 5. Option 03 Wood fibre insulation (Mooney, 2023)

Option 03 used wood fibre internal timber frame which created the desired U-value of 0.15W/m2K.

This section of this study looks at the thermal resistance of the three options of the extension wall. As this study is focused on insulation to help form accurate comparisons the same structure and cladding will be used. In this case the structure will be timber frame wall with an internal raking board also acting as a vapour control layer. This is due to timber frame being the most common structure type suggested during the survey responses and with the use of an internal raking board it reduces the need for a vapour control layer. The cladding will consist of horizontal timber cladding. Internal finish will be plasterboard fixed to timber frame with a service cavity.

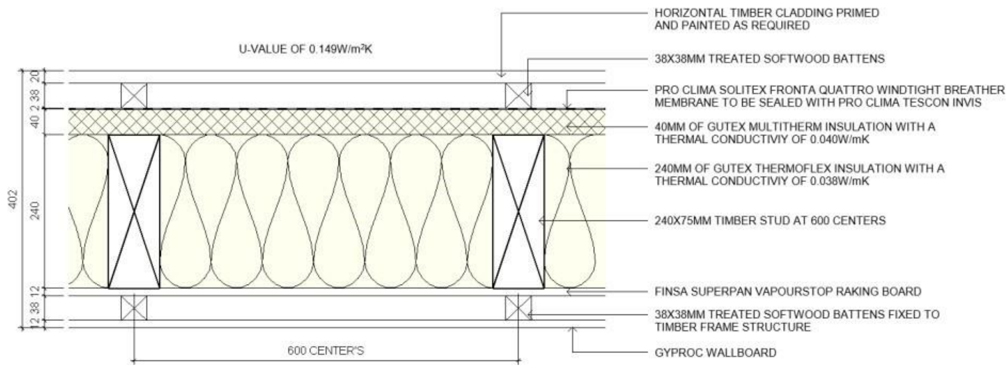


Figure 6. Option 01 Wood fibre insulation (Mooney, 2023)

Option 01 used wood fibre as the insulation type which created a U-value of 0.149W/m2K.

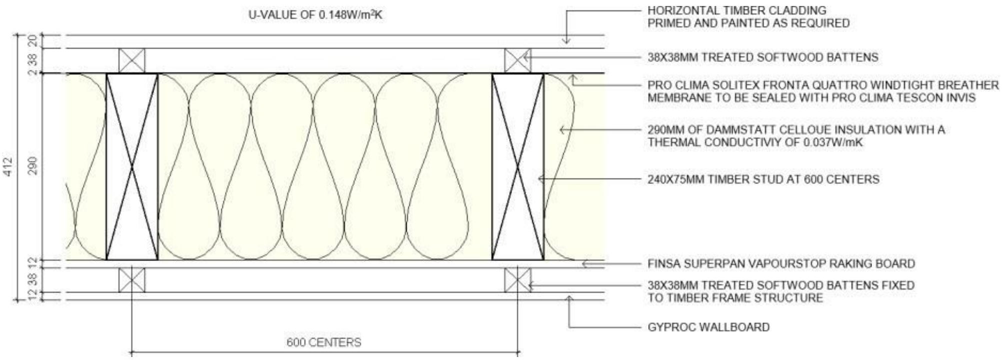


Figure 7. Option 02 Cellulose insulation (Mooney, 2023)

Option 02 used cellulose as the insulation type which created a U-value of 0.148W/m^{2}K.

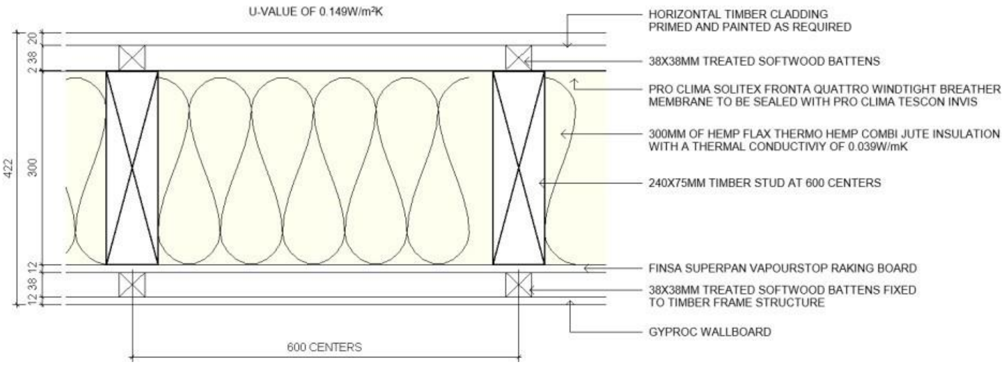


Figure 8. Option 03 Hemp insulation (Mooney, 2023)

Option 03 used hemp as the insulation type which created a U-value of 0.149W/m^{2}K.

2.2.2.2. Condensation Risk

Due to the extension walls being new construction thus having a low risk of condensation, only the retrofit of the existing wall has been investigated using a condensation risk software of WUFI Pro 6.0.

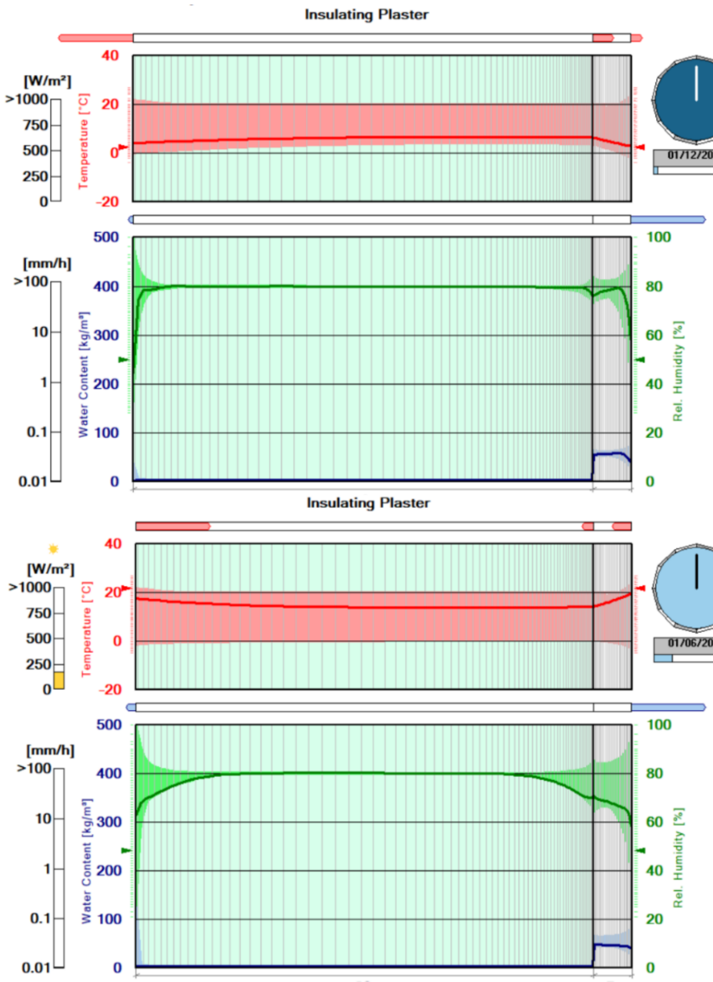


Figure 9. WUFI analysis of option 01 (Mooney, 2023)

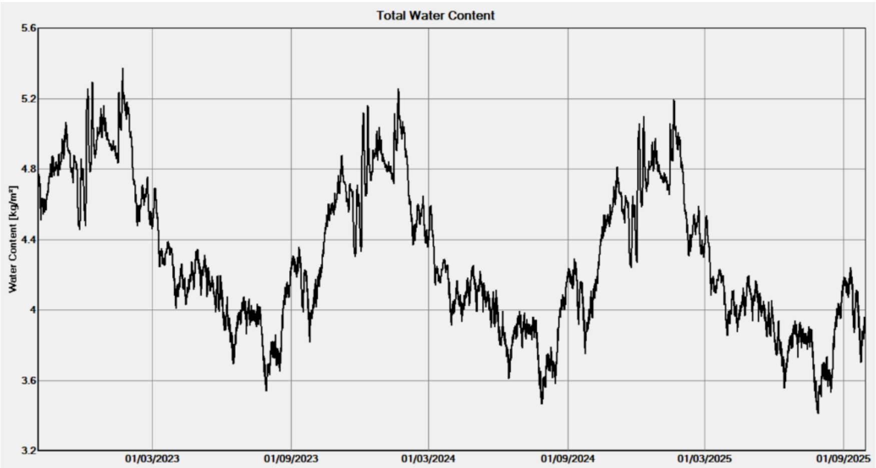


Figure 10. Water content of Option 01 (Mooney, 2023)

From carrying out this analysis it shows the water content staring to lower and level off by the end year 2.

Option 01 has a relatively low risk of condensation due to Diathonite having a high vapour diffusion rate. Thus, allowing it to transfer any moisture absorbed from internal humidity to layers behind the insulation.

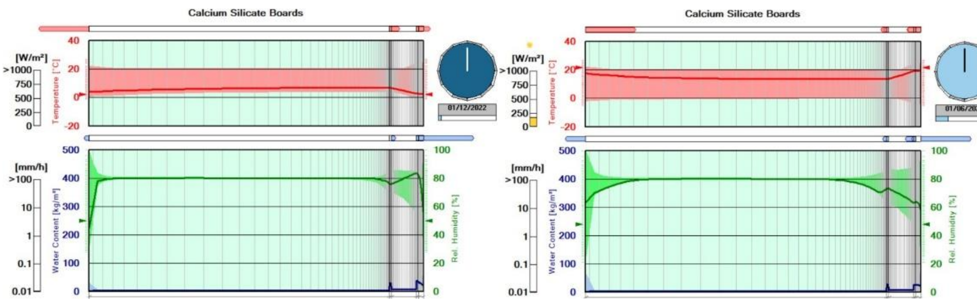


Figure 11. WUFI analysis of option 02 (winter right) (Mooney, 2023)

Figure 12. WUFI analysis of Option 02 (summer left) (Mooney, 2023)

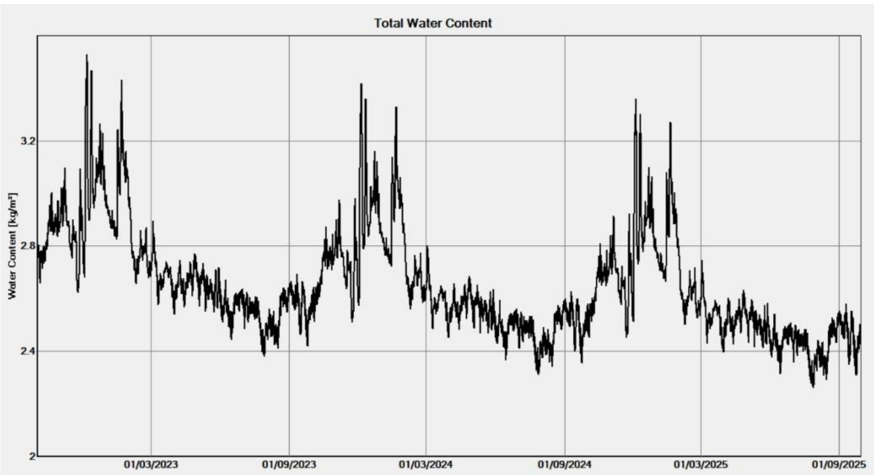


Figure 13. Water content 0f option 02 (Mooney, 2023*)*

Option 02 has the lowest risk of condensation. Out of the three retrofit strategies it has the lowest maximum total water content. As calcium silicate is composed of lime and sand it has good vapour diffusion and capillary properties which allows any moisture that comes in contact with it to swiftly be moved through the layer lowering the risk of condensation and total water content.

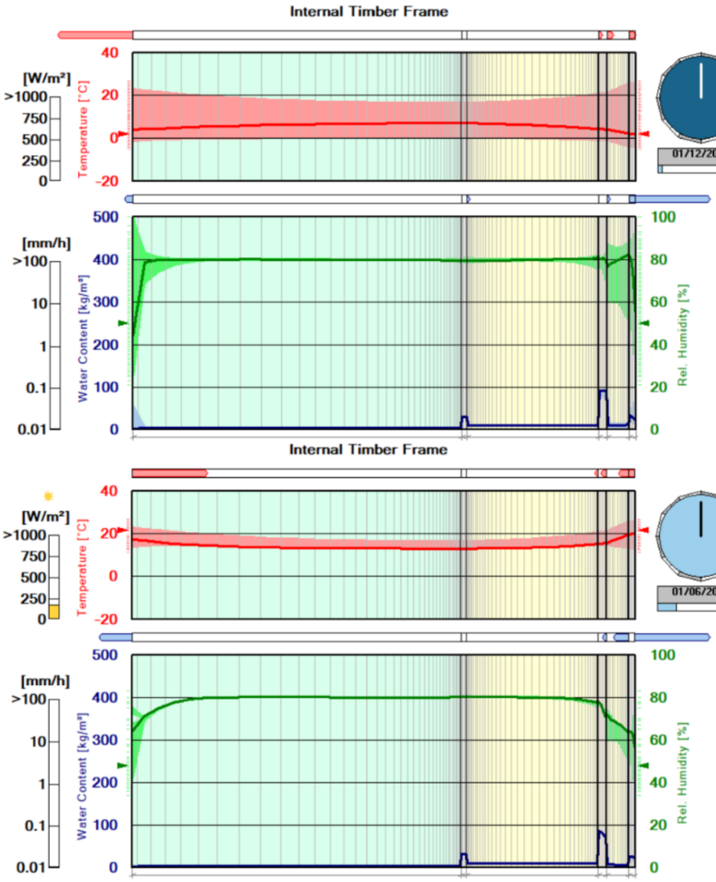


Figure 14. WUFI analysis of Option 03 (Mooney, 2023)

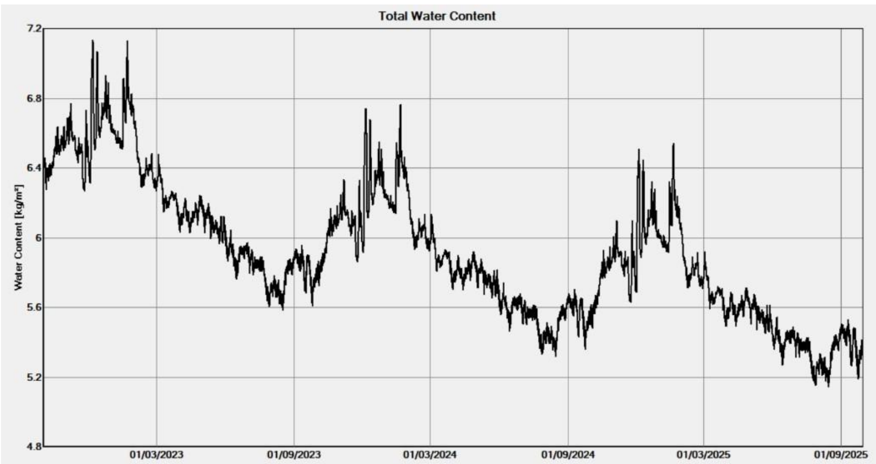


Figure 15 Water content of Option 03 (Mooney, 2023)

Option 03 has the greatest risk of condensation. This is due to the thickness of insulation and the vapour diffusion rate of the insulation. It can be seen in Figure above that the total water content is gradually reducing over the years but still has a relatively high-water content.

3. Results

3.1. RETROFIT EXTERNAL WALL

From carrying out U-value calculations and condensation risk analysis on the three internal insulation retrofit options, Option 01 – Diathonite insulating plaster reduced the U-value of the existing wall by two-thirds while having a low risk of condensation due to its breathability. Option 02 – Calcium silicate boards achieved a higher U-value nevertheless achieved the lowest risk of condensation of the three options. Option 03 - Wood fibre internal timber frame achieved the required EnerPHIT standard but at a cost of a high risk of condensation throughout the assembly, resulting in an unsuitable option. Option 01 is found to be the most suitable option due to low risk of condensation, good thermal resistance and ease of buildability.

3.2. PROPOSED EXTENSION WALL

From carrying out U-value calculations on the three options, all assemblies achieved the required Passive House Standard resulting in three suitable options for an extension wall to meet Passive House Standard. Option 02 – Cellulose achieved a slightly lower U-value and had a lower embodied energy resulting in most suitable option.

5. Conclusions and Recommendations

5.1. CONCLUSIONS

1. Passive House Institute is the regulator of EnerPHIT and Passive House Standards. The U-value required to meet both standards is 0.15W/m2K with some differences between the standards.
2. A selection of natural insulation materials was researched in Section 2.1.5 of this study. A table of properties for each insulation type was compiled with properties such as thermal conductivity, recyclability and embodied energy to help form comparisons.
3. From researching suitable internal insulation options only one option had the ability of meeting EnerPHIT Standard. This option resulted in the thickest assembly, highest risk of condensation and also had the greatest impact on the floor area. In conclusion, meeting EnerPHIT Standard for the retrofit of an existing solid stone wall, such present in the case study on Columban Hall would not be a viable solution due to the risk of interstitial condensation and the impact it would have on

the internal floor area. From this research it was found that Option 01 - Diathonite was the most suitable option due to the U-value achieved and low risk of condensation.

4. Sustainable external walls were analyses with the use of U-value calculations. Three wall build-ups were designed incorporating natural insulation types in order to achieve circular economy design. Each wall was required to meet Passive House Standard by achieving a U-value of 0.15W/m2K or below. All three option resulted in a suitable assembly and found that Option 02 – Cellulose insulation was the most suitable wall build-up.

4.2. RECOMMENDATIONS

It is recommended that other internal insulation methods be researched such as aerogel insulation. Thermal bridging assessment could be conducted with each retrofit option to assess the impact at junctions such as the windows and floor.

Acknowledgements

I would like to thank the participants of the questionnaire.

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THE IMPACT OF AIRTIGHTNESS AND LOW VENTILATION ON AIR QUALITY IN DOMESTIC BUILDINGS AND THEIR EFFECT ON OCCUPANTS

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Abstract. One of the facets of responding to climate change is energy conservation which has become so imperative to both domestic and non-domestic buildings. The increasing idea of better insulation and airtightness in a bid to save energy in buildings tended to lead to higher risks of low ventilation and low air quality of the indoor environment. Furthermore, the resulting impact on occupants' thermal comfort and well-being are often untested.
The aim of this paper is to examine how to balance airtightness with energy consumption and low ventilation to enhance good indoor air quality to meet carbon emission reduction targets in accordance with World Health Organisation (WHO) stipulated guideline to satisfy occupants comfort and wellbeing. The focus will be on domestic dwellings in Scotland.
A mixed method approach was used to carry out an assessment of the perception and satisfaction of occupants. In addition to a survey of occupants, measurements of indoor air quality indicators of the sample dwellings, including carbon dioxide, relative humidity, air temperature, air velocity and other pollutant such as benzene, formaldehyde, TVOC, PM2.5, PM10. An assessment of the building fabric performance was also conducted to establish levels of energy efficiency and carbon emissions.
Preliminary findings seem to indicate that the CO2 level in some of the sample dwellings are above the WHO recommendations for occupant and the level of the PM2.5 are not suitable for human habitation. Hence, there may be health implication for occupants in those buildings due to the elevated level of CO2 and PM2,5. Further analysis of the data collected will be carried out before final conclusions are established.

Keywords. energy conservation, Indoor air quality, Low Ventilation, Carbon Emissions, Thermal Comfort, Wellbeing.

1. Introduction

The growing awareness of the impact of the indoor environment on occupants' health in passive buildings is of great importance, with respect to indoor air pollution. Recently conducted research shows that energy efficient buildings tend to put the emphasis on low energy consumption and thermal comfort. However, the impact of pollution on indoor air quality in passive buildings is still not adequately discussed in these research due, often, to lack of technical knowledge and skills to address the issue (Alejandro,et al 2018).

Notwithstanding the increased airtightness in the construction of building envelopes, primarily for energy efficiency reasons, results in low natural ventilation rates. The latter necessitate the application of modern technologies and use of building material which may reduce the indoor environmental quality, if proper and adequate measures are not taken into consideration (Howieson et al., 2014).

The effect of reducing the rate of natural ventilation in passive buildings combined with increased insulation, to improve energy efficiency, and hence reducing the rate of carbon emissions, without adequate consideration of alternative means of ventilation measures or strategies may result in pollution of the indoor environment. As this may be hazardous, toxic, and negatively impact occupants' health and wellbeing in the long-term (Howieson, et al 2013).

There are several indoor pollutants that may impact occupant health, with long term and short-term effects, thereby causing different health problems such as respiratory complications, runny noses, potentially cancer, cardiovascular problems, and hypertension. Such pollutants are identified as Particulate matter such as PM2.5, CO_2, CO, VOC etc. (Azuma et al., 2016) The short-term health effect of indoor pollutants includes the irritation of the eyes, nose and throat, headaches, dizziness, and fatigue. These are easily treated either by removing the affected person from the pollution sources. Although, symptoms of some diseases such as asthma develop immediately if one is exposed to the indoor pollutant. The long-term health effect of indoor pollutant includes respiratory diseases, hearts diseases and cancer which can be so serious. These show after a long time of exposure to the indoor pollutants or frequent exposure to the indoor pollutants. However, ensuring adequate and clean indoor air quality is paramount for occupant health and comfort despite symptoms not manifested, as reactions differ when exposed to the indoor pollutants (EPA, 2022).

In domestic buildings the indoor sources of pollution are mostly due to exposure exposed to surface dampness or condensation due to low ventilations (Jesica Fernández-Agüera, 2019). Other sources also vary, either from the occupant's behaviour and activities and the building materials and furnishing such as product for household cleaning, carpet, furniture etc. The effect of these pollutants to occupants/human health is on the rise, most especially in passive building, as different threshold has been set for each pollutant, according to the world Health Organization (WHO, 2021).

The basic understanding of air exchange and building airtightness is a vital decision to be incorporated during the design and operation of a building. Hence, adequate performance of the ventilation system in a building will significantly impact the internal thermal comfort and the indoor air quality of that buildings (Kisilewicz et al., 2019).

To achieve a full energy saving potential, airtightness is a crucial factor affecting energy consumption in buildings. While, on the other hand, the rate of ventilation either natural or mechanical has a major effect on the quality of air in the indoor environment it is also an important criterion for an effective building performance (Eskola et al., 2015).

These are major concerns in a cold climate where daily management of energy consumption, to save energy cost, is a prime preoccupation of many householders particularly in buildings with airtight envelopes (Salehi et al., 2017). The thermal performance of residential buildings can as well be affected, due to their construction characteristics (Litvak et al., 2000).

2. Environmental Impact of Pollution on Occupants' Health and Comfort

To ascertain that occupant health and comfort are met and given priority in current buildings, fossil fuels such as heating oil, natural gas, electricity, and liquefied petroleum gas used for cooking and space heating meet the strictest environmental safety measures. The carbon monoxide gas must be effectively controlled due to its poisonous nature and adequate ventilation is provided for the appliances and care must be taken to avoid exposing Nitrogen oxide gas emitted from gas stoves. Current appliance installations safety standards cater for these requirements when adhered to. However, the burning of solid fuels such as fire wood as source of heating, which are uncontrollable cannot be compared with the gaseous fuel heating such as boiler, which are significantly controlled to emit significantly lesser amounts of pollution, comprising particulate matter (PM2.5), volatile organic compounds (VOC) such as aldehydes and carcinogenic compounds like benzene, and 1, 3 – butadiene and polycyclic aromatic hydrocarbon, which affect eye irritation (Zhang et al, 2016).

2.1 OCCUPANTS BEHAVIOUR

Occupant behaviour means the contact and interaction with building systems to monitor their health environment and achieve environmental, visual, and acoustic comfort in buildings. The ability of humans to monitor environmental factors is not only restricted to the natural world, but also to their living areas. The improvement of air quality (in terms of fresh air, air pollution and odour elimination), acoustic conditions (with no undesirable noise and vibration), visual or lighting quality (in terms of the regulation of luminance ratios, reflection, and glaring) through their involvement and activities in the house, occupants may thus affect the indoor climate and overall well-being.

In the late 19th century, the term "thermal convenience" was introduced. The American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) defined the principal concept of thermal comfort as "that mindset that expresses thermal environment satisfaction and is subjectively evaluated." Two quantitative formulas developed by Fanger were used in their calculation, though subjective, thermal comfort: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD). PMV models include temperature, humidity, air velocity, metabolic heat rates and thermal garments worn, all of which are important for predicting the thermal comfort level. After its foundation, several researchers have investigated and updated heat comfortable applications in different building types worldwide and PMV and PPD models (Fanger, 1970).

In addition to passive metabolic heat generated by occupants in the occupancy section of energy simulation software, total energy consumption in buildings is also affected by active utilization. Occupants interact with the control systems and building components so that they achieve their ideal personal level of comfortable facilities in various ways: use of opening and closing window systems for the house, use of lighting and controls for solar shading (e.g., changing blinds) and use of HVAC systems. As illustrated in figure 1, thermal comfort in a dwelling is a function of occupants' status, their occupancy behaviour and energy cause. The latter criteria are significant to the aim of this paper i.e., how to balance energy consumption and ventilation to be able to achieve good indoor air quality.

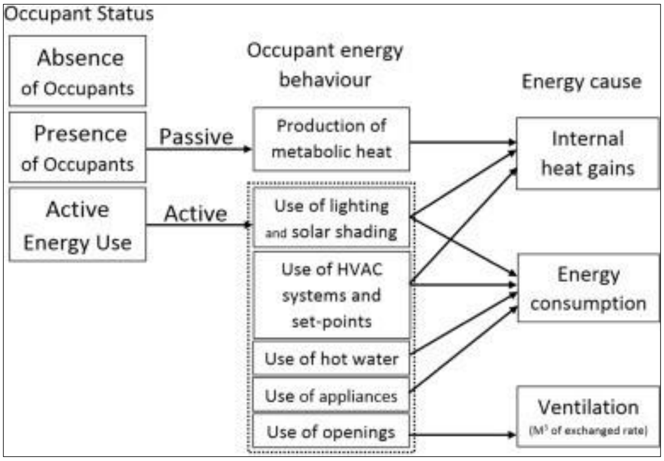

Figure 1. Occupants Status and Energy behaviour (Delzendeh et al., 2017)

2.1.1. Rationale

Airtightness of the building envelope constitutes one of the major factors of achieving energy efficiency in buildings. Furthermore, energy efficiency, reducing carbon emission and greenhouse gas emissions is one of the aims of the sustainable development goals (SDG) (M. Kraus, 2016). Air quality and its impact on occupants' thermal comfort and well-being tended to be often forgotten in the building energy debate. Well insulated, airtight, and naturally ventilated domestic buildings are energy efficient and have low carbon footprint, but they are often vulnerable to an increased risk of dampness and condensation, which may result in poor indoor air quality.
Another aim of this paper is to evaluate occupants' lifestyle response to energy performance, air infiltration rates, the possible risk of CO_2 concentration, and the formation of condensation in residential buildings (A. Hashemi, N. Khatami, 2015).

The paper is part of a PhD research programme the overall aim of which is to investigate how to effectively balance the impact of energy saving, reducing energy cost and carbon emissions and at the same time devise strategies for adequate indoor environment and air quality for occupant's comfort and wellbeing (Howieson et al., 2014).

3. Methodology

A mixed method approach was utilised to assess occupants' perception and satisfaction. These are the qualitative, quantitative, and computational fluid dynamic approaches to explore the occupants' satisfaction and perception of energy usage and the impact of airtightness upon the indoor environment.

To measure human behaviour, that is the measurement of occupants' wellbeing and thermal comfort, an online qualitative questionnaire was administered using google forms. The questionnaire was structured in five different sections including:

1. Occupant demography,
2. Building indoor air quality and sources of indoor pollutants
3. Energy consumption impact on indoor air quality
4. Occupant satisfaction/perception of Indoor Air Quality (IAQ) and Indoor Environmental Quality (IEQ).
5. Occupant perception of / Satisfaction with indoor thermal comfort and ventilation.

The target population included occupants living in 3 dwelling categories: housing association properties, local authority properties, and private properties. There were forty-seven valid responses from the questionnaire.

To assess indoor thermal comfort as well as air quality indicators, a series of quantitative measurements were conducted within the sample dwellings. Measured indicators included carbon dioxide, relative humidity, air temperature, air velocity and other pollutants such as benzene, formaldehyde, PM2.5 and PM10.

An assessment of the dwellings' fabric performance was also conducted to establish levels of energy efficiency and carbon emission. Two sample standard residential buildings in different locations in Edinburgh were used. The houses were constructed in 1980s, and 2020s. The choice of these 2 houses is the first stage of a larger sample of contemporary units used for the PhD research programme. Various building fabric indicators were assessed to establish the energy efficiency and carbon emission rate using the Standard Assessment Procedure software (SAP12).

3.1 EQUIPMENT

The equipment used for indoor measurements are illustrated in figure 2. The Chauvin Arnoux Indoor Air Quality Monitor was used to measure indoor air quality and thermal comfort indicators. This piece of equipment is capable of measuring Temperature, Relative Humidity and Carbon Dioxide. While the Orium (Quaelis 40) indoor air quality monitor is capable of measuring Particulates (PM2.5, PM10, HCHO, Benzene and TVOCs). It measures particulate in real time and all parameter Monitors benefit from built-in data logging. The data was then analysed using Excel spreadsheet. Also, an ATP instrument was used to measure indoor air velocity.

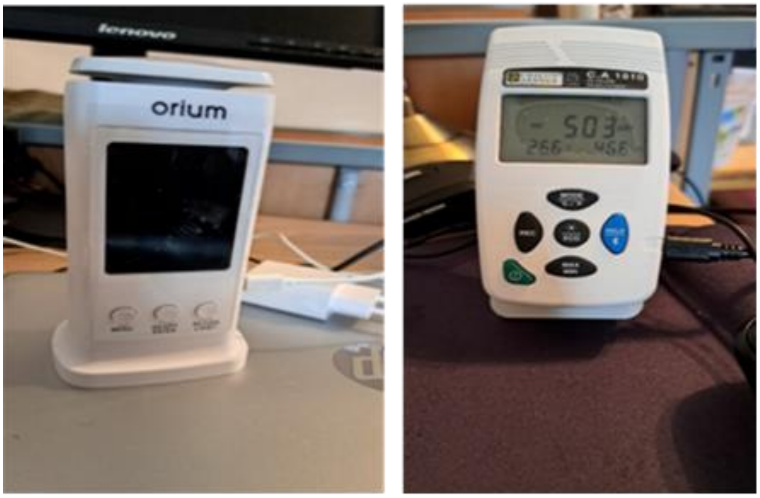

Figure 2. Quaelis 40 monitor & C A 1510 monitor

3.2. SAMPLE HOUSES USED IN THE RESEARCH

As explained in the methodology (paragraph 3 above), the 2 houses below form the first phase of a larger sample utilised to assess the fabric performance, carbon emission and indoor air quality. A measured survey was conducted by the author for each house to determine the data required for the energy assessment simulation. Data of the building elements are provided in Table 1.

Langloan House is an End Terrace house. It was built less than ten years ago. The envelope is brick walls with an average thermal transmittance of 0.21 W/m²K. The Roof Average thermal transmittance is 0.14 W/m²K, and the Floor Average thermal transmittance 0.17 W. The house is situated close to a 40 mile per hour main road and centrally heated. The fuels used are gas and electricity with solar hot water panels. It is 3-bedroom house with 3 adults and three children and one infant, total of seven occupants.

Kilkliston House was built over 30 years ago with brick walls and internally insulated to reduce heat losses. It was built to prevent draught and unwanted air leakages. The floor is suspended wooden floor, and the windows are double glazed. The fuels used are gas and electricity, with central heating. The occupants living in this three-bed house are a total of eight: three Adults, three children above 10 years and two infants. This semi-detached house external walls are made of brick finished in rough cast render.

Figure 3. Langloan House (left) and Kilkliston House (right) Edinburgh (Source: Authors)

TABLE 1. Building Elements Data (Source: Authors' Survey)

	Langloan House (A)	**Kilkliston House (B)**
Element	**Description**	**Description**
Walls	Type of wall: cavity / timber frame average of thermal transmittance of 0.21 W/m²K	Cavity walls, filled cavity
Roof	Pitched / flat Average thermal transmittance 0.14 W/m²K	Pitched, 200 mm loft insulation
Floor	Average thermal transmittance 0.17 W/m²K	Suspended, no insulation (assumed)
Windows	High performance double glazing	Fully double glazed
Main heating	Boiler and radiators, mains gas	Boiler and radiators, mains gas
Main heating control	Programmer, room thermostat and TRVs	Programmer, room thermostat and TRVs
Secondary heating	None	None
Hot water	From the main system	From main heating system
Air tightness	Air permeability of 6.0 m^3/h (Assumed)	Air tightness Air permeability 6.0 $m^3/h.m^2$ (assumed)

3.3 ENERGY PERFORMANCE ANALYSIS (SAP12)

The targets to tackle the impact of climate change in view of reducing carbon and greenhouse gas emission in buildings vary across the world. National targets in the European Union (EU) including UK align with the commitments under the Paris agreement toward achieving carbon neutrality by 2050 at the latest. While the Passivhaus (PH) was developed in Germany for homes with low rise domestic buildings, this standard has been applied to houses in a range of other countries including non-domestic buildings. In Scotland, Passivhaus targets are being assimilated in the national targets and expected to be integrated in the technical standards. The following baseline benchmarks are used in this paper for analysis purposes (Straube 2009).

- CO_2 emissions: 0 -15 Kg/m2/y
- EPC band: A or A+
- SAP value: 92 – 100
- Typical regulated energy consumption: 4622 kwh/y.

The Standard Assessment Procedure (SAP12) was used to calculate the energy performance of the sample dwellings as illustrated in table 2. House A annual energy consumption is 5775.66 kwh/year, with a total annual CO2 emission of 1596.5 (13.47 Kg/m2/y). While the total annual energy consumption in House B is 5388.65 kwh/year and annual total CO_2 emission is 3023.2 Kg/year (60.17 Kg/m2/y). The annual energy consumption of both houses is close but above the typical 100 m2 house consumption in UK of 4622 KWh per annum. This may be due to the number of occupants, occupants' ages, and pattern of use. House A CO_2 emissions is within the benchmark (0 – 15 kg/m2/y) whereas that of house B is 4 times above the benchmark maximum. The explanation resides in 2 main factors, house A is less than 10 years old with better standard of fabric as well as PV panels supply energy for hot water, hence total energy consumption higher but CO_2 is much lower than House B.

TABLE 2. Energy Performance from SAP12 for both houses

Performance values		
SAP Performance	House A, Langloan	House B, Kilkliston
Total delivered energy KWh/year	5775.66	5388.65
Total CO_2 Kg/year	1596.5	3023.2
SAP Value	85.45	54.42
SAP Band	B	E
CO_2 Emission Kg/m^2/year	13.47	60.17
(EI Value) Kg/m^2/year	87.41	58.89
EI Rating (Kg/m^2/year)	87	59
Potential Performance values		
EI Band	B	D
Target Emission Rate (TER)	15.24	63.81
Dwelling Emission Rate (DER)	15.36	65.04
Annual Space heating fuel KWh/year	3374.78	3552.74
Water heating fuel KWh/year	1898	1012.13

This confirms that the environmental impact is dependent on renewable energy sources regardless of total energy consumption. With EPC ratings of B and E (potential D), both houses remain well below the A band target for potential upgrades to meet future carbon neutrality targets.

4 Data collection and analysis

4.1 DATA COLLECTION

The baseline of the measured data according to the World Health Organisation and US Environmental Protection Agency (EPA), are indoor CO2 should not exceed the limit of 1000 ppm, the temperature (dry bulb) range should be 23 - 26 C during summer and 20 - 23 during winter. The PM2.5 should be within the range 10 - 50µg/m3 for an average of 24 hours (WHO, 2021). Also, to reduce the possibility of transmission through air, the World Health Organisation recommends a natural ventilation rate of at least 60 Litre per second and per person and at least six air changes per hour (WHO, 2020a; WHO, 2020b). Relative humidity indoors should range between 30 – 70% for human thermal comfort.

TABLE 3. Langloan House and Kilkliston House Average CO2, Temperature Relative Humidity and air velocity

Average, Minimum and Maximum values of the measured parameters					
House Measured	Descriptives	CO2 (PPM)	TEMP (°C)	RH (%)	Air Velocity (m/s)
House A, Langloan	Mean	689	24	35	0.9
	Minimum	417	22	31	0.08
	Maximum	2290	25	41	0.34
House B, Kilkliston	Mean	618	23	38	0.06
	Minimum	452	20	30	0.02
	Maximum	971	25	50	0.1

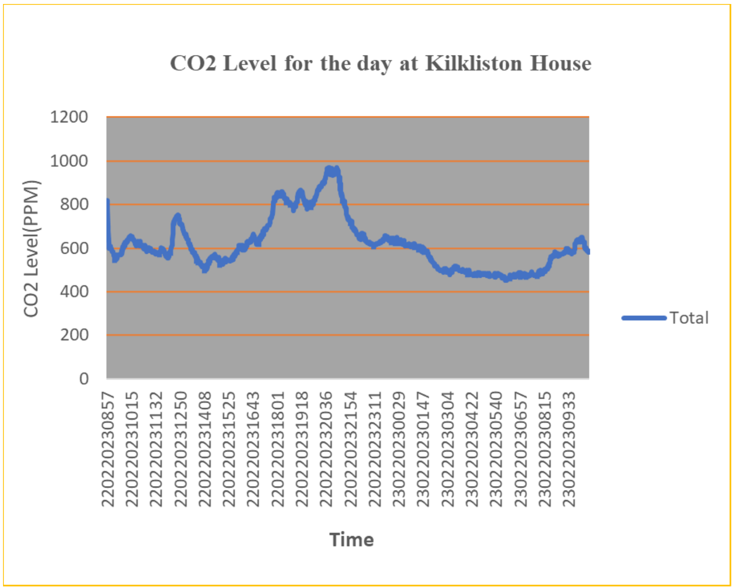

Figure 4. CO_2 level for the day at Kilkliston House

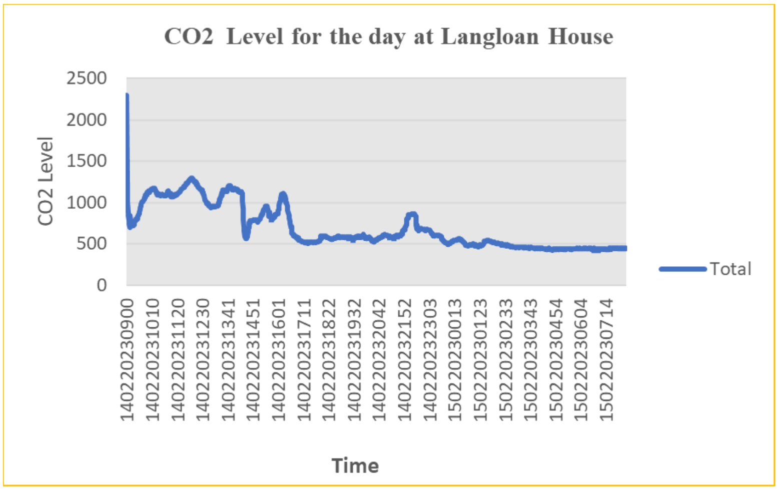

Figure 5. CO_2 level for the day at Langloan House

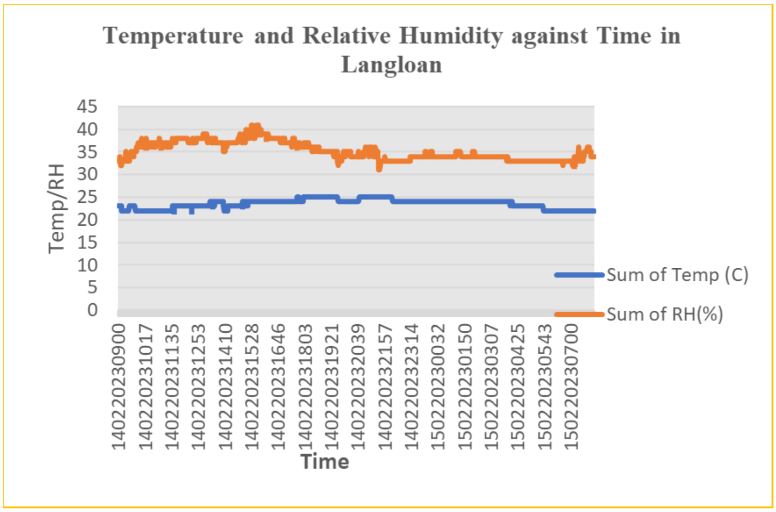

Figure 6. Temperature and Relative humidity against Time in Langloan house

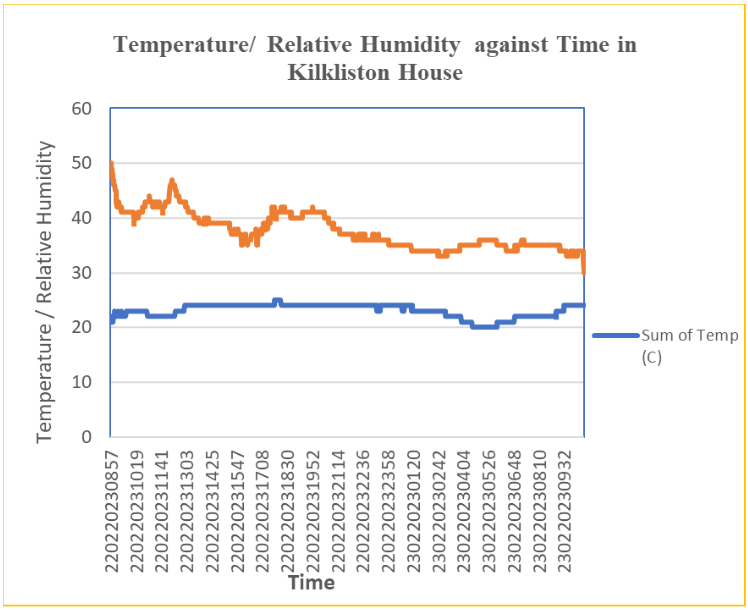

Figure 7. Temperature and Relative humidity against time at Kilkliston house

4.2 DATA ANALYSIS

With reference to figure 6 and 7, it is shown from table 3, that the minimum and maximum temperature in Langloan House is 22 and 25 degrees, while in the Kilkliston house the minimum and maximum temperature is 20 and 25 degrees, this range of temperature is within the acceptable WHO threshold. The relative humidity in the Langloan house range from 31 to 41, while in the Kilkliston house the relative humidity ranges from 30 to 50%. Hence, the relative humidity is within the WHO acceptable threshold. However, the relative humidity of the Langloan house fall below 40 to 60% threshold of WHO acceptable guideline,

Table 3 illustrates the average data collected for the indoor air quality parameters for House A and House B. From the graph in House A, the CO_2 at a point rose twofold above the stipulated standard to over 2000 PPM (Figure 5), although this was not uniform for 24 hrs. The mean carbon dioxide levels recorded are less than 1000ppm. The mean recordings for both houses are within the recommended standard by the World Health Organisation (WHO Std). As such it is suitable for occupant's comfort and wellbeing. Relative humidity and temperature recorded for both houses are still within the recommended threshold. Mean air velocity, an indicator of natural ventilation, is 0.9 m/s for house A which is within an acceptable range for winter conditions under UK CIBSE standards. In house B, however, the mean air velocity of 0.06 m/s is well below the benchmark of 1 m/s. This may result in increased air pollution. Apart from the lower level of natural ventilation in house B, all other values of indoor air quality are within the standard benchmarks.

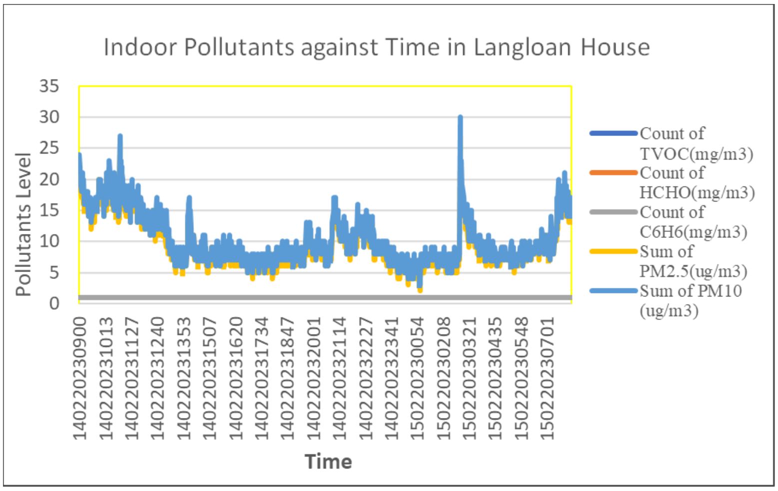

Figure 8. Indoor pollutants against time at Langloan House

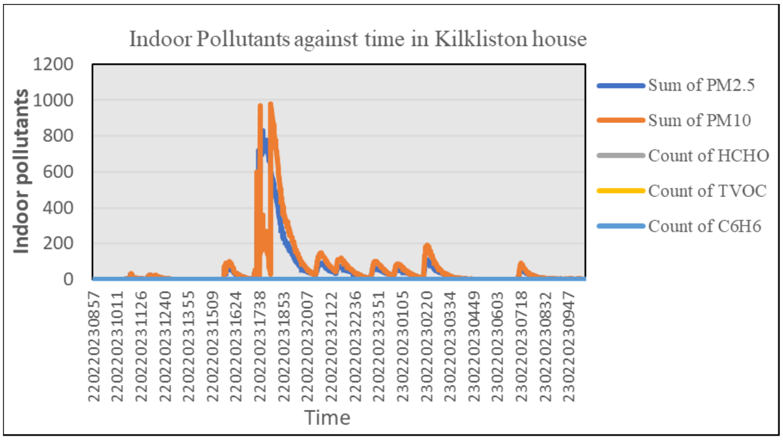

Figure 9. Indoor pollutants against Time at Kilkliston House

TABLE 4. Indoor Pollutants at Langloan and Kilkliston Houses
(*WHO 2006 and 2021 Guidelines)

	Formaldehyde HCHO (mg/m3)	TVOC (mg/m3)	Benzene C6H6 (mg/m3)	Particulate matter PM2.5 (ug/m3)		Particulate matter PM10 (ug/m3)	
Benchmark*	0.1mg/m3	Under 0.25 mg/m3.	N/A 2.6–5.8 mg/m3	Annual	5	Annual	15
				24 hrs	15	24 hrs	45
House A Langloan	Min-Max 0.01 – 5.67	Min-Max 0.31 – 2.67	Min-Max 0.07 – 0.56	Min-Max 2 - 27		Min-Max 3 - 30	
House B Kilkliston	Min-Max 0.00 – 0.10	Min-Max 0.31 -0.75	Min-Max 0.07 – 0.15	Min-Max 0 - 830		Min-Max 0 - 980	

4.3 ANALYSIS OF INDOOR POLLUTANT

Table 4 shows the level of indoor pollutants in both houses, also graphically depicted in figure 8 and figure 9. The range of formaldehyde pollutant level in Langloan house is from 0.01–5.67, well above the recommended benchmark, while the level in the Kilkliston house ranges from 0.00 to 0.10 and below the recommended value by WHO. The range of TVOC level in both houses is above the WHO recommendation. In contrast the measured levels of benzene pollutant in houses A and B are well below recommended benchmark.

Measured data shows that Pm2.5 pollutant in House A ranges from 2 to 27, slightly above the world health organisation guidelines (WHO, 2021) while in House B the level ranges from 0 to 830. This is extremely above the WHO guideline maximum level of 15 ug/m3, although this was for a very short period as illustrated in figure 9.

The level of PM10 pollutants in House A ranges from 3 to 30, this is within the acceptable guideline or benchmark of the WHO, however, the level of PM10 of House B ranges from 0 to 980, this is extremely far above the acceptable WHO benchmark or guidelines.

Comparing houses, A and B results, the levels of PM2.5 and PM10 in House A are relatively low and within the WHO benchmarks as these could be attributed partly to the fact that the building is less than 10 years old and partly to occupants’ pattern of use. While in House B, the levels of PM2.5 and PM10 are extremely higher than the WHO benchmark even though for a very short period over a 24-hour period (between 17.38 and 20.07). One explanation for the spike in PM10 and PM2.5 in house B may be partially explained by the timing which coincides with dinner time and associated cooking and other household activities.

5. Questionnaires results

For the purposes of this paper, data analysis will be focused on indoor air quality, sources of indoor pollutants and occupants’ perception of /satisfaction with indoor thermal comfort and ventilation. However, the questions centred on the building IAQ and indoor pollutant sources. The responses to the questions related to the building indoor air quality and sources of indoor pollutants are illustrated in Table 4 below. A copy of the questionnaire is available in Appendix 1.

TABLE 4. Percentage of Building indoor air quality and sources of indoor pollutants

	Pollen Sources	Animal dander	Dust	Allergic to mould	Air freshener
Strongly Agree	36.96%	45.65%	60.87%	63.04%	52.17%
Somewhat agree	24.00%	24.00%	14.67%	14.67%	14.67%
Strongly Disagree	7.02%	1.75%	1.75%	3.51%	5.26%
Somewhat Disagree	3.75%	1.87%	3.75%	3.75%	7.49%
Neither agree nor disagree	9.69%	7.75%	7.75%	3.88%	7.75%

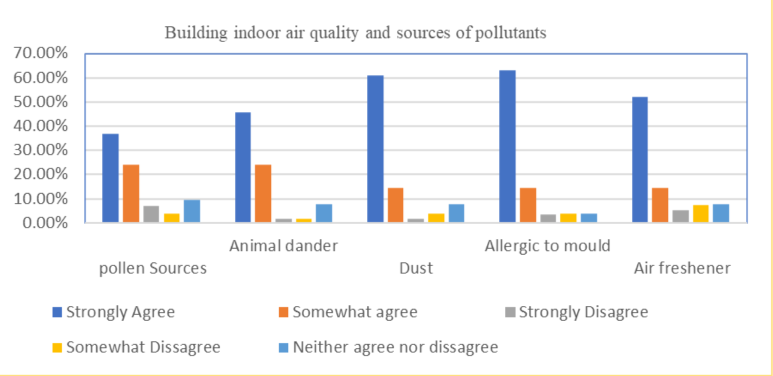

Figure 10. Building indoor air quality and sources of indoor pollutants

Occupants' perception/satisfaction with indoor thermal comfort and ventilation are shown in the Table 5 below. The responses were based on how satisfied or dissatisfied by the indoor thermal conditions, heating and cooling, air movement (high/low), indoor humidity (dry or wet) and overall airtightness perception.

TABLE 5. Percentage of Occupants perception of indoor air quality and Ventilation

	Uneven temperature	Hot/cold surfaces	Heating/ cooling	Air movement too high	Air movement too low	Dry humidity	Wet humidity	Overall airtightness
Dissatisfied	21.74%	23.91%	18.37%	21.74%	34.78%	15.22%	32.61%	13.04%
Neither satisfied nor dissatisfied	10.98%	8.64%	17.98%	12.20%	21.05%	14.12%	16.88%	3.49%
Satisfied	30.14%	29.73%	21.92%	25.00%	21.67%	24.66%	23.44%	30.12%
Very Dissatisfied	5.88%	7.69%	1.75%	5.56%	0.00%	3.64%	6.12%	6.90%
Very Satisfied	4.17%	4.17%	12.50%	9.80%	2.13%	13.21%	0.00%	14.81%

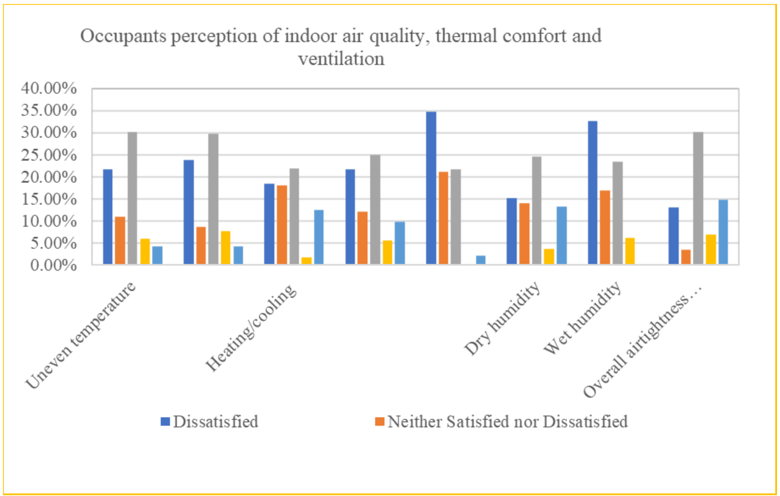

Figure 11. Occupants Perception of indoor air quality, thermal comfort, and ventilation

5.1 DISCUSSION OF QUESTIONNAIRE RESULTS

The analysis in this section discusses the questionnaire's response with respect to sources of indoor air pollution in domestic buildings as illustrated in Table 4 and Figure 11 above. Regarding the effect of pollen and plants and their impact on indoor air pollution, the responses indicate that about 36.96% strongly agree that they contribute to the indoor air pollution while about 3.75% somewhat disagree. Furthermore, 45.65% strongly agree on the effect of animal dander contributing to the indoor environment pollution. 60.87% responded strongly agree that formation of dust in the building contribute to the indoor pollution. On the other hand, 63.04%, strongly agree that condensation and dampness lead to allergies related to mould and about 52.17% strongly agree on the impact of air fresheners on indoor air pollution.

Responses related to uneven temperature distribution in the different houses show (Figure 11), only 30.14 + 4.17% were satisfied or very satisfied which leaves about 65% either dissatisfied or unsure. In response to heating/cooling, a crude indication of thermal comfort, 21.92% responded satisfied. However nearly a third felt unsatisfied and another third unsure. This seems to indicate that at least two thirds of respondents are not fully happy with their thermal conditions. In response to air movement being too high 25% are satisfied. Also, when air movement is too low, responses show that 34.78% are dissatisfied and 21.67% response satisfied. These results are variable, and it is difficult to draw any clear results. As for dry humidity conditions 24.66% are satisfied, while on the wet humidity conditions 32.61% are dissatisfied. The response on the overall airtightness, shows that 30.12% are satisfied with the overall airtightness.

Meanwhile, from the measurements conducted from the two houses, the average parameters measured (Table 3 above) include CO_2, temperature, relative humidity, air velocity and indoor air pollutants such as TVOC, HCHO, C6H6, PM2.5 and PM10. The average CO_2 for House A, Langloan is 689ppm, while the maximum value is 2290ppm and the average CO_2 for House B, Kilkliston is 618ppm and the maximum value is 971ppm. The average temperature for house A is 24 °C, average relative humidity is 35% and average air velocity 0.9 m/s. Meanwhile the average temperature for House B is 23 °C, average relative humidity is 38 % and average air velocity 0.06 m/s.

6 Conclusions

In conclusion this paper has attempted to address the impact of airtightness and low ventilation on the indoor air quality in domestic buildings. Data presented in this paper and hence related findings only represent partially the outcomes of the full PhD research which is still ongoing.

The assessment of the fabric of the two dwellings seems to indicate that recently built housing stock overall fabric thermal performance is good (EPC band B) compared to houses build 30 years ago (EPC band E). Despite such an improvement, the fabric performance of recent and currently built housing in Scotland remains short of band A target. This will make any retrofitting upgrades more onerous and costly if climate change targets are to be met.

Indoor air pollution measurements indicate that most parameters are within the WHO standards as measured over a 24-hour period and provide healthy conditions. The sample is too small to draw any reliable general conclusions and future analysis of the full set of data is needed. In contrast, the initial and partial findings from the questionnaire seem to paint a mixed picture. No conclusive opinions were made by respondents with regards to Min-Max values of the areas covered. The highest positive or negative response percentage was around 60% which leaves at least 40% with an opposite or unsure opinion.

The two main factors investigated in this paper, namely airtightness and ventilation, remain inconclusive from the questionnaire responses. However, when contrasted with the fabric and key indoor parameters data, both factors seem adequate for the limited sample size.

Further investigation will be carried out with a larger sample size to assess in further detail the impact of ventilation and air tightness in indoor environment given the fact that new build as well as retrofit are expected to be more airtight and even better insulated to try to meet carbon neutrality targets.

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CROSS LAMINATED TIMBER VS CONCRETE – A COMPARATIVE LIFE CYCLE ASSESSMENT OF A RESIDENTIAL CASE STUDY BUILDING IN IRELAND

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Abstract. With the construction and built environment sector equalling the agricultural sector as the highest emitting industry in Ireland, new and more sustainable methods of construction should be explored. CLT is a building material growing in popularity worldwide and may be a suitable replacement for concrete. This study focused on a comparative life cycle assessment (LCA) of an Irish residential case study building to determine the amounts of CO_2 that can be saved using Austrian sourced CLT and locally sourced CLT. Further on in the study, design for deconstruction (DfD) was explored as a method of additionally decreasing the potential emissions that are associated with construction using CLT. To test this, models were created in a building information modelling (BIM) program, Revit, and assessed using the LCA software, Tally. The results of this study resulted in the existing building's global warming potential (GWP) being over 2,500,000 kg CO_2eq. LCAs show a 52% reduction in GWP if the existing concrete structural system were to be replaced with Austrian sourced CLT. With high transportation emissions tied to this design option, hypothetical Irish CLT would further reduce the emissions of this building by ~80,000 kg CO_2eq. For the CLT options, the end-of-life stage has the highest emissions. This is due to the scope for CLT included in the LCA software used. Calculations were carried out which showed that a further ~440,000 kg CO_2eq would be saved if DfD were implemented in the Irish CLT design option.

Keywords: Life Cycle Assessment (LCA), Concrete, Cross Laminated Timber (CLT), Design for Deconstruction (DfD), Tally.

1 Introduction

During the Celtic Tiger years, residential construction in Ireland peaked. In 2006, over 90,000 dwellings were constructed in Ireland, however, in the years following, residential construction effectively halted and in comparison, only 11,000 new dwellings were constructed in 2014 (Downey, 2022). This dramatic change has resulted in a serious lack of housing for residents in Ireland. Currently, the government's Housing for All plan states the need for over 300,000 new homes by 2030, meaning that the yearly requirement for new homes is 33,000 units (Department of Housing, 2021).

To meet such a high requirement, the modern methods of construction in Ireland must be explored. Currently, the most widely used material for producing primary structures is concrete. According to Kuijpers (2020), concrete is used in half of all buildings in the world with 70% of the world's population living in a concrete structure. This extensive use of concrete does not come without certain disadvantages, such as its production process which has a massive environmental impact (Kuijpers, 2020). The highest polluting element is cement, which is the main ingredient of concrete. Every tonne of cement created produces 822kg of CO_2. This means that since 1928, an estimate of over 38 billion tonnes of CO_2 have been produced due to concrete worldwide (Andrew, 2019).

Studies comparing the embodied carbon emissions of multiple buildings can provide valuable information on what is expected when using a particular structural material. Kaethner and Burridge (2012) examined the embodied carbon of construction elements in concrete office buildings, with the superstructure contributed to 42%, construction 16%, substructure 13%, external cladding 13%, floor finishes 7%, partitions 4%, and other finishes 2%. The results provide the authors with a claim that structure should be the first area of focus when exploring a reduction in embodied carbon for a concrete building as, if construction is included, structure produces an average of 71% of a building's total embodied carbon emissions.

With concrete's high CO_2 emissions, it is important to look at Ireland's environmental goals. Ireland's construction and built environment sectors equal the agricultural sector for the highest emitting industry at 37% of Ireland's CO_2 emissions with 14% of the 37% coming from the production and transport of buildings and their materials (Department of Housing, 2022a). The construction industry is to reduce its carbon emissions by 29-41% by 2030 (Department of the Taoiseach, 2021). This means that a sustainable replacement for concrete must be found if these targets are to be met. Recent advancements in timber engineering have resulted in high-performance engineered wood products (EWPs), enabling the construction of taller, safer, and more cost-effective timber buildings. EWPs such as glue laminated timber (Glulam) and cross laminated timber (CLT) have been used to construct structures of up to 24 stories proving their ability to be a replacement for traditional construction materials such as steel and concrete (COFORD, 2022).

To compare with concrete, there are several publications relating to the excellent environmental performance of timber (Zeitz et al., 2019; Younis and Dodoo, 2022). Saade et al. (2020) compared the results of published papers that deal with this topic. 5 out of 6 papers resulted in timber frames having lower embodied carbon than steel, 14 out of 22 papers concluded that concrete structures had a lower embodied carbon than steel, and 8 out of 8 papers showed that timber structures had lower embodied carbon than concrete structures (Saade et al., 2020). COFORD (2022) has released a statement to highlight and promote wood products' role in climate change mitigation. Wood products contribute to reducing emissions of buildings through low embodied CO_2, carbon storage and substitution effects.

The literature review revealed that CLT is gaining popularity as a building material worldwide and has the potential to serve as a suitable substitute for concrete. However, there is limited information available on the environmental impact of CLT specifically in an Irish context, particularly regarding the amount of CO_2 that can be saved through its use compared to conventional structural materials. As a result, this study focuses on conducting a comparative Life Cycle Assessment (LCA) of a residential case study building in Ireland to determine the potential CO_2 savings achievable by utilising CLT sourced from Austria or locally sourced CLT. To further increase the recycling potential of CLT at the end-of-life, this study also explores the methods of Design for Deconstruction (DfD) based on the findings of project InFutUReWood (Cristescu et al., 2020).

There are four main objectives of this study. Firstly, a BIM model of the case study apartment block was constructed to represent three construction types; existing – cast-in-place concrete, proposed – CLT sourced from Austria and proposed – CLT hypothetically sourced from Ireland. The next objective was to conduct LCAs of the three selected construction types. The third objective was to explore DfD methods to increase the circularity of the mass timber buildings at the end-of-life stage and calculate the difference this will have on the LCA result of the Irish CLT design option. The final objective was to determine a hierarchy of highest to lowest global warming potential construction types. Overall, this research aims to address the existing knowledge gap by investigating the environmental impact of CLT as a building material in an Irish context, with a specific focus on CO_2 savings. The study explores various design options and considerations to determine the most environmentally friendly and sustainable approach to construction, taking into account the use of CLT and potential DfD elements.

2. Methodology

2.1. LIFE CYCLE ASSESSMENTS

2.1.1. LCA Process

To compare the carbon emissions of a building throughout its lifetime, LCAs are carried out as set out by the National Building Specification (NBS, 2012) in BS EN 15978. The plan for completing an LCA is set out by the International Organization for Standardization (ISO, 2020) in ISO 14040 through 14044, which define the methods of calculating the results.

There are three types of LCAs: a cradle-to-gate LCA includes stages one to four, cradle-to-utilisation includes stages one to six and cradle-to-grave includes all seven stages. For this research, the cradle-to-grave approach to LCAs was used and the building's lifetime was selected as 60 years.

2.1.2. LCA Software & Methodology

The LCAs conducted in this study were performed using the Revit plug-in Tally. Tally uses the GaBi 2018 datasets to conduct life cycle assessments and generates results based on the TRACI 2 characterisation scheme's impact categories, for example, global warming potential (GWP). The process of performing an LCA with Tally is depicted in Figure 1. The first step is to define the materials within the project. Tally allows for a partial LCA and a full LCA, which was selected for this study to allow for changing elements within the building such as insulation thickness when utilising Timber. The end goal for an accurate LCA is to have all elements highlighted with a green circle, meaning that all materials are connected to related materials within Tally's databases. This process was carried out three times to gather the results for the concrete building, the CLT sourced from Austria building and the CLT sourced from Ireland building.

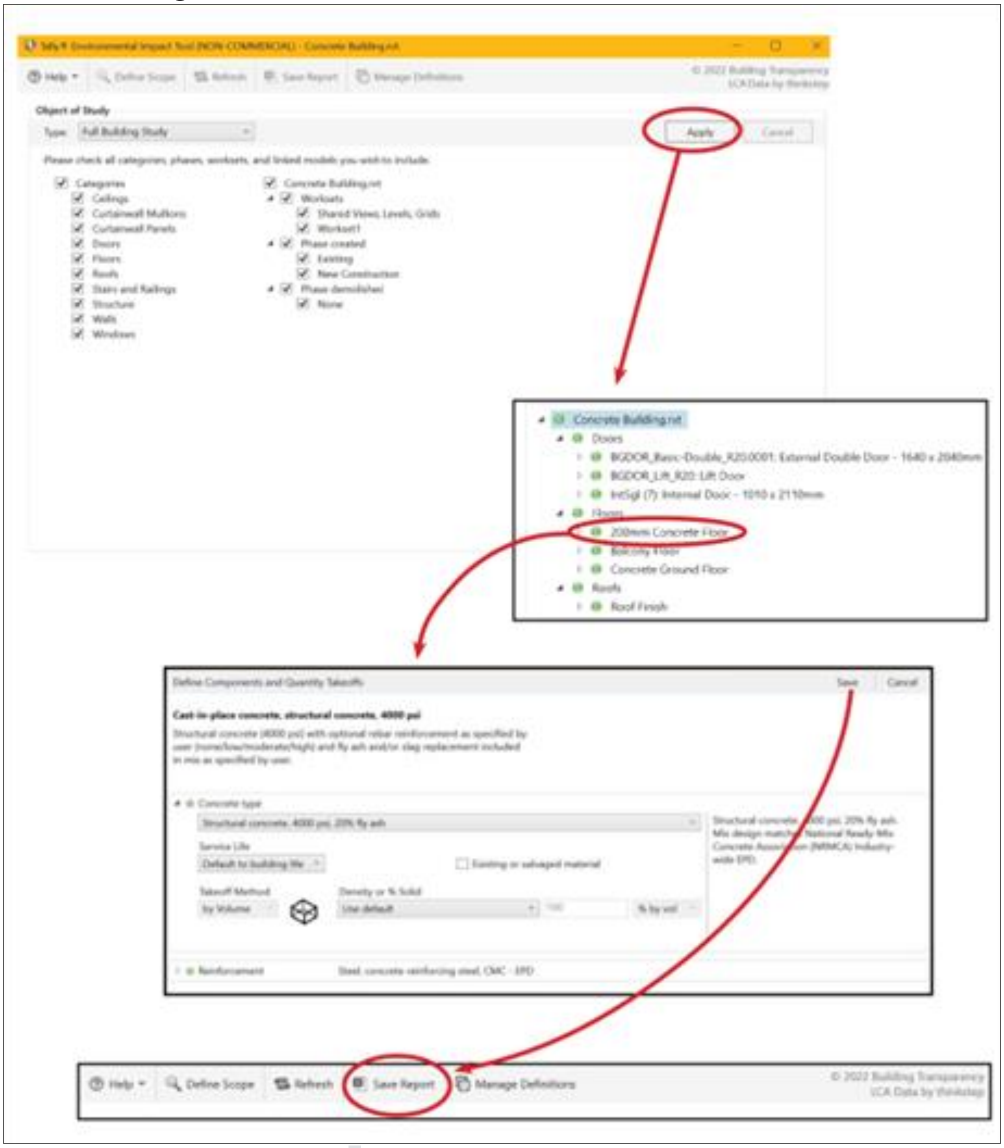

Figure 1: Process of Completing a Tally LCA

2.1.3. One Click LCA Carbon Heroes Benchmark

As a method of presenting the performance of the building design options, One Click LCA's 'Carbon Heroes Benchmarking' (Figure 2) was used. One Click LCA uses thousands of verified projects to create a grading system depending on the type of project and the location of the project.

The grade of a building is achieved through a simple calculation of dividing the global warming potential by the area of the building ($kgCO_2eq/m^2$). The result is a figure which will fall under one of the grades of the relevant category.

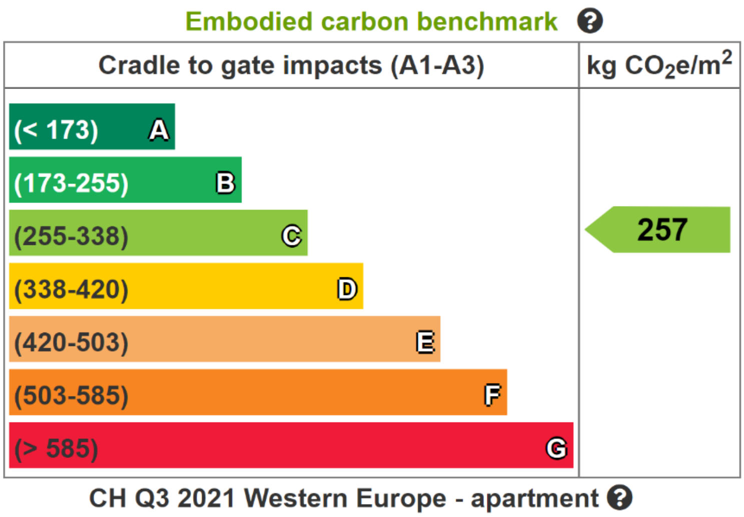

Figure 2. Carbon Heroes Benchmarking

2.2. CASE STUDY

As this study is centred around a comparative analysis between concrete and CLT construction, it is important to select a case study building that can be used to accurately assess these design options without changing the remaining elements of the building. Using Revit, the structure can be easily replaced, which aligns with the scope of this study.

The case study in question is a five-storey apartment block of cast-in-place reinforced concrete construction. The building has a gross floor area of 4096m² and is located in Rathfarnham, Co. Dublin. The building was completed in December 2022 and is designed by John Fleming Architects, who kindly gave access to the construction information and drawings which were used to construct accurate BIM models.

2.3. CONCRETE

The first Revit model that was constructed was the existing, cast-in-place reinforced concrete building. The building has 200mm thick concrete slab floors, 200mm thick concrete slab walls and 150mm thick concrete slab walls on the top level.

As per the supplied technical information, the wall build-up is 102.5mm brick, 50mm cavity, 110mm insulation, 200mm reinforced concrete, 25mm mineral wool and a 12.5mm gypsum wallboard. The U-value of this wall was calculated to be 0.18 w/m² K, shown in Table 1, which meets the standards (Department of Housing, 2022b).

TABLE 1: Concrete Wall U-Value Calculation

Layer	Description	Thickness (m)	Thermal Conductivity λ(W/mk)	Thermal Resistance (m^2K/w)	
1	Rse	na	na	0.04	
2	Brick	0.1025	0.96	0.107	
3	Cavity	0.05	0.17	0.294	
4	Insulation	0.11	0.034	3.235	
5	Concrete	0.2	0.2	1.000	
6	Mineral Wool	0.025	0.034	0.735	
7	Plasterboard	0.0125	0.13	0.096	
8	Rsi	na	na	0.13	
	Total R			5.638	
	U-Value			0.177	w/m^2k
	U-Value			0.18	w/m^2k
	Overal Wall Thickness	0.5			

It is important to note the travel distances associated with concrete construction which come out to 3.7km, a six-minute drive by mixer truck to the nearest concrete supplier, Kilsaran.

2.4. CLT (AUSTRIA)

Following the concrete model, the next model replaced the concrete elements with CLT panels sourced from Austria. The build-up is as follows; 200mm CLT panel floors, 200mm CLT panel walls, 140mm CLT panel top-level walls and a reinforced concrete ground floor The reasoning behind the remaining concrete ground floor is to reduce ground contact with the timber. This prevents fungus, moisture, rot and insects.

The wall build-up remains the same as the concrete building, except for the structural elements. This results in a significant change in the U-value of the walls with a result of 0.16 w/m2 K, shown in Table 2. The increase in the wall's performance comes from the improved thermal conductivity of CLT in comparison to concrete. This allows for a reduction in the amount of insulation needed throughout the building, which will greatly reduce the emissions of the building. With a reduction of 30mm of insulation throughout the building, the wall's U-value meets the minimum requirements of 0.18 w/m2 K (Table 3) (Department of Housing, 2022b).

Table 2: CLT Wall U-Value Calculation

Layer	Description	Thickness (m)	Thermal Conductivity λ(W/mk)	Thermal Resistance (m²K/w)	
1	Rse	na	na	0.04	
2	Brick	0.1025	0.96	0.107	
3	Cavity	0.05	0.17	0.294	
4	Insulation	0.11	0.034	3.235	
5	CLT	0.2	0.12	1.667	
6	Mineral Wool	0.025	0.034	0.735	
7	Plasterboard	0.0125	0.13	0.096	
8	Rsi	na	na	0.13	
	Total R			6.304	
	U-Value			0.159	w/m²k
	U-Value			0.16	w/m²k
	Overal Wall Thickness	0.5			

Table 3: CLT Wall U-Value Calculation (Reduced Insulation)

Layer	Description	Thickness (m)	Thermal Conductivity λ(W/mk)	Thermal Resistance (m²K/w)	
1	Rse	na	na	0.04	
2	Brick	0.1025	0.96	0.107	
3	Cavity	0.05	0.17	0.294	
4	Insulation	0.08	0.034	2.353	
5	CLT	0.2	0.12	1.667	
6	Mineral Wool	0.025	0.034	0.735	
7	Plasterboard	0.0125	0.13	0.096	
8	Rsi	na	na	0.13	
	Total R			5.422	
	U-Value			0.184	w/m²k
	U-Value			0.18	w/m²k
	Overal Wall Thickness	0.47			

CLT sourced from KLH Massivholz in Austria has a large distance to travel to reach the site. The CLT panels must travel 1770km from Austria to England by truck, 230km by container ship from England to Ireland and a further 33km by truck from Dublin Port to the site. This totals a distance of 2033km of travel that the panels require.

2.5. CLT (IRELAND)

The final variation of the building's design is of CLT panels but hypothetically sourced from Ireland. This means that the build-up and U-value exploration of the previous design option stands true to this option.

Currently, Ireland does not have a CLT manufacturer but with Irish timber being utilised for mass timber construction, the building's emissions could be reduced. The selected location of the hypothetical manufacturer is Kerry. This was chosen to show the reductions in emissions even if the manufacturer was not near the site.

The travel distance of the CLT hypothetically sourced from Ireland is 328km, a four-hour drive by truck.

2.6. DESIGN FOR DECONSTRUCTION (DFD)

When analysing the results of the LCAs, the author noticed that the majority of emissions produced from the two CLT design options were from the end-of-life stage. The author wanted to explore how the results of the LCAs would change if DfD was implemented into the buildings. The first step was to look at Tally's CLT end-of-life scope. This showed that, according to the LCA, 14.5% of CLT in the buildings is recovered, 22% is incinerated and 63.5% is sent to landfill. This led to the calculation of how much kg CO_2eq is to be saved if the CLT that was meant to be sent to the landfill was to be recovered and reused instead.

2.6.1. Background

The primary method for DfD is the use of mechanical connectors, highlighted in Figure 3 and Figure 4, rather than connections using adhesives. The author explored this through research on the topic and developing an understanding of how these connections work. It was found that the most common ways of CLT connecting are through steel L-brackets and self-tapping screws. The latter of which would produce fewer emissions due to the reduced usage of steel.

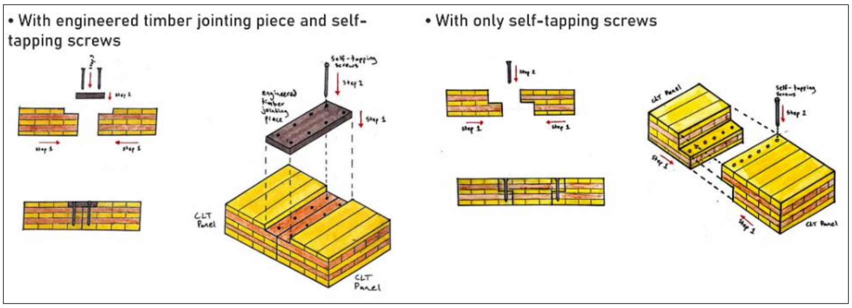

Figure 3. Showcase of Two DfD Methods of CLT Floor-to-Floor Connection

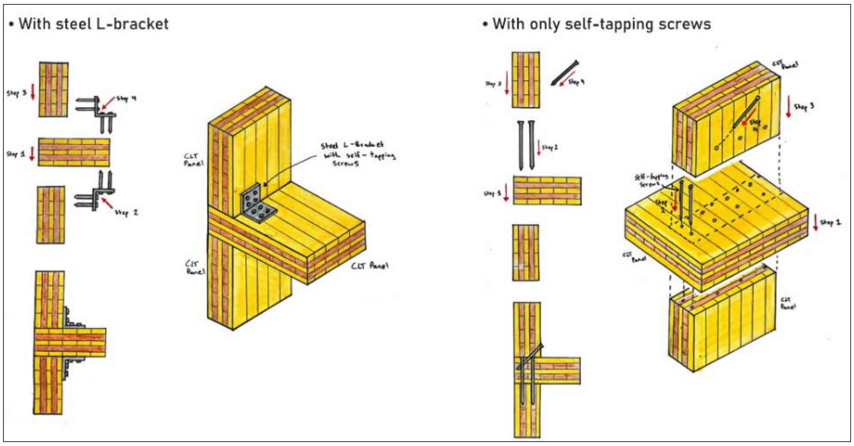

Figure 4. Showcase of Two DfD Methods of CLT Wall-to-Floor Connection

2.6.2. Calculations

To calculate the impact of DfD, the author extracted figures from LCA charts and graphs produced by Tally. Through calculation, a result was achieved, see Figure 5.

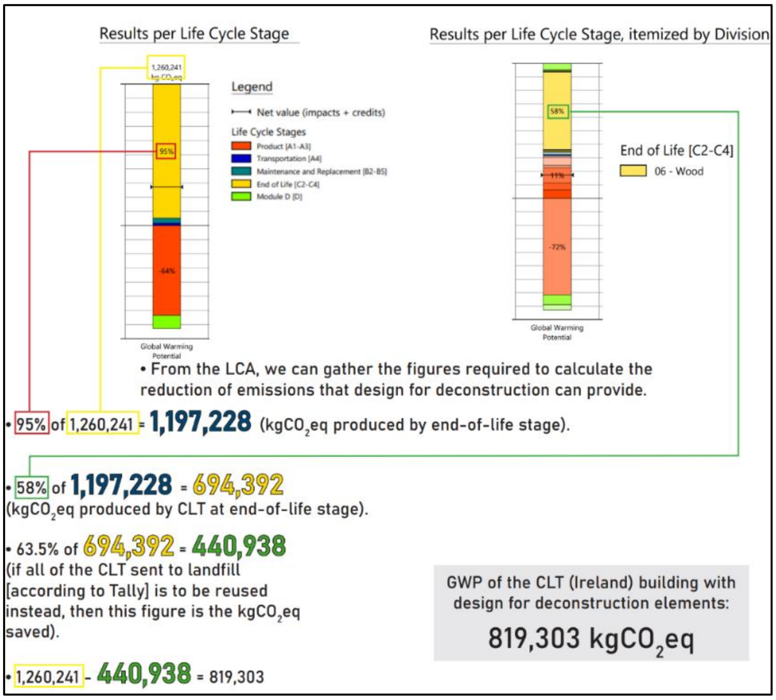

Figure 5. CLT (Ireland) with DfD Calculation

Note. Method of using the LCA results to calculate the amount of CO_2eq to be saved through the use of DfD in the CLT (Ireland) design option.

3. Results and Discussion

The results of the three LCAs (Concrete, Austrian CLT and Irish CLT) and how the implementation of DfD affects the Irish CLT building provided key figures which can be used to explore how much CO_2 can be saved by using CLT instead of concrete for residential buildings in Ireland.

3.1. CONCRETE BUILDING

Key figures found in this LCA:

- 2,574,205 kg CO_2eq was produced throughout the lifetime of this building.
- 85% of GWP emissions come from the production stage.
- 9% of GWP emissions come from the end-of-life stage.
- Concrete causes 58% of the building's material emissions.
- Metals cause 27% of the building's material emissions, this includes concrete reinforcement.

To explore how this building ranks compared to similar projects, the Carbon Heroes Benchmark was calculated. The building received a figure of 628 which equated to an 'E' rating for an apartment block in Western Europe.

3.2. AUSTRIAN SOURCED CLT BUILDING

Key figures found in this LCA:

- 1,346,337 kg CO_2eq was produced throughout the lifetime of this building.
- Production stage provides a 54% or 807,802 kg CO_2eq reduction to the building's GWP.
- 89% of GWP emissions come from the end-of-life stage.
- 8% of GWP comes from the transportation stage.
- Concrete causes 31% of the building's material emissions.
- Metals cause 16% of the building's material emissions.

The Carbon Heroes Benchmark that this building received is a 'B' rating of 328 when assessed to comparable projects.

3.3. IRISH SOURCED CLT BUILDING

Key figures found in this LCA:

- 1,260,241 kg CO_2eq was produced throughout the lifetime of this building.
- Production stage provides a 64% or 806,554 kg CO_2eq reduction to the building's GWP.
- 95% of GWP emissions come from the end-of-life stage.
- 2% of GWP comes from the transportation stage.
- Concrete causes 31% of the building's material emissions.
- Metals cause 16% of the building's material emissions.

The Carbon Heroes Benchmark that this building received is a 'B' rating with 307 when assessed to comparable projects.

3.4. IRISH SOURCED CLT BUILDING WITH DFD

If the building with Irish sourced CLT were to have DfD elements incorporated, then, according to the completed calculations, the total building emissions would be 819,303 kg CO_2eq. This result receives the highest Carbon Heroes Benchmarking rating for a Western Europe apartment block with an ‘A’ grade and a score of 200.

3.5. COMPARISON OF RESULTS

Starting with the overall emissions of the building, changing the structure from concrete to CLT reduces the building’s GWP by about 52% or 1,227,868 kg CO2eq. The use of locally sourced CLT further reduces the GWP by 86,096 kg CO2eq, as depicted in Figure 6.

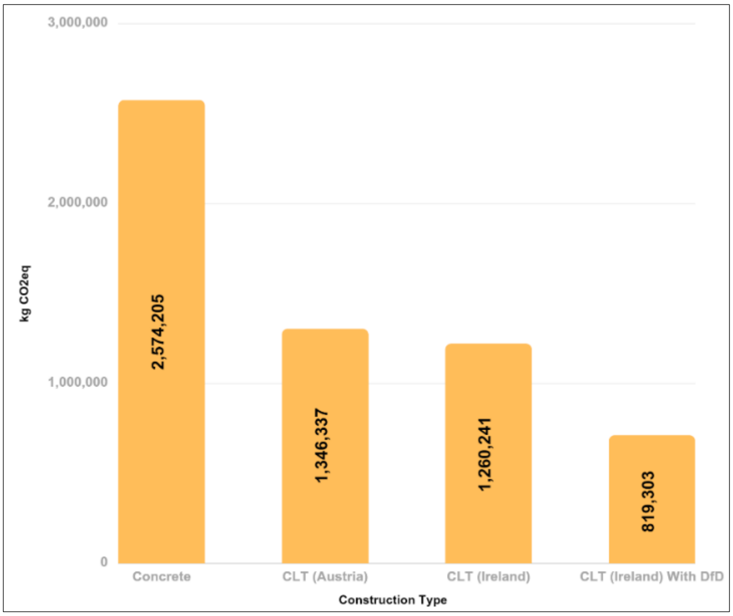

Figure 6. Bar Chart Comparison of GWP

There is a large variation between the design options when assessing the emissions by life cycle stages. With the concrete building, the production stage is by far the highest emitting stage at 85%. The use of CLT reduces this stage’s emissions to zero and even decreases the building’s overall emissions by about 800,000 kg CO_2eq due to timber’s sequestered carbon properties, as shown in Figure 7.

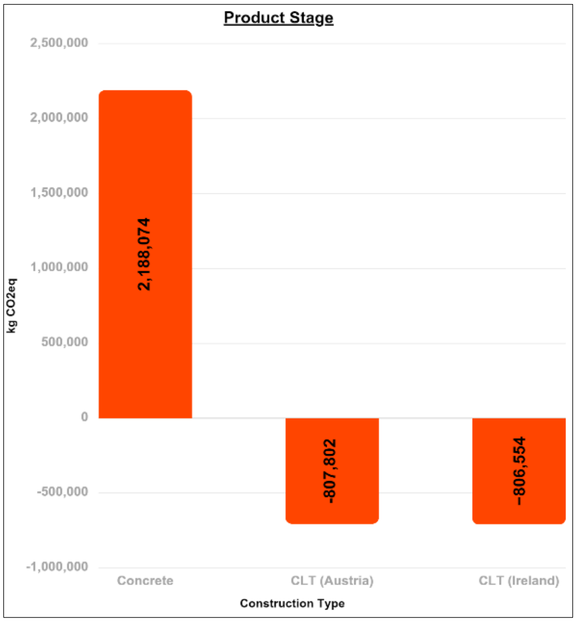

Figure 7. Bar Chart Comparison of Product Stage Emissions

The transportation stage for the concrete building holds a minimal portion of the emissions for the building at 12,871 kg CO_2eq but for the Austrian CLT building it is 8%, or 104,168 kg CO_2eq. This is reduced to 2%, or 24,391 kg CO_2eq, of the building's emissions if the CLT were to be sourced from Ireland. The Irish CLT has higher transport emissions than the concrete building due to the location of the hypothetical manufacturer. With a local manufacturer, emissions can be equal to or even less than concrete, see Figure 8.

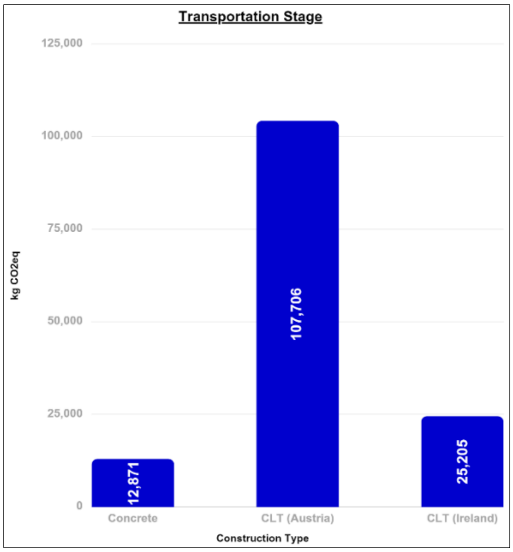

Figure 8. Bar Chart Comparison of Product Stage Emissions

The most significant stage for CLT buildings is the end-of-life stage at 89% and 95% of the Austrian CLT and Irish CLT building's emissions, respectively. This is the reasoning behind the exploration of the implementation of DfD.

The calculation of how much CO_2eq can be saved using DfD for the Irish CLT building saw a reduction of 440,938 kg CO2eq. This figure is if the CLT in the building that was to be sent to the landfill were to be reused. The total GWP of the Irish CLT building with DfD is 819,303 kg CO2eq which is a reduction of 65% for the Irish CLT building's GWP, see Figure 6 above.

The material emissions of the building saw concrete's massive impact even with the significant decrease in its usage in the CLT buildings. The concrete building saw that 58% of its GWP was directly caused by concrete. Despite only the ground floor of the CLT buildings being concrete, the material still held 31% of the two design option's material emissions. This is also true for the emissions tied with metals as more concrete directly impacts the amount of metal reinforcement needed in the building. 27% of the concrete building emissions are linked to metals and for the CLT buildings, this is 16%, see Figure 9.

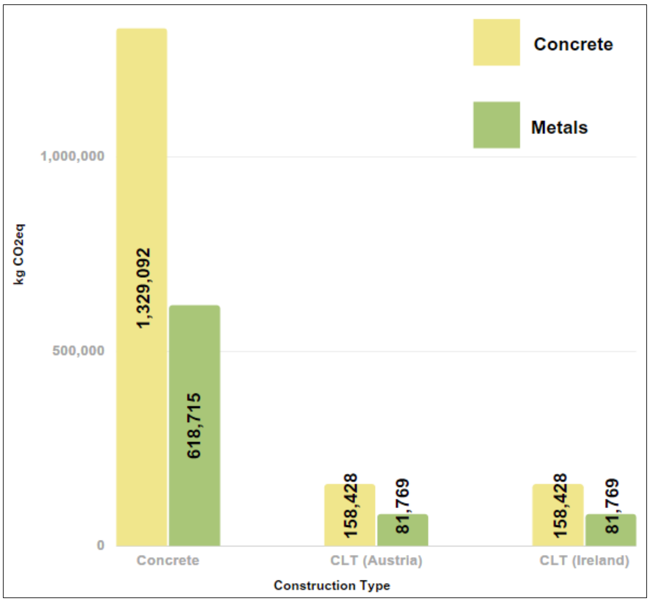

Figure 9. Bar Chart Comparison of Concrete and Metal Related Emissions

At an 'E' Carbon Heroes Benchmarking rating for the concrete building, this design option falls under the 'poor' category. The impact that using CLT is clear when you see that both the CLT design options received a 'B' rating. This rating was once again improved in the Irish CLT building with DfD. The option with DfD scored an 'A' rating which is the highest rating that the benchmark can give in a Western Europe context.

These results clearly show how large of an impact concrete has on the environment. The author believes that CLT should be the new standard structural material due to how much of a difference there is between the materials in terms of CO_2 emissions.

4. Conclusions

This study aimed to compare the environmental results of a concrete frame apartment block, an Austrian-sourced CLT frame apartment block and an Irish-sourced CLT frame apartment block using LCAs. In response to the results, an additional design option was introduced of Irish CLT with DfD implemented. The results of these LCAs allowed for a ranking of each of the design options from highest to lowest GWP.

The results of the concrete building's LCA allowed the author to calculate the building's Carbon Heroes Benchmark result which, in turn, proved that the building's GWP was very high. The LCA results also allowed the realisation of the key areas that caused the building's high GWP.

To begin to resolve the key areas of emissions, an Austrian-sourced CLT design option was introduced. The results of the LCA for this option showed a reduction of about 52% of the building's GWP and the Carbon Heroes Benchmark rating showed this improvement with a 'B' score. The LCA showed that the most prominent life cycle stages for this building were the transport and end-of-life stages.

To further reduce the building's GWP, the transport stage was analysed. With the building's CLT being sourced from an existing manufacturer in Austria, the next step was to have a local source of CLT. Hypothetically sourcing the CLT from Ireland reduces the building's emissions by a further ~86,000 kg CO_2eq. However, this reduction was not significant enough and meant that the building remained at a 'B' Carbon Heroes Benchmarking rating.

In a quest to achieve an 'A' benchmarking rating, a fourth design option was introduced. The author reflected on the highest emitting stage for both the Austrian CLT and Irish CLT buildings which was the end-of-life stage. After analysis of Tally's end-of-life scope for CLT, the author found that the majority of the CLT in these design options was to be sent to a landfill. After research, the implementation of DfD for the Irish CLT building was decided as the fourth option. Calculations were completed which showed a crucial reduction of ~440,000 kg CO_2eq if the previously incinerated CLT was to be reclaimed instead. With the inclusion of elements from the previous design options and the addition of DfD, the fourth option received an 'A' Carbon Heroes Benchmarking rating.

To conclude, it is clear that the concrete design option has the highest emissions, followed by the Austrian CLT option. The Irish CLT option has a slight reduction of GWP compared to the Austrian CLT, but all these options fall short of a sustainable building such as the Irish CLT with DfD design option.

5. Future research

Further work in this area could include the analysis of the cost of the various design options to determine if the environmentally friendly options are financially viable. However, with the growing emphasis on the consideration of sustainable building, the cost may become a secondary thought behind the GWP of a building. Research into the ability to produce mass timber products in Ireland should be completed. Irish mass timber products over imported products could encourage firms to utilise timber construction which, in turn, would be a big step in reducing the GWP of a building as shown in this study. Finally, the speed of construction could be analysed to show whether mass timber construction can further supplement the need for new housing in Ireland.

Acknowledgements

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INFLUENCE OF TRADITIONAL BALCONY GLAZING AND FRAMELESS RETRACTABLE GLAZING ON ENERGY EFFICIENCY AND THERMAL COMFORT OF DWELLINGS IN A DRY MEDITERRANEAN CLIMATE

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Abstract. The need of governments to reduce energy consumption in homes has given rise to a rethinking of architecture from an energy point of view, in which energy is the protagonist material. This research focuses on the thermal behaviour of a passive solar system applied for the energetic rehabilitation of 40+ year old houses in the BShs climate. The effect of a solar gallery to store energy in the form of heat by exploiting the energy potential of the climate is analysed. The study focuses on the effect of terrace glazing as a solar gallery on the thermal behaviour of dwellings. In the on-site measurements of the system, the annual improvement of the hygrothermal conditions of the houses in Alicante is tested. The different measurements are carried out with different orientations, materials and mechanical elements. The aim of this methodology are different solar collection systems that define the type of thermodynamic use. The results show an improvement in the hygrothermal behaviour of the houses. The energetic use of these collectors is reflected in the improvement of the interior comfort of the rooms. The conclusions show that the combination of solar galleries with mechanical ventilation systems such as heat recovery systems reduces energy consumption and improves comfort. The system allows an appropriate use in the different seasons of the year through the application of artificial intelligence.

1. Introduction

This work challenges these regulatory limitations and explores the possibility of using sunrooms as a passive method to heat houses in winter and natural ventilation to cool houses in summer. The thermal behaviour of several homes with the same predominant south orientation with glazed and non-glazed terraces is analysed. The experimental design includes a study of the current hygrothermal conditions of the buildings, and a study of the thermal comfort and energy efficiency of the homes analysed through in situ measurements and computer simulations.
To do this, the energy performance of several homes in the southeast of Spain is studied. On the Spanish Mediterranean coast there have been an abundance of residential buildings with large balconies (Martínez Medina, 2016), which provide a large outdoor place to enjoy the warm and sunny climate of the Mediterranean coast

(Jaén Urban et al., 1999) (Martínez Medina, 2016), in addition, they protect the glazing from the high solar radiation of this geographical area (Chazarra Bernabé et al., 2018). However, the terraces have been progressively glazed over the last decades so that they can be used as indoor spaces throughout the year. In many cases, these glazed terraces are joined to the living room, eliminating the original façade enclosure of the building. In other cases, the original façade enclosure is maintained so the terrace forms an independent and complementary area to the living room (Navas, n.d.). This distribution causes a significant change in the thermal behaviour of the indoor environment, especially in a climate characterized by high annual solar radiation (Aelenei et al., 2014) (Simon et al., 2019). However, these indoor thermal effects are often ignored by homeowners, who do not know or foresee the consequences of those changes on the energy efficiency and indoor thermal comfort of their homes (Borrallo-Jiménez et al., 2021).

Previous research has demonstrated the high greenhouse effect generated by glazed surfaces in the BShs climate (Pérez-Carramiñana, Maciá-Mateu, et al., 2022) and the beneficial effect of natural ventilation to dissipate excess of heat from the indoor environment (O' Donovan et al., 2019). However, there is a lack of studies regarding the important effects (positive and negative) on the energy efficiency and interior thermal comfort of homes due to terrace glazing in this specific climate (Edenhofer et al., 2015). The particularly high solar radiation of the BShs climate (Pérez-Carramiñana, Maciá-Mateu, et al., 2022) requires different energy saving strategies compared to continental and Central European climates (Alhamad et al., 2019). In winter, sunrooms can be used as "sun galleries" to capture the heat of the sun (Pérez-Carramiñana, González-Avilés, et al., 2022) (González-Avilés et al., 2022) and in summer, sunrooms can be opened to take advantage of the benefits of natural cross ventilation to reduce heat (Gao & Lee, 2011). However, regulations and software energy certification does not facilitate the use of this type of passive systems and does not allow the natural ventilation of homes to be considered (AICIA, 2021) (Real Decreto 390/2021, de 1 de Junio, Por El Que Se Aprueba El Procedimiento Básico Para La Certificación de La Eficiencia Energética de Los Edificios, 2021) (MINISTERIO DE FOMENTO, 2019).

2. Materials and Methods

The case studies are located in San Juan Beach, Alicante (Spain).
This geographical area corresponds to the dry Mediterranean climate (BShs) within a warm semi-arid climate (BSh) according to the Köppen-Geiger climate zones [55], and to climate B4 according to Spanish legislation 56. The area has a temperate climate, with mild winters and hot, dry summers. The sea breeze acts as a thermal regulator, reducing the sensation of heat and making it possible to improve comfort and energy efficiency with economical passive methods [57]. However, for this research, the most remarkable aspect of this climate is the high solar exposure during the whole year, with more than 3000 h of sunshine per year (Fig. 1).

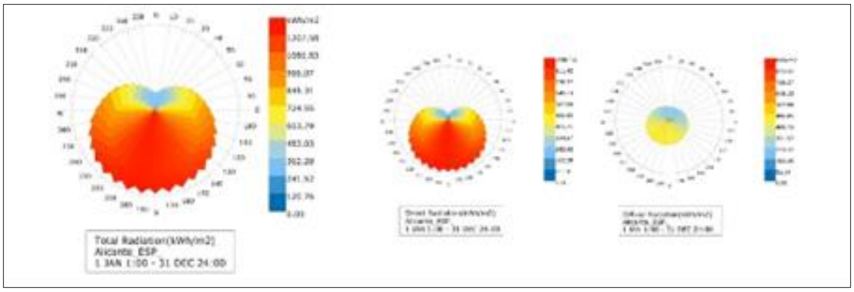


Figure 1. Types of radiation in Alicante

The studied dwellings are a very common type of home in this area. Four homes in the same building with different renovations were studied (Fig. 2).

Figure 2. Energy study building

One of them keeps the original design with the open-air terrace. Another house was renovated by glazing the terrace and joining it to the living room, eliminating the original enclosure that separated the living room from the terrace. The third dwelling was renovated by glazing the terrace but maintaining the original façade windows and enclosures between the terrace and the living room. And the fourth dwelling was refurbished by glazing the terrace with a frameless retractable glazing balcony system (Fig. 3).

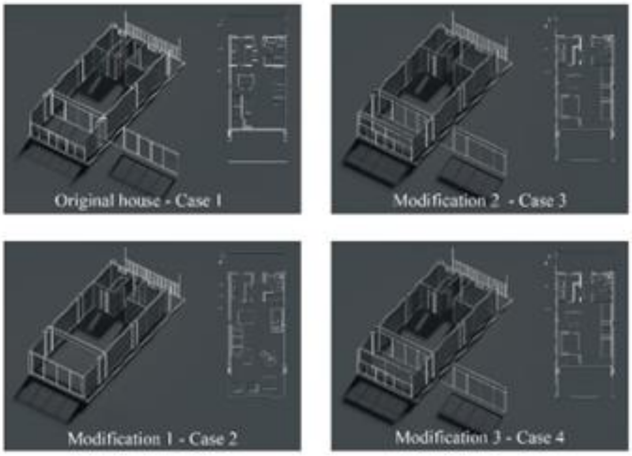


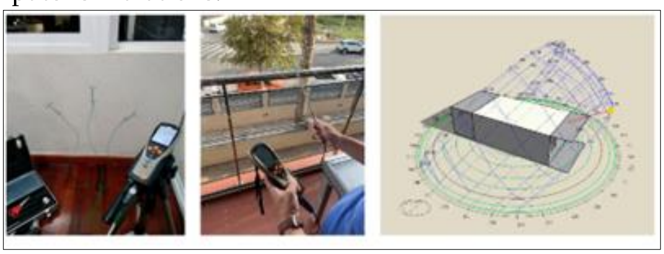
Figure 3. Study cases

In these homes, the orientation of the terrace is always south and without any type of solar control, since in all of them we have the shade of the terraces themselves. All the terraces are adiabatic, and this is considered in the calculation program. In addition, they do not present any type of insulation on their surfaces and the block of buildings is free of any type of external shadow caused by the surrounding buildings.

The height of these apartments is on the third floor. We have defined the thermal envelope in the enclosure in the following table. In in situ measurements and thermal calculations, all heating and cooling devices are disconnected, except in energy calculations, where they are activated to know the improvement of each case.

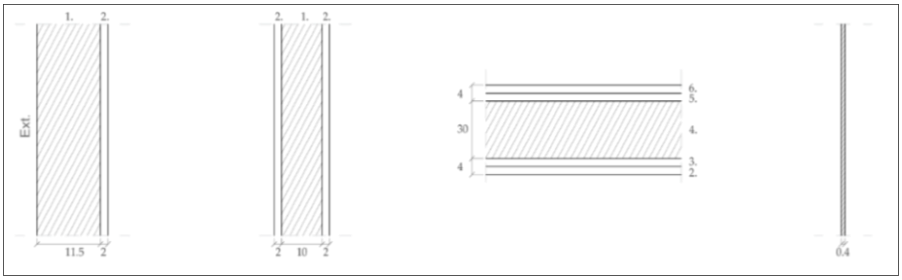
The methodology (Fig. 4) used in this work consisted of three phases. First, a study of the constructive conditions of the thermal envelope of the dwellings was carried out (Table 1). Materials: 1. 1/2 ceramic brick; 2. low-hardness gypsum d < 600; 3. mass concrete 2000 < d < 2300; 4. unidirectional slab with ceramic beams; 5. cement mortar; 6. ceramic tile; 7. monolithic glass, Ug = 5.70 W/m^2 K, g = 0.85; 10. ggl; sh; wi = 0.68; 11. Uf = 2.2 W/m^2 K (dimensions in cm).

Second, a systematised study of current thermal performance, thermal comfort and energy demand of the dwellings was carried out with on-site temperature measurements, surveys of building users and recordings of electricity consumption. Third, some modifications to improve the energy performance of the dwellings were studied by computer simulations.



(a) (b) (c)

Figure 4. Mmethodology: (a) First study; (b) Second study; (c) Third study.



(a) (b) (c) (d)

Figure 5. Current constructive composition of the dwellings: (a) façade constructive section; (b) inner division section; (c) slab section; (d) glazing section.

TABLE *1*. Summary of the construction composition of the thermal envelope in the original house.

Parameter				**Applicable Regulation**
	People/m^2	Metabolic rate	Schedule	DB-HE
Occupation	0.05	1	Activated 24/7	Application Guide 2019 [64]
	Cop	Months	Schedule	DB-HE Annex D
Cooling equipment	4	6/7/8/9	0:00–24:00 27 °C	Operational conditions and
Heating equipment	3.5	½/3/4/5/10/11/12	0:00–24:00 19 °C	use profiles
	Ren/h		Schedule	
Mechanical ventilation	0.44		Activated 24/7	DB-HS3
Natural nocturnal ventilation	0.44		0:00–08:00 100%	
	Average illumination	Power		
Internal lightning loads	200 lux	2 W/m^2	0:00–07:00 10%	Royal Decree 486/1997
			07:00–19:00 30%	Annex IV
			19:00–23:00 100%	
			23:00–24:00 50%	

3. Results and Discussion

From the analysis of the indoor temperature calculations, it was found that the indoor temperatures of the dwelling with open terrace (Dwelling 1) are comfortable for less than a half of the annual hours, i.e., 46%. In addition, the thermal oscillation between the maximum daily temperature and the minimum daily temperature inside the dwelling is approximately 4 °C. The overhang of the external terrace roof protects from solar radiation in summer (Fig. 6), but also reduces solar radiation and heat gains in winter.

By glazing the terrace connected to the living room (Dwelling 2), the thermal behaviour of the dwelling is greatly improved in winter, increasing indoor winter temperatures by about 4 °C. The new glazing in Dwelling 2 does not have the solar shading of the roof overhang as in Dwelling 1 (Fig. 6). This allows comfortable temperatures almost all winter long, between 19 and 27 °C, reducing discomfort hours to 16% in winter. However, the indoor environment in the dwelling overheats in summer, increasing temperatures by 5–6 °C, reaching even to 34 °C and increasing discomfort hours in summer by up to 84%. In addition, the daily temperature variation increases to 5 °C in winter and 6 °C in summer, due to overheating of the external glazing in the middle of the day and cooling at night.

By glazing the terrace separately from the living room (Dwelling 3), the average daily indoor temperatures in winter are increased by about 6 °C compared to the original dwelling. This solution makes it possible to maintain comfortable indoor temperatures almost all winter long, between 19 °C and 27 °C, reducing the hours of discomfort to 8% in winter. Furthermore, this solution reduces the daily temperature variation in winter to less than 1 °C. This is due to the fact that the terrace space, being located between two glazing units, acts as a “thermal buffer” that dampens the temperature difference between the house and outdoors (Fig. 6). On the negative side, the temperature in summer also increases by 3–4 °C compared to the original house, reaching 31 °C and with 88% of discomfort hours in summer.

The solution that offers the best thermal performance inside the house involves glazing the terrace separately from the living room with a balcony frameless retractable glazing system (Dwelling 4). In this solution, the mean daily indoor temperatures in winter are increased by about 8 °C compared to the dwelling 1 without balcony glazed system. This solution makes it possible to maintain comfortable indoor temperatures almost all winter long without the use of heating systems and also reduces the daily and annual thermal oscillation.

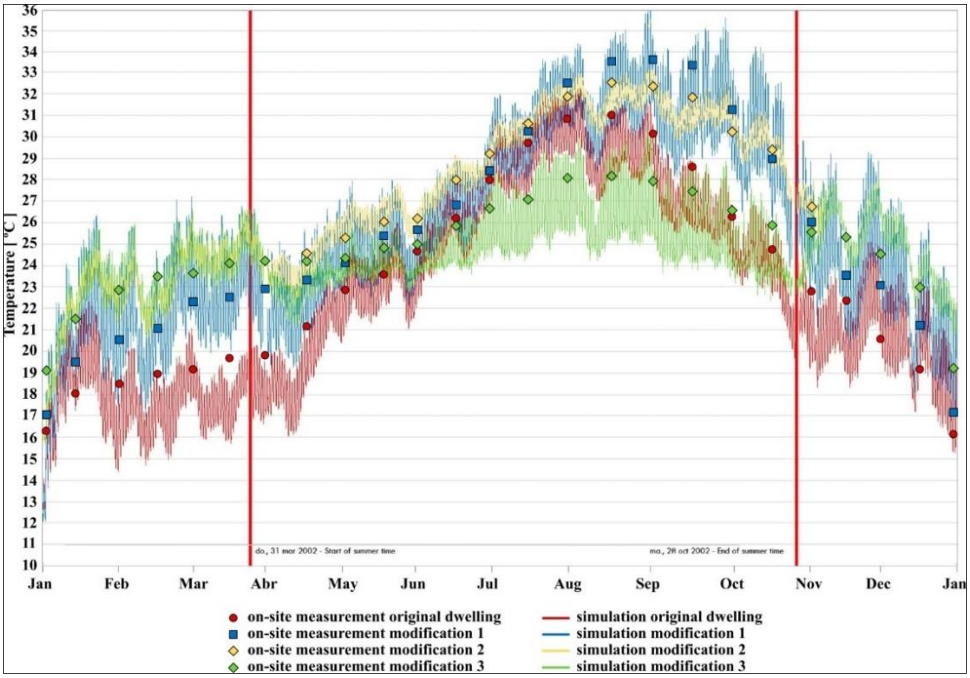


Figure 6. Indoor temperatures considering the four case studies: on-site measurements and simulation results.

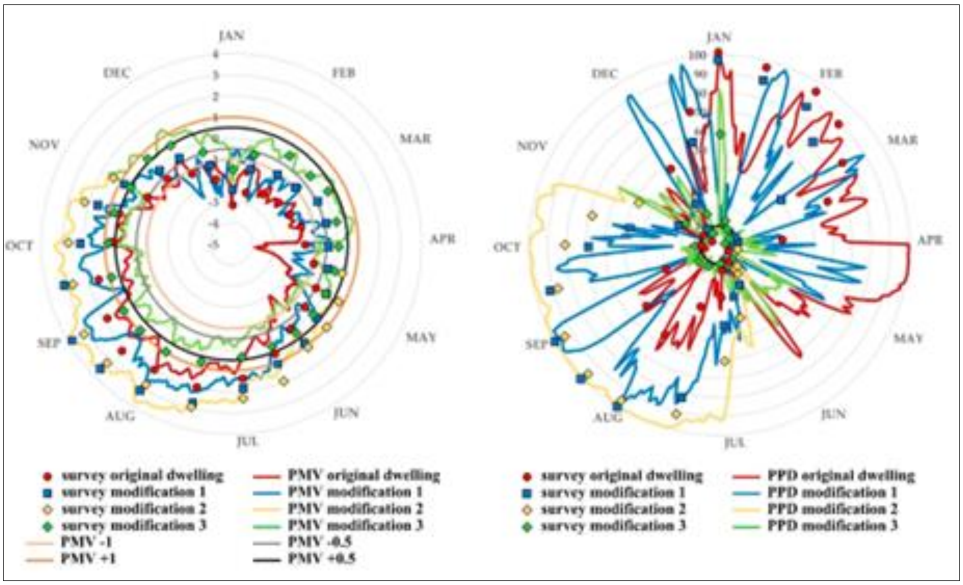
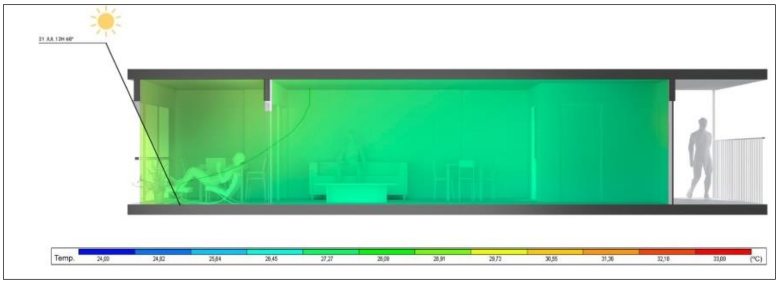


Figure 7. Thermal comfort analysis considering the four case studies: (a) results of user surveys on indoor thermal sensation and predicted mean vote (PMV) calculated using the Fanger analytical method; (b) results of the percentage of dissatisfied according to the surveys and predicted percentage of dissatisfied (PPD) calculated using the Fanger analytical method.

Dwelling 4, with natural ventilation in summer maintains comfortable indoor temperatures throughout the winter and dissipates the heat excess in summer (Fig. 7).

In winter, the free-standing and insulated terrace space creates a “thermal buffer” between the indoors and outdoors. In summer, the balcony frameless retractable glazing system allows the terrace to be completely opened. With this solution, average daily temperature is between 19 °C and 27 °C throughout the year. The only negative aspect is that the daily temperature fluctuation is high in summer due to the dependence of the outside air temperature on natural ventilation (Fig. 8).

This involves peak temperatures of over 29 °C in the hot season and the 28% of the discomfort hours in the summer. Despite this, this solution reduces the annual thermal oscillation, flattening the temperature graph in winter and summer. As a result, a more thermally stable house is achieved throughout the year, reducing annual discomfort hours (Fig. 8).



(a)

(b)

Figure 8. CFD results of indoor air temperature simulation in Modification 3:
(a) July 21; b) December 21.

Finally, as seen in (Fig. 9), applying natural ventilation in modification 3 demonstrates the significant improvement in cooling. Significantly reduces cooling needs in the summer, decreasing by 29%. These results translate to a 57% reduction in total annual energy needs for heating and cooling compared to the original home. The possibility of opening the terrace on hot days helps dissipate heat from the home. In addition, opening the exterior glazing does not contribute to the greenhouse effect, and the overhang of the slab protects the interior of the home from direct solar radiation, reducing the solar heat gains.

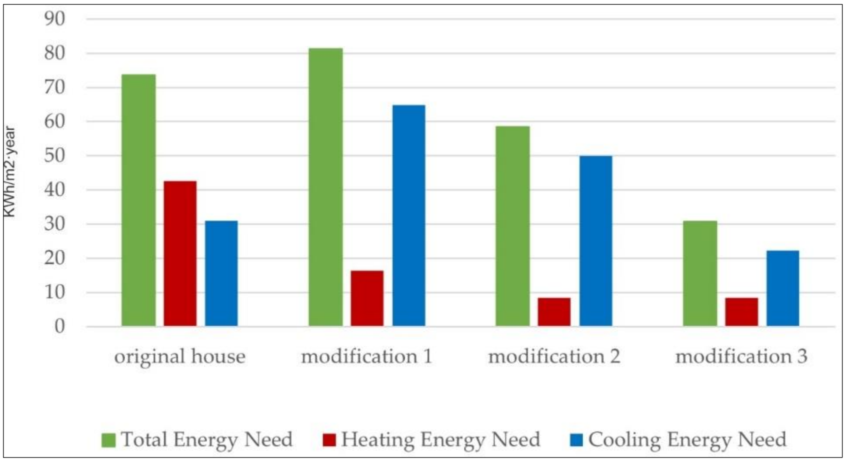


Figure 9. Simulation results of the calculations of heating and cooling demands.

4. Conclusions

(1) The research carried out demonstrates the strong influence of solar radiation on the thermal performance of residential buildings in a warm semi-arid Mediterranean climate (BShs). Therefore, the specific characteristics of this climate, with many hours of sunshine per year, must be taken into account when designing and renovating of dwellings to allow more effective and economical passive solutions.

(2) The glazing of terraces in such buildings influences energy efficiency and indoor comfort. The installation of glazed enclosures on terraces allows the generation of a greenhouse effect to heat the house in winter for free and enables the dissipation of heat excess in summer with natural ventilation.

(3) The typical solution of glazing terraces being connected to the living room improves the energy efficiency of the original house in winter, but greatly worsens its thermal behaviour in summer. The results show that this solution allows heating requirements in winter to be reduced by up to 62%, but cooling requirements in hot weather also increase by up to 110%. As a result, the total annual energy requirement is increased by 10% compared to the original house.

(4) The optimal solution to improve the hygrothermal performance and energy efficiency of the existing dwelling is to glaze the terrace while maintaining the original façade enclosures and windows between the terrace and the living room. With this solution, an intermediate space is created to captures the heat from solar radiation and acts as a "thermal buffer" between the house and the outside in winter. In hot weather, the terrace can be opened to provide natural ventilation to dissipate heat and to protect the interior living space from direct solar radiation by reducing solar gains. Research shows that this solution allows heating requirements in winter to be reduced by up to 80% and cooling requirements in hot weather to be reduced by up to 28%. As a result, the annual energy requirement is reduced by up to 58% compared to the original house, reducing the operational needs of air-conditioning systems and their energy consumption.

(5) The use of balcony frameless retractable glazing systems further improves the thermal comfort and energy efficiency of dwellings. It has been demonstrated that

balcony glazing with a higher proportion of glass and a higher opening capacity offers greater energy benefits.

(6) Indoor thermal performance improvements of the dwelling are greater if glazed terrace remains insulated and separated from the rest of the house in winter and if it is adequately ventilated in summer.

(7) This study demonstrates the effectiveness of passive systems as an alternative to the widespread use of active air-conditioning systems for the hygrothermal control of residential buildings in the BShs climate. The results and conclusions of this work can be extrapolated to many residential and tourist buildings with similar characteristics to the cases studied, adapting the energy rehabilitation methodologies to the characteristics of this specific climate. The results of this work open up the possibility of using terrace glazing as a method of energy rehabilitation of buildings.

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AUGMENTED REALITY IN DECONSTRUCTION: ASSESSING THE POTENTIAL FOR ADVANCING CIRCULAR METHODS

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Abstract. Augmented Reality (AR) is a technology that overlays a computer-generated model onto a user's view of the real world, resulting in an integrated perspective. The purpose of this study was to test the use of AR software as a tool during the deconstruction stage of buildings. It was found that AR can be used to visualise hidden building elements, view corresponding data and implement a Waste Management Plan (WMP) on a deconstruction site. This could play an important part in reducing the amount of Construction and Demolition (C&D) waste sent to landfill by improving the material harvesting process. Firstly, a physical prototype was constructed to test the different capabilities of AR in the context of deconstruction. Key findings from this prototype were then used to format a case study simulation on the deconstruction of a domestic dwelling. The building was modelled using Building Information Modelling (BIM) software, and an in-depth waste management plan was developed for the site using Life Cycle Assessment (LCA) software. Key points from this document such as the building's main waste streams, instructions for sorting wastes, recycling goals and safety measures were then implemented on-site with AR. A potential workflow for developing and implementing a waste management plan was created as a result of this study. The workflow involves utilising BIM to LCA software to obtain material take-offs that include end-of-life environmental impacts. An eco-conscious waste management plan can then be produced that considers the LCA data. Building elements and various main points of this WMP can then be visualised and understood on-site through the use of AR. This system is applicable to hitting goals to reduce the embodied carbon of buildings by improving the organisation of selective deconstruction wastes.

1. Introduction

1.1 OVERVIEW

This paper investigates the potential environmental benefits of using Augmented Reality (AR) technology as a tool during the demolition or structural alteration of a building. The author has researched different deconstruction methods, the process of creating a Life Cycle Assessment (LCA) with Building Information Modelling (BIM) and AR. The author analysed results from a literature review, physical prototyping and a case study that simulated the use of LCA, the development of a Demolition Waste Management Plan (DWMP) and AR to be employed on an end-of-life site.

1.2 RATIONALE

The construction industry is a major contributor to global greenhouse gas emissions; the built environment generates 40% of annual global CO_2 emissions with a significant portion of these emissions (13%) coming from the materials used in building and infrastructure projects (IEA, 2022). The accumulation of carbon in our building is shifting over time. Lowering costs of renewable energy solutions due to policy decisions have already started to reduce the Architecture, Engineering and Construction (AEC) industry's operational carbon. As indicated in Figure 1, with the decarbonization of energy supply, embodied carbon is becoming the primary source of carbon impacts from buildings.

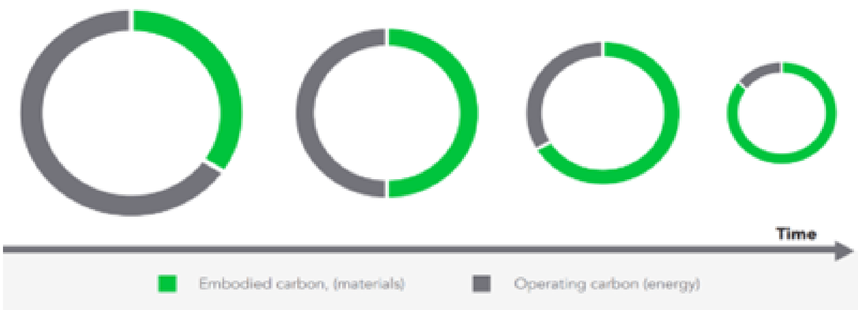

Figure 1. The importance of embodied carbon (materials) grows as operational energy decarbonizes.

In recent years, there has been a growing movement towards a Circular Economy (CE) in the construction industry, with the goal of reducing the amount of material waste sent to landfill and maximizing the use of resources (Spence & Mulligant, 1995) . One potential tool for advancing the CE in the construction industry is the use of AR technology as a tool for evaluating buildings and their materials during the end-of-life stages.

AR allows for the overlay of digital information onto the physical world, and has the potential to revolutionise the way that architects and builders design, visualize, and construct buildings (Azuma, 1997). By providing real-time visualization of building material locations as well as a pre-developed DWMP that was created with emphasis on the Global Warming Potential (GWP) and potential reuse data of the materials, the author tested the potential for AR to help to visualize and plan for the reuse or decommissioning of buildings towards the end of their lifespan.

The motivation for beginning the thesis on the topic of circular deconstruction was driven by the significant impact that the AEC industry has on the environment (Yılmaz & Bakış, 2015). In addition to this, during the author's professional practice placement, they were introduced to the possibilities of Virtual Reality (VR) as a tool for architecture, which piqued their interest. VR can be limited to the fact that it completely immerses users into an artificial reality, in comparison to AR which can indicate how digital elements relate to the physical world (Ping et al., 2019).

1.3 RESEARCH AIMS AND OBJECTIVES

The purpose of this research is to investigate the potential of AR technology to be utilized as a tool to support sustainable deconstruction practices. Specifically, the research aims to identify the ways in which AR can be used to visualise hidden building elements, display their environmental data and aid in implementing a DWMP during the end-of-life building stage. In order to achieve this aim, the objectives of this study are as follows:

1. To conduct an extensive literature review into AR as a construction tool, the upward trajectory of BIM and LCA software and how these advancements could be linked with improving circular deconstruction.
2. To develop a physical prototype model that displays the potential of AR technology to visualise BIM models and their corresponding data at a 1:1 scale.
3. To create an end-of-life building case study that demonstrates how LCA data can be incorporated into a DWMP and utilizes AR on-site to enhance deconstruction methods.
4. To produce a video recording showcasing the implementation of AR technology in the context of circular dismantling.
5. To evaluate the effectiveness of using AR and LCA data during the end-of-life stage of a building, and to identify any barriers or limitations to the widespread adoption of this technology in the AEC industry.

Through a review of the literature and case studies of relevant projects in the construction industry, as well as simulating the use of AR on-site, this study aims to provide insights into the potential of AR to advance the CE through enhanced deconstruction.

1.4 SCOPE OF RESEARCH

The extent of this research is to determine if there is an application for AR to be used during the deconstruction of a building and to evaluate whether it would be a useful tool for improving sustainable end-of-life practices. A literary review was conducted that focused on gaining an understanding of the different elements of this research that are to be brought together. The current state of AR technology in the construction industry was analysed, as well as current circular deconstruction methods. Knowledge of the use of BIM and LCA calculations to create an eco-conscious DWMP was also gained during this stage.

A physical prototype was constructed to test the different capabilities of AR in the context of deconstruction, with key findings from this prototype testing being further developed during the formatting of a case study. For this case study, the deconstruction of a domestic dwelling was simulated with a BIM model being created through the accurate measuring of the building. An LCA of the building was then calculated with the main material waste streams and their end-of-life environmental impacts identified. This information was then used to create the site-specific DWMP. Key content from this DWMP was embedded into the AR model and projected onto the deconstruction site. A workflow was created as a result that utilizes the use of BIM and LCA software to create a DWMP, with AR aiding in locating building materials and implementing the DWMP on-site.

Due to the case study demolition being fictitious, there were some conclusions that were outside of the scope of research. A material recovery and cost analysis comparing this study’s methodology to traditional methods on an actual deconstruction site would be the next step in this research.

2. Literature Review

2.1 INTRODUCTION

To achieve the overall aim of investigating the potential of AR to promote sustainable demolition practices, the author has examined relevant literature on the current applications of AR in the AEC industry, circular deconstruction and building LCA methods. This section also provides a detailed exploration of BIM and its functionalities, along with an analysis of the potential advantages that can result from using LCA software incorporated into precise BIM models.

2.2 AUGMENTED REALITY IN CONSTRUCTION

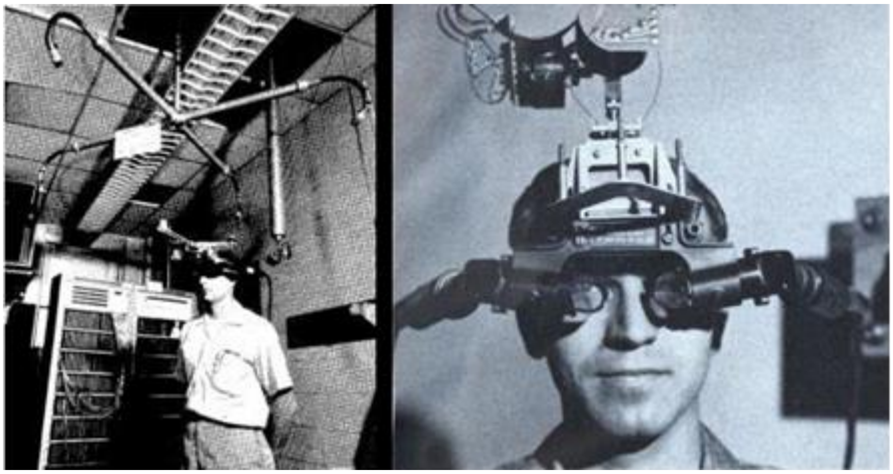

Figure 2. The Sword of Damocles (First AR Head-Mounted Display)

Augmented reality is a technology that allows users to experience and interact with virtual content in the real world. AR has a long and varied history (K. Chen & Xue, 2022) (Sünger & Çankaya, 2019), with roots dating back to the 1950s and 1960s with the development of head-mounted displays presented in Figure 2. In recent years, AR has gained widespread attention and adoption due to the proliferation of smartphones and other portable devices equipped with AR-enabled hardware and software (Arth et al., 2015).

There are various technologies and platforms used in AR, including computer vision, depth sensing and machine learning algorithms (Y. Chen et al., 2019). These technologies allow AR systems to recognise and track real-world objects, surfaces and environments while also overlaying virtual content in a way that is seamless and realistic. Some of the most popular platforms for AR include smartphones, tablets, head-mounted displays, and smart glasses. AR content can be accessed through dedicated AR apps, web browsers, QR codes and other software applications (Van Krevelen & Poelman, 2010). In addition to its use in entertainment and gaming, AR has also found applications in education, training, healthcare, construction and other sectors.

Amin et al. (2023) completed a study using 55 published articles on the topic of BIM-based AR platforms since 2010. The construction stage that each study refers to was noted and six key functions of these studies were identified: Positioning (P), Interaction (I), Visualisation (V), Collaboration (C), Automation (A) and Integration (T). These key functions, referred to as 'PIVCAT' serves as a methodology for completing a trend analysis of recent studies on the topic of BIM and AR.

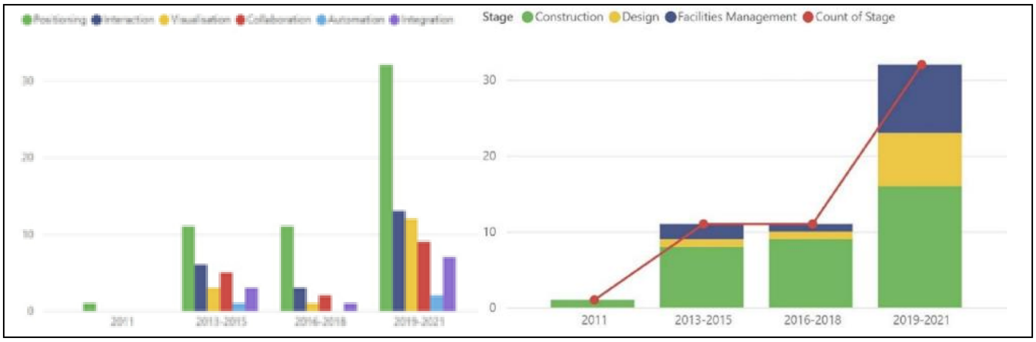

Figure 3. The number of BIM-AR publications since 2010 and the addressed lifecycle stage (left). Research trends based on key functions from 2010 to 2021 (right).

Figure 3 indicates that research into the topic of AR and BIM as a tool for the use-stage (Facilities Management) of a building is becoming more common. However, there has not been enough research into AR to improve end-of-life deconstruction methods. This identified research gap acts as another rationale point behind this study on top of the previously discussed in '1.0 Introduction'. Figure 3 also displays the trends of AR functions, with the positioning of the AR simulation consistently being the most popular AR function trend.

2.3 CIRCULAR DECONSTRUCTION

From a historical perspective, the reuse of building materials deconstructed and taken from previous constructions is quite common throughout the history of human life. The triumphal Arch of Constantine, situated in Rome and constructed in approximately 315 A.D, serves as an example. Some of the elements used to construct the arch were taken from previous monuments dedicated to emperors Trajan, Hadrian and Marcus Aurelius (Bertino et al., 2021). The breakdown of the materials and their ages can be seen in Figure 4.

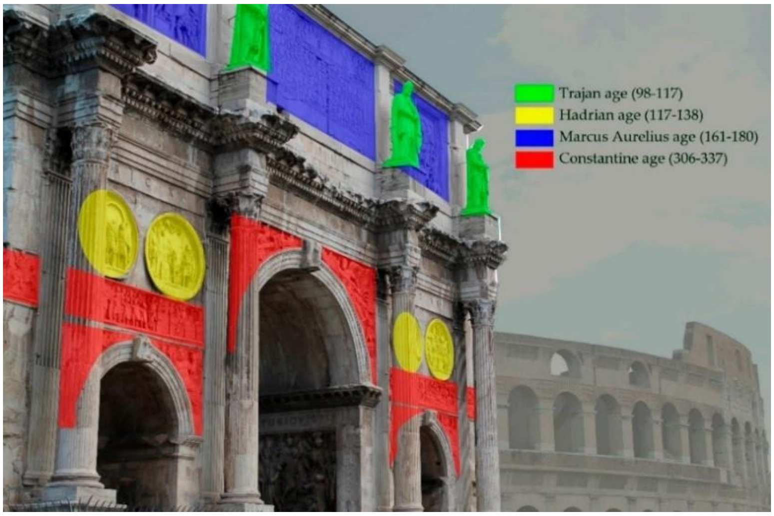

Figure 4. The reliefs of the Arch of Constantine, reused from buildings of previous emperors.

Circular deconstruction can be defined as a well-considered selective dismantlement of building components in the prevision of future reuse, repurposing, or recycling. In contrast, standard demolition of a building involves using heavy construction machinery to clear the construction site quickly and normally requires minimal material filtration, meaning a large amount of waste to landfill. To select the most environmentally friendly deconstruction approach (waste management strategy), an evaluation of multiple contributing factors is necessary. Some of the contributing factors include an understanding of the building materials, site conditions, recycling process, price of disassembling, energy use and energy costs (Akbarnezhad et al., 2014).

The Irish Green Building Council released a case study completed on the demolition of Oisín House, a five-storey 1970s office block. It was set to be demolished as part of Trinity College's development plan with the goal of having 'Zero Waste to Landfill' (IGBC, 2018). To achieve this, a DWMP specific to the site was developed, and the main waste streams from the building identified. To guarantee that the concrete arisings would be suitable for reuse, the non-structural elements of the building were harvested first. Through the use of a soft strip demolition phase shown in Figure 5, the materials were separated into their appropriate waste bins for recycling purposes. Following this stage, the mechanical demolition commenced, where all concrete arisings were pulverised to provide piling platforms and for the levelling out of the site. All supporting rebar was separated magnetically and sent for recycling.

Figure 5. Deconstruction of Oisín House with the goal of "Zero Waste to Landfill".

An analysis of environmentally conscious deconstruction case studies serves as a useful exercise to determine the key trends of sustainable demolition and the methodology involved in avoiding end-of-life waste. The implementation of AR to enhance these steps in circular deconstruction can then be assessed. Ge et al., (2017) developed a case study where BIM was used to improve estimation accuracy for developing waste management plans. Phasing was used to display the timeline of the removal of all building materials, with BIM software such as Autodesk Revit calculating material quantities for each phase.

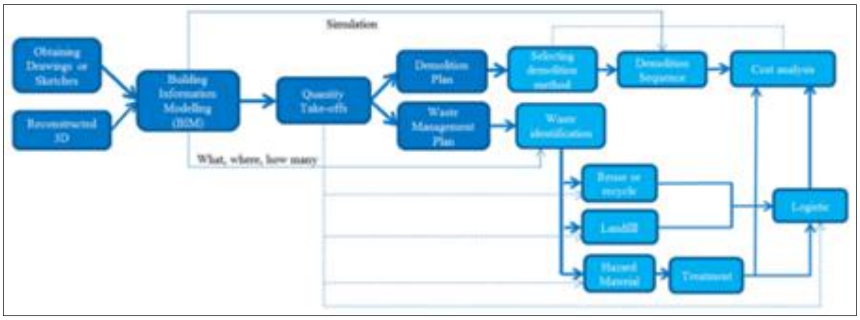

Figure 6. Developed deconstruction and waste management process

The approach set out by Ge et al., (2017) in developing a waste management process with the use of BIM, illustrated in Figure 6, is used by the author as a basis for their own case study in this research. LCA calculation improves the 'Quantity Take-offs' process as it breaks down the end-of-life environmental effects of the material quantities as well as calculating the amounts of waste. AR implementation is added to the latter stages of the waste management process, where the waste identification sub-categories can be identified on-site and sorted accordingly. A demolition sequence can also be implemented on-site through the use of AR and is tested during the case study.

A method to obtain more detailed material and quantity take-offs is the use of LCA plugins with BIM software. An example of BIM-LCA integration is Tally, a plugin for Autodesk Revit that quantifies the environmental impacts of building materials based on the LCA method (Soust-Verdaguer et al., 2017). The growing adoption of BIM in construction project design presents opportunities to efficiently integrate LCA in the early stages of design, with minimal additional workload for the design team. Various levels of integration can be envisioned, ranging from a bill of quantity export based on the BIM model to import native LCA software, to real-time LCA calculations within the original design environment that provide instant feedback on design choices. Another option is to utilize the standardized BIM-information exchange format IFC (Wastiels & Decuypere, 2019).

A visual breakdown of the different types of BIM to LCA integration is shown in Figure 7. If this information is added in the early design stages, it will be accessible during the end-of-life of the building and can be useful for developing a DWMP. Databases and environmental product declarations (EPDs) offer information on the various environmental effects of construction materials, components or elements. Databases can be distinguished based on their scope and completeness (Martínez-Rocamora et al., 2016).

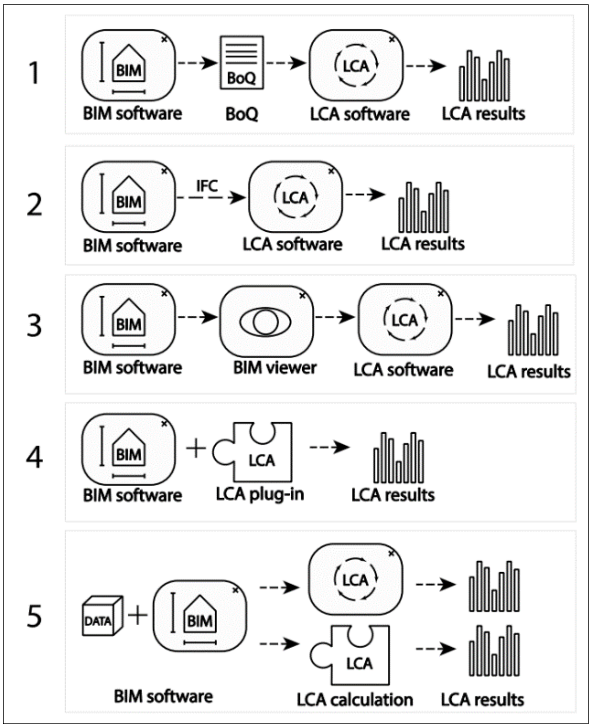

Figure 7. BIM-LCA integration types

Wong and Zhou (2015) conducted a literature review that centred on the use of BIM for monitoring environmental sustainability and managing buildings across their entire life cycle. Out of 82 green BIM studies analysed, 12 focused on the potential of the use of BIM and LCA in the demolition stage of buildings. Kuikka (2012) showcased the use of end-of-life LCA data to determine whether a selective or conventional demolition alternative was more environmentally preferable. Similarly, the focus of this study is to utilize LCA software to calculate end-of-life environmental impacts of materials that are to be harvested, reused or recycled and to develop an eco-conscious DWMP as opposed to adhering to conventional demolition methods. Modules C1-C4 and Module D can be calculated using LCA plugins to BIM models and offer important information that can be helpful when developing a waste management plan (Delem & Wastiels, 2019).

2.5 PROJECT DISCOVERY – AUGMENTED REALITY AS A TOOL FOR DECONSTRUCTION

The potential to import BIM models containing family properties information into AR applications could enhance the utilization of BIM-LCA integration into a tool that is useful to be implored on a deconstruction site. "By combining BIM with interactive visualization, managers can understand which materials are placed where; identify the areas of demolition that need attention or special treatment. Safety measures can be taken and the amount of waste can be predicted. Managers can make better decisions and develop tailor-made demolition plans and waste management strategies in order to save costs and achieve reuse and recycle targets" (Ge et al., 2017). The author aims to prove that AR can be a valuable deconstruction tool by demonstrating its ability to provide on-site access to a vast database of predetermined end-of-life information through imported BIM properties, as indicated in Figure 8.

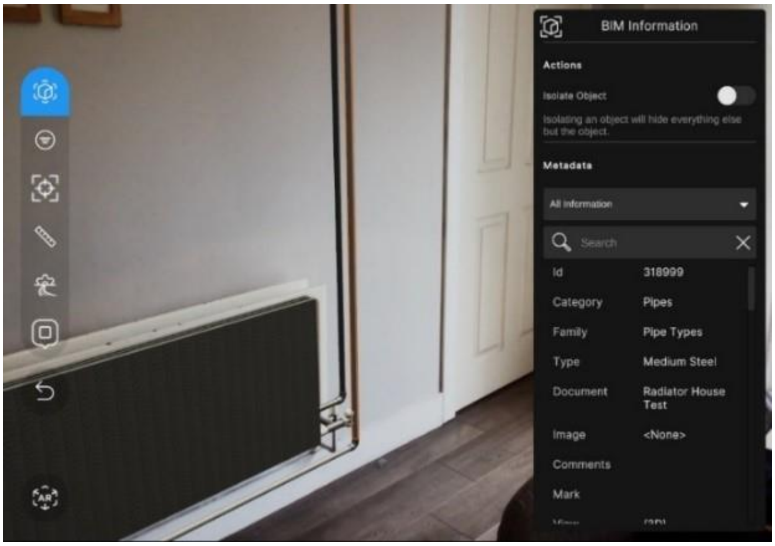

Figure 8. BIM Model of Radiator and Pipes in AR with BIM Metadata Information present

Furthermore, the author intends to showcase that AR's capability to filter and visualize associated groups can serve as a visual aid in deconstruction sequencing on-site, refer to Figure 9. This is to align with a pre-developed waste management strategy. With accurate modelling, AR can indicate the location of hidden building elements, this could make the material harvesting process more efficient.

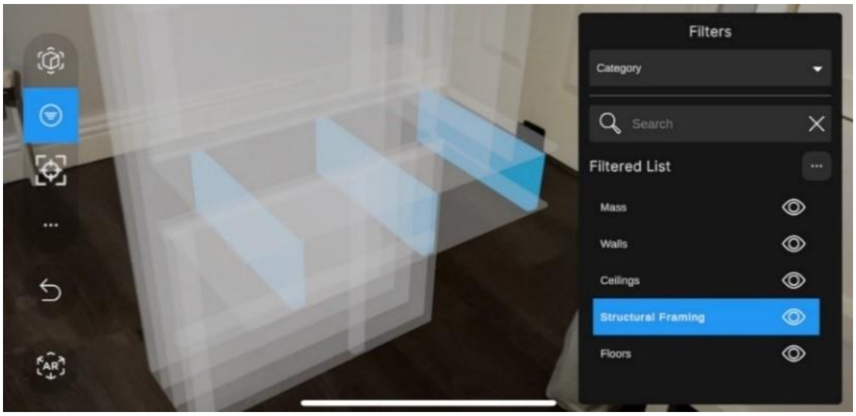

Figure 9. Filtering by BIM categories in AR

3. Methodology

3.1 INTRODUCTION

This section covers the theoretical and practical aspects of the research. It describes the epistemological perspective and reasoning behind the research decisions made, as well as the methodology utilized for data collection. Additionally, it includes an overview of the limitations included in the study as well as conclusions drawn from the chapter.

3.2 METHODOLOGY – DESIGN SCIENCE RESEARCH FOR BIM

This paper's research relies on the methodology of design science research (DSR) to evaluate and execute BIM processes, as proposed by Kehily and Underwood (2015). The approach of DSR involves utilizing collected data to resolve issues, enhance existing solutions and generate new knowledge, insights and scientific theories (Dilhan et al., 2022). This study utilizes the DSR methodology by examining an established theory on the implementation of augmented reality as a construction tool and then applying the six guidelines outlined below to showcase an alternative to the existing theories on the topic.

- Identification and Recognition – Specify the exact research problem and suggest a solution.
- Objectives of a Solution – Formulate objectives for addressing the defined problem.
- Design and Development – Develop the artefactual solution.
- Demonstration – Show the effectiveness of the proposal in resolving the problem.
- Evaluation – measure the efficiency of the solution for addressing the problem.
- Conclusion – conclude and communicate the importance of the solution for the problem (Hevner et al., 2004).

3.2.1 Identification and Recognition

The paper's introduction highlights the reasoning behind the research, which focuses on the construction industry's significant carbon footprint and its potential to become a leading industrial sector in global economic growth (Cihat Onat &

Kucukvar, 2020). This research paper explores the potential of AR and BIM technology to help to minimize greenhouse gas emissions in the AEC industry by improving the deconstruction process of buildings. The literature review identified a research gap concerning the use of AR as a tool for the end-of-life construction stage but also highlighted this technology as a potential solution.

3.2.2 Objectives of a Solution

The 'Research Aims and Objectives' section of the introduction established a series of objectives designed to analyse the use of AR and BIM as deconstruction tools to tackle the issue of the construction industry's global emissions. The conclusion of this study then discusses the objectives and evaluates the effectiveness with which they were achieved.

3.2.3 Design and Development

During the 'Literature Review', the potential of AR for sustainable deconstruction was investigated, and early testing was conducted during the development of the 'Methodology'. The solution hypothesis was formulated by addressing specific ways in which this technology could be utilized to aid in the end-of-life building stage.

3.2.4 Demonstration

The 'Methodology' section outlines the demonstration of AR technology for deconstruction, which is achieved through a case study, physical prototyping and video documentation. These approaches are implemented to demonstrate the effectiveness of the proposal in the context of realistic scenarios.

3.2.5 Evaluation

The subsequent chapters labelled 'Results and Analysis' and 'Discussion' evaluate the effectiveness of each approach. This section includes an evaluation of how well AR was able to accomplish the objectives outlined in the study, which is subsequently summarized in the following chapter.

3.2.6 Conclusion

The final chapter of the research paper provides an overview of the entire study and highlights the significance of BIM and AR for future deconstruction methods. The importance of this solution is discussed in the context of potential environmental benefits.

3.3 SOFTWARE

The software employed for this research can be categorized into three subheadings: BIM, AR and LCA.

- BIM – Autodesk Revit is used in this study for digital prototype development and seamless integration to AR and LCA calculation.
- LCA – Tally is a life cycle assessment software tool that is employed to compute the environmental impact of designs and has a direct Revit plugin.
- AR – Unity Reflect is an augmented reality software that integrates with Revit, allowing for the export of any BIM properties embedded within a project.

3.4 PHYSICAL PROTOTYPE DEVELOPMENT

Figure 10. Prototype model (left). Prototype BIM Model overlayed in AR (right).

To create a model that displays the capabilities of AR technology in terms of accurate surface anchoring, material location, and data visualisation, a simple wall build up was developed using cereal boxes, wrapping paper and card, shown in Figure 11 to the left. The physical model was then accurately measured and modelled in Revit. Material EPD data was linked to the model and exported to Unity Reflect. The BIM model, presented in Figure 10 on the right, displayed accurate positioning, hidden building element location (battens behind plaster) and data visualisation. These capabilities were demonstrated to showcase the potential of AR as a practical on-site deconstruction tool.

3.5 CASE STUDY DEVELOPMENT

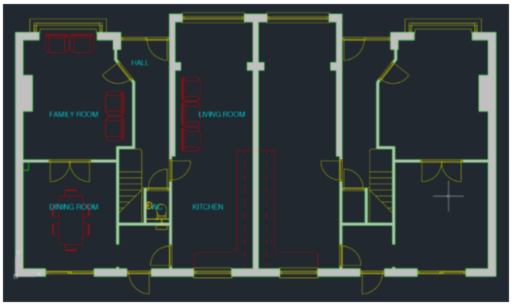

Figure 11. AutoCAD Ground Floor Plan created from accurate surveying.

To further develop the initial hypothesis that AR can enhance circular deconstruction, a case study that applies the technology and any necessary processes for waste management planning is required. To accomplish this, a typical residential house is utilized to simulate a sustainable deconstruction approach with AR implementation on-site. Following the waste management process outlined by Ge et al., (2017) in Figure 6, 2D drawings were obtained by accurately surveying and measuring the existing conditions with a laser measurer. As depicted in Figure 11.

Figure 12. Google Street view of case study semi-detached dwelling (left). Revit model of case study semi-detached dwelling (right).

Subsequently, a 3D BIM model was created to facilitate material take-off calculation, LCA and AR software integration. Based on previous architectural drawings, the building's key junction build-ups were identified to enable precise modelling of concealed construction elements. The case study dwelling as built can be seen in Figure 12 to the left, with the 3D BIM model shown to the right.

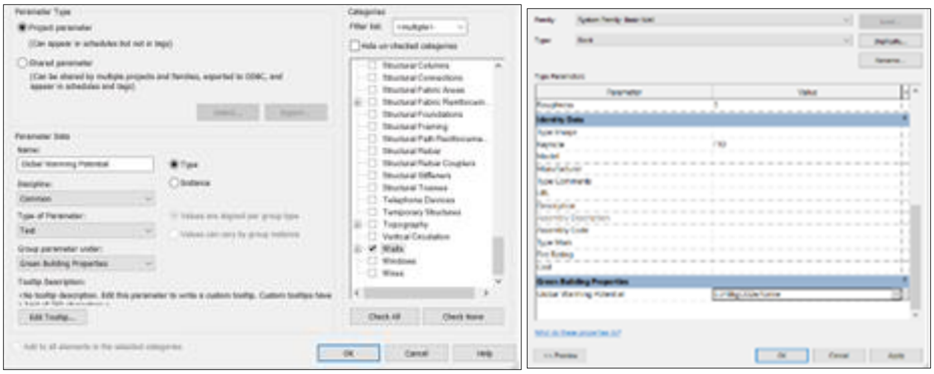

Figure 13. End-of-life GWP parameter grouped into wall family (left). GWP (kg CO_2 e/tonne) statistic displayed in basic block wall properties (right).

This BIM model was then transferred to Tally in order to produce material take-offs, identify main waste streams and create a demolition sequence. After generating the LCA for the demolition of the dwelling, a site-specific DWMP was developed that considered the end-of-life environmental impact data. Data from this DWMP was linked to the BIM model using shared parameters. Figure 13 indicate the process of integrating this type of information into the BIM model.

The final step of this case study involved simulating the use of AR on the 'deconstruction site' to display the information obtained from the previous steps. Two different methods, corner alignment or QR code scanning, can be used with Unity Reflect to align a BIM model to the real world in AR. By using the QR code method, the virtual position of the QR code is accurately represented in the BIM model to reflect its physical placement on-site (Chernick et al., 2021). This QR scanning method is showcased in the physical prototyping. However, it was discovered that the corner alignment method was more effective in this scenario.

Figure 14 displays the implementation of the corner alignment technique in the context of this case study. It shows the alignment of the BIM model's external walls on the exterior corner of the dwelling. A horizontal surface (ground floor) and two vertical surfaces (east-facing and south-facing external walls) are selected in the BIM model, generating a corner point. The same surfaces are then scanned in the real world, generating the corner point in the same location. The BIM model is then projected from this corner point in AR. #

Figure 14. Example of corner alignment of BIM model into real world AR visualisation

4. Results and Analysis

4.1 LITERATURE REVIEW FINDINGS

By conducting an analysis of literature related to AR in construction, selective deconstruction and LCA methods, several key findings were identified.

Recent years have seen an increase in the number of BIM-related AR studies covering different building life cycle stages, including design-stage, construction-stage and use-stage research. However, there remains a gap in research on the potential of AR and BIM as tools for deconstruction or in the end-of-life building stage.

Existing studies on circular deconstruction provided valuable insights into the methodology for designing a waste management strategy, identifying primary waste streams and creating a demolition sequence. These studies highlighted how BIM can simplify the process by providing a comprehensive overview of the building's components and materials. Using the ability to link BIM models into AR, a hypothesis was developed detailing the use of AR in deconstructing buildings. Mobile-based AR software allows for on-site data visualisation, ease of material location and visual aid to deconstruction sequencing. This review aimed to test the effectiveness of these functions.

After reviewing the literature on BIM and LCA software, various types of BIM-LCA integration were found to be possible. A particular method involving direct LCA plugins into Revit was identified for this study. Furthermore, the study analysed other research that employed end-of-life LCA data to determine deconstruction strategies.

4.2 PHYSICAL PROTOTYPE FINDINGS

QR codes can be easily scanned to access AR models, which makes them an ideal tool for showcasing the capabilities of AR during presentations. Demonstrating the technology's capability through live QR code scanning was a crucial aspect of the presentation of this thesis, as static images alone fail to showcase the technology's adaptability to movement. A methodology for acquiring BIM information in an AR model was identified using Revit's shared parameters during this stage. This methodology employed to conduct the digital elements of this prototype development was subsequently applied on a larger scale for the case study.

The positive outcomes of the physical prototype testing served as a foundation for formulating the methodology of the case study. During the creation of the physical prototype, knowledge of the functionalities of AR software and their direct connections to Revit was acquired. These findings were subsequently utilized throughout the entire study. The precise projection of AR allowed for the visualisation of concealed battens located behind the plasterboard in the physical prototype, see Figure 15. This discovery was developed further during the case study, where the modelling of all hidden structures making up the dwelling were identified and exhibited during the AR simulation on-site.

Figure 15. Visualisation of concealed battens with AR

4.3 CASE STUDY LIFE CYCLE ASSESSMENT FINDINGS

A real-world application of BIM and LCA was demonstrated through a comprehensive case study, which focused on developing an efficient DWMP for an end-of-life building. The study explored how the use of AR technology could help in executing the deconstruction plan by identifying the location of hidden building elements, giving access to the DWMP data while on-site and visualising a deconstruction sequence. Following the creation of a 3D BIM model of the existing dwelling, accurate EPD assignment to materials begun while calculating the LCA for the building. From this completed LCA, results were drawn on the main waste streams and the environmental impacts of these materials. This LCA data was used in the development of a site-specific DWMP. The GWP for each stage of the building life cycle were examined. As depicted in Figure 16, it was discovered that the deconstruction of the building contributed to 30% (Module C) of the full building life GWP.

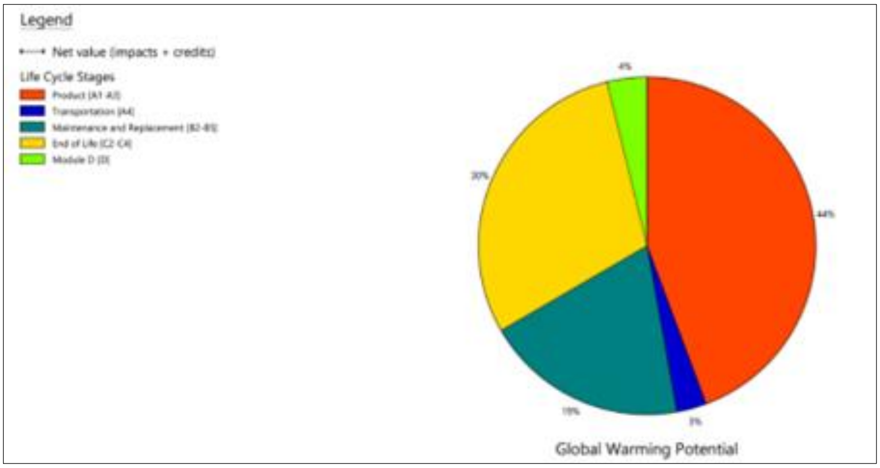

Figure 16. Pie chart indicating GWP associated with each life cycle stage of case study building.

The case study LCA identified the building's main material waste streams as well as the embodied carbon of these materials and can be envisioned in Figure 17. An estimate of the waste material that will be produced throughout each phase of deconstruction is key to creating an in-depth DWMP (Akbarieh et al., 2020).

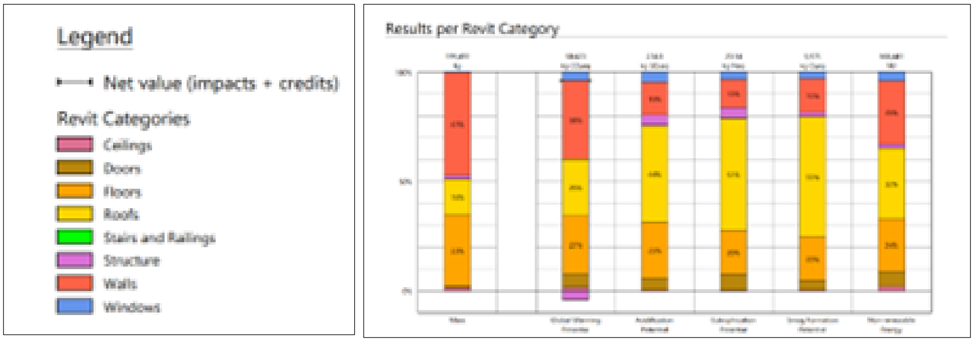

Figure 17. Chart displaying the accumulation of materials and their corresponding environmental impacts.

End-of-life scope averages for materials used in the LCA (e.g., 45% of brick recycled, 55% sent to landfill) were utilized as a starting point for formulating the recycling, salvage or reuse goals for the main waste streams of the site, as indicated in Figure 18. These goals were then embedded into the AR model to reinforce the project's sustainability goals on-site.

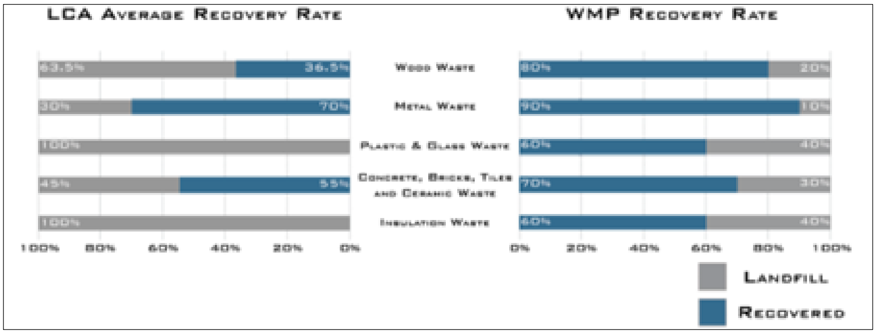

Figure 18. Chart indicating the average recovery rates used in LCA compared to decided recovery rates for DWMP.

During the case study, a DWMP specific to the dwelling was developed following the creation of a BIM model and LCA calculations. This DWMP was created following guidelines set out by the Environmental Protection Agency (EPA) for the preparation of resource and waste management for construction and demolition projects (EPA, 2021). Each guideline is covered in detail throughout the DWMP document, however some of the key sections that are required by the EPA for developing a DWMP in Ireland are highlighted below:

- Estimated types and quantities of waste generated from the demolition site.
- A strategic deconstruction sequence.
- Waste recycling, salvage or reuse goals.
- Intended procedures for handling the waste.
- Detailed instructions for the subcontractors and labourers on how to separate or collect the materials at the job site.
- Proposed and intended disposal methods for these materials.

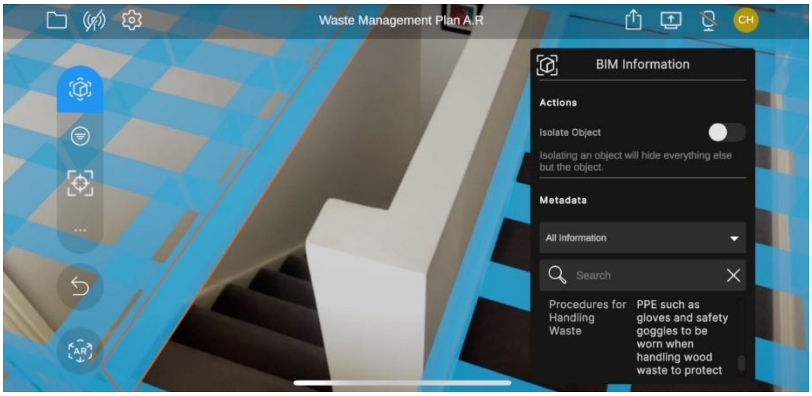

Figure 19. Safety procedures assigned to timber structural framing in AR.

Results from these guideline headings were identified during the development of the DWMP and then linked back to the case study BIM model to be deplored on-site in the form of AR implementation, see Figure 19 for specific procedures for handling timber wastes.

The National Waste Collection Permit Office (NWCPO) have a database of permitted waste collectors in Ireland that can be filtered by List of Waste (LoW) code and county. Using this database, waste materials from the case study site were designated their LoW codes in the DWMP. These LoW codes were then assigned via Revit parameters to each relevant material in the BIM model for the purpose of identifying the types of waste with AR on-site and aiding in the separation and collection process.

TABLE 1. Example of case study waste materials and their associated LoW code

Waste Material	LoW Code
Concrete, Bricks, Tiles & Ceramics	17 01
Concrete	17 01 01
Bricks	17 01 02
Tiles and Ceramics	17 01 03
Mixture of Concrete, Bricks, Tiles & Ceramics	17 01 07
Wood, Glass and Plastic	17 02
Wood	17 02 01

Sorting these wastes in bins labelled by their LoW code was the proposed method of disposal for these waste materials. With the identification of the different types of waste through the AR model's embedded LoW data, harvested materials were to be brought to their designated waste bins following their LoW code label.

A top-down deconstruction sequence was identified in the DWMP that consisted of fifteen different phases of removal. These phases were also linked back to the BIM model for the purpose of identifying which materials were to be removed at specific phases throughout the deconstruction project. If adhered to, this ensures that a strategic planning of waste collection without overloading the on-site waste bins can be achieved. The final deconstruction sequence for the case study deconstruction is as follows:

- Phase 1: Utilities Disconnected (Electricity, Plumbing, Water Lines, etc.,)
- Phase 2: Furniture Removal
- Phase 3: Internal Doors Removal
- Phase 4: Hazardous Material Removal
- Phase 5: Roof Removal
- Phase 6: Attic Structure Removal
- Phase 7: First Floor Windows Removal
- Phase 8: First Floor Internal Walls and MEP Removal
- Phase 9: First Floor External Walls Removal
- Phase 10: First Floor Build-Up Removal
- Phase 11: Ground Floor Windows and External Doors Removal
- Phase 12: Ground Floor Internal Walls and MEP Removal
- Phase 13: Ground Floor External Walls Removal
- Phase 14: Ground Floor Build-Up and Slab Removal
- Phase 15: Strip Foundation and Rising Wall Removal

4.5 CASE STUDY AR IMPLEMENTATION FINDINGS

During the AR simulation on-site, the corner alignment technique was preferred over QR scanning because of the growing imprecisions with distance from the QR scanning point. The corner alignment method can be repeatedly used on any corner within the dwelling to achieve room-based accuracy and to realign the model.

Figure 20. Location of hidden structural framing (joists, rafters) from external view

The simulation conducted on-site effectively utilized AR technology to locate concealed structural elements (evident in Figure 20), present relevant DWMP data and highlight building elements in accordance with the project's deconstruction sequence.

5. Discussion

To provide a straightforward explanation, this research has indicated that with accurate modelling and documentation, the use of AR can lead to on-site ease of location and data visualisation. This study provides a preliminary exploration of the potential uses of AR technology in a typical end-of-life scenario, indicating the need for further research to fully understand the range of applications in the AEC industry.

There has been limited research on the use of AR and BIM during the facility management and end-of-life stages of buildings, this is understandable as AR was initially thought to be primarily for visualizing concept designs in their future locations. However, the benefits of using AR in the use stage and deconstruction of buildings are becoming increasingly clear. Giving professionals access to a technology that allows users to visualise hidden services and structure can help with decision-making during any building alterations or deconstruction. The next step in a study on the benefits from the use of AR to implement a DWMP, would be a comparison between a standard demolition of a dwelling compared to the use of AR to deconstruct the same dwelling. This would allow for definitive conclusions such as returns of investments, cost-analysis, material recovery percentages, etc.

A potential area for further investigation within the scope of this research is scanning technology. Reconstructed 3D models from scans can also be brought into AR technology similarly to BIM models (Liu et al., 2020). As Lidar scanning capabilities on smartphones become increasingly effective with Artificial Intelligence (AI) platforms improving the technology, it would be valuable to explore the possibility of documenting scans at various life cycle stages of buildings. This would provide users with a library of their buildings and how their construction timeline occurred.

Figure 21. Reconstructed 3D model from multiple scanning points

For instance, if a scan was taken after all services were installed during the construction stage of a building but before the plasterboard was added, it could serve the same purpose as this study in terms of visualising hidden building elements. Capturing Reality (2023) reported that the St. Alexander Nevsky Cathedral in Sofia was reconstructed from 1338 drone photos and 2976 ground images, illustrated in Figure 21.

However, the worth of BIM importation into AR lies in the associated data with individual BIM families, and the ability to filter through these elements, which was a significant factor in demonstrating the value of this technology as a deconstruction tool. The effectiveness of AR as a deconstruction tool is directly proportional to the effort invested into its projects. The increasing adoption and development of BIM technologies, along with the growing use of LCA in architectural firms, will enhance the potential of AR as an end-of-life tool. With the availability of 3D BIM models, it becomes easier to perform material take-offs and calculate the LCA of the building which were essential tasks in the development of a DWMP. Cloud-based platforms such as Autodesk's BIM360 are increasingly being used to link digital construction models to on-site work, improving the accuracy of BIM models and ensuring alignment with what is really being built. Further use of BIM360 or similar software will help to ensure that AR projected BIM models are accurately aligning with what was actually constructed.

6. Conclusion

The purpose of this research was to investigate the potential of AR technology to be utilized as a tool to support sustainable deconstruction practices. Different research aims and objectives were outlined in the '1.0 Introduction' section. Throughout the study each objective was hit and resulted in the creation of a proposed workflow for developing an environmentally friendly waste management strategy and using AR to implement the strategy on-site. From the creation of a physical prototype, knowledges of the functions of AR software such as its ability to visualise hidden building elements, its data importation and its direct connection to Revit were acquired and these findings were essential to the creation of the case study.

Through a case study, it was found that LCA data can be utilized to create an in-depth DWMP with emphasis on sustainability and that AR can be used to implement this DWMP onsite. A short video presentation was created following the case study and showing the potential of using AR during the deconstruction phase. An existing workflow, shown in Figure 6, for utilizing BIM software in a waste management strategy was leveraged to create this study's workflow that included LCA calculation and AR implementation on-site. Observe Figure 22 for this study's waste management strategy workflow.

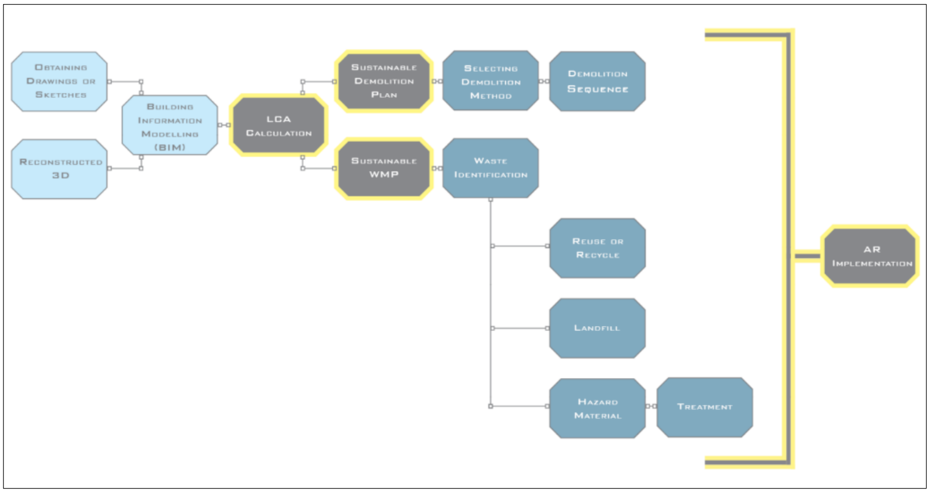

Figure 22. Sustainable waste management strategy with LCA and AR

A potential workflow for developing and implementing a DWMP was created as a result of this study. The workflow involves utilising BIM to LCA software to obtain material take-offs that include end-of-life environmental impacts. An eco-conscious DWMP can then be produced that considers the LCA data. Building elements and various main points of this DWMP can then be visualised and understood on-site through the use of AR. This system is applicable to hitting goals to reduce the embodied carbon of buildings by improving the organisation of deconstruction wastes. With on-site visualisation of all the materials associated with a building and their embodied carbon, the selective deconstruction process could be advanced. The choice of removing segments of buildings depending on the build-up of GWP associated with specific materials could be achieved with on-site visualisation of AR and material data.

In conclusion, this study has explored AR in depth, providing a comprehensive analysis of its application in the end-of-life construction stage. The research has contributed to the understanding of sustainable deconstruction and has identified potential solutions and areas for future investigation. Overall, the study has important implications for the deconstruction industry and underscores the need for improvement when it comes to the avoidance of sending waste to landfill.

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REALTIME DIGITAL AUGMENTED CONSTRUCTION
A Technological Readiness analysis with a practical and technological approach

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Abstract. Augmented reality has been promoted as one of the technologies under the concept of Build 4.0 to have a large influence on the future of the construction industry both internationally and nationally in Denmark. In this paper we will address the following question: What is the technology state for the construction industry, which allows the artisanal to be able to perform construction work using model-based augmented reality head mounted displays? The question is developed through a smaller literature review where the scope of the problem is narrowed down. The majority of the literature focuses on primarily applying it for visual management and not as a hands-free execution tool for the craftsmen on the construction site. The methodology of the research is based around design-based research and is a practical and theoretical exploration of technological readiness. This is performed through a series of tests, using Microsoft HoloLens 2, Trimble XR10 edition and the Trimble Connect application. This is used to determine a benchmark for the technological limitations in the formulated use cases. The output of the tests is based on the use of the technology from a two-sided approach: the inexperienced versus the experienced user.

The initial conclusions show that the precision in positioning 3D models in relation to physical objects is far from the tolerance requirements determined at an industry level for the performed artisan's work. This calls for further technological development in positioning and alignment of 3D models in the physical world. Furthermore, the tests show that the user needs some competencies in understanding- and interacting with the technology and the underlying concepts of use for better and more accurate performed work. Which requirements are needed for the technological readiness to become an applicable standard in the industry, where the focus on the 3D model created by advisors, is used as a basis for executing the construction project on site. At the same time, it is important to focus on the necessary methods and skills which will be a requirement for the industry in order to fulfil the potential of model based augmented artisanal workflow. As a part of the conclusion of the research a framework for further work is established were a more human-centred approach is defined.

Keywords: Build 4.0, Technological readiness, Model-based augmented artisanal work, Augmented reality head mounted displays, Microsoft Hololens 2, Trimble XR10, Construction industry.

1. Introduction

Building Information Modelling (BIM) has been a part of the Architecture, Engineering and Construction (AEC) industry for over 20 years and has gained a substantial influence in the work processes performed by the designers. The processes have an influential impact on the knowledge and information needed to design better, efficient, sustainable, and aesthetic buildings based on the requirements for the design, and through that, be able to decide better decisions in the process. On the other hand, BIM has not had the same influence on the artisan work conducted by the craftsmen on the Construction_site. The biggest influence has overall been in the project management area where time, cost planning and visualization of the project can be seen as the biggest influence. Yet the information delivery from the designers and to craftsmen is still conducted through drawings either printed on paper or digital accessible through the pdf-format – almost the same work method as in the ancient Egyptian time. This way of delivering information from one stakeholder to another is surrounded by challenges if not conducted seamlessly. Lack of information and old or inappropriate information are some of the challenges that the industry is facing through the use of drawings. The concept of "old drawings" (BUCH & ODGAARD, 2010) which is handed out randomly can lead to mistakes and rework throughout the construction process and can be seen as one of the factors in the large amount of rework done in the construction industry.

Build 4.0 as a concept has been predicted to have a large potential on the future use of technology and digitalization to streamline and optimize the many work- and decision-making processes involved in a construction process (SØRENSEN, SONNE, & STENBERG, 2018). One of the technologies is augmented reality and is expected to have "…the potential to be a transformative technology to the industry" (NASSEREDDINE, HANNA, VEERAMANI, & LOTFALLAH, 2022, s. 13)

The scope of this paper is to examine a hypothesis that deals with replacing the use of drawings with access and use of the newest updated BIM-models through the use of augmented reality.

The examination of the hypothesis will be focused on the technological aspect and the research question: What is the technology state for the construction industry, which allows the artisanal to be able to perform construction work using model-based augmented reality through head mounted displays?

In 2019 the former Danish ministry of Transport, Building and Housing (TRAFIK-, BYGGE- OG BOLIGSTYRELSEN , 2019), came out with a new strategy for the use of digitalization in the Danish construction industry. The purpose of the strategy was to set a common ambition for the industry to deal with some of the difficulties in the construction industry – low productivity and effectiveness. The strategy does that by bulletin five areas of action, ranging from "better use of digital tools" to more "more sustainable construction through digitalization".

The strategy is stating that digital tools can be an efficient enabling factor in the future and therefore the use must be developed and implemented in the industry to capture those potentials.

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2. Augmented Reality in construction

2.1. SCOPE OF RESEARCH FOCUS

A small literature review has been conducted to be able to get an overview of the literature within the research scope. The focus has been to determine in which direction the use of augmented reality has been predicted. The use cases developed by the literature mainly focus on three aspects: visual management, visual presentation, and training and not the use within the scope of the research question. Thus, there are some examples that can be mentioned, for example, using augmented reality to build very complex shaped masonry walls (MITTERBERGER, et al., 2020).

The research and developed proof of concept of Augmented Bricklaying shows that it is possible to use Augmented Reality to perform the artisanal work in construction of complex structures, in their case, multi-concave brick walls at a winery in Greece. The focus in the research is not solely on precision of the technology, but more on the possibility of creating structures that only can be done with the help of technology. Bricklaying is normally done with the use of a modular approach where the Augmented Bricklaying concept was done with individual positioning of each brick in the wall. In normal bricklaying it is possible to work with common defined tolerances that can be monitored and controlled with measurement methods. At the time of the development of the concept, the technological maturity of head mounted displays2, was at a state where it could not support the focus of the concept, and the use of external camera and display technology needed to be used.

Furthermore, a larger study published in 2022 (NASSEREDDINE, HANNA, VEERAMANI, & LOTFALLAH, 2022) shows that the biggest barrier to the implementation of Augmented Reality is the maturity of the technology. It is indicated that the technology will develop over time in accordance with Morre’s Law (DANKER & JONES, 2014). The article (NASSEREDDINE, HANNA, VEERAMANI, & LOTFALLAH, 2022) points out that the development of Microsoft Hololens 2 would help to mature the technology on an overall and broadly level.

2.2. TECHNOLOGIES

Augmented reality is a use of computer aided visual overlay of the real world (SPRINGER, 2006) through either a head mounted lens or camera in portable devices such as a mobile phone or tablet. The reality becomes augmented with digital information, in the focus of this paper, such as 3D representation of an interior wall that is going to be built on a construction site. The focus of this paper is to examine the technology state in the use of head mounted displays where the hands-free possibilities to conduct artisanal work and by that means, the research will not focus on the hand-held devices.

Augmented reality has gone through a quite long period of maturity, from the start in the late 1960s until today. In accordance with the Gartner Hype Cycle analysis (STENINA, 2023), it showed up in 2005 with a predicted plateau of productivity of 5-10 years and it peaked at its inflated expectations in 2011, still with predicted plateau of productivity of 5-10 years. In 2018 it reached the period of disillusionment and further analysis did not include Augmented Reality. This can be seen as technology has reached a mature state where the industry stakeholders can benefit from the use, and it has maybe reached its plateau of productivity.

In 2016 Microsoft Released its first generation of the HoloLens and in 2019 the second generation was released at the same time the Trimble XR 10 edition of the HoloLens was released. The Trimble XR 10 was developed under the Microsoft HoloLens Customization Program (MICROSOFT , 2022) and is developed to suit the workers on a construction site considering the safety measurements this originates from. The HoloLens 2 is integrated in a construction safety helmet and integrates with HoloTint, an additional tinted lens to accommodate bright environments where the use may be limited by sunlight.

The HoloLens 2 uses several different types of cameras and censors in order to map the spatial environment around it together with eye tracking, speech recognition and two-handed hand tracking for interaction. The HoloLens 2 uses its own Operative System and the use is application based.

Trimble has developed its own integrated application, Trimble Connect MR (TRIMBLE, 2023), that connects with their cloud platform Trimble Connect and can be used to import BIM models into the augmented reality experience.

3. Methodology

3.1 CASE USED

The used case developed to test the technology in relation to the research question, was done with the focus of gathering different kinds of data. First of all, precision in the placed digital objects in the physical environment and secondly the ease of use and triangulation to the data from the precision factors. In order to get some valid data, we created a test environment where only an interior wall should be placed in relation to an existing corner of two walls. This setup was chosen with the focus of testing the technology accuracy and not the complexity in the artisanal work. This setup should represent an artisan/carpenter placing the layout for interior stud walls with no use of digital or physical 2D drawings. The (Key Performance Indicators (KPI) for the precision was to compare the data from the test with the common agreed tolerances in the Danish construction industry (DANSK INDUSTRI BYGGERI, 2023). The KPI's for the ease of use was to analyse whether the data from the precision tests was different when three different test persons used the same technology and the same placement and alignment measures.

3.2 TEST

The test was conducted using different kinds of software and hardware.

Revit 2021 was used to create the digital environment where the existing walls and floors were modelled together with the new interior stud wall. The level of detail was held in a very generic form where only the outline of the objects where represented. The geometry was then exported to the Trimble Connect application with the use of the Trimble Connect add-in for Revit.

In the cloud-based use of Trimble Connect, QR-code markers were placed in three different locations represented by surfaces on the three existing building parts, two walls and the floor. The QR-codes are used to place the 3D geometry in relation to the real-life constructions3. This setup aligned the data collection with the different axis of the 3D environment and the placement of the QR-codes. This was done to test if the placement of the QR-codes has an influence in the precision of the placement of the 3D geometry and would bias the measurement to the responding sides.

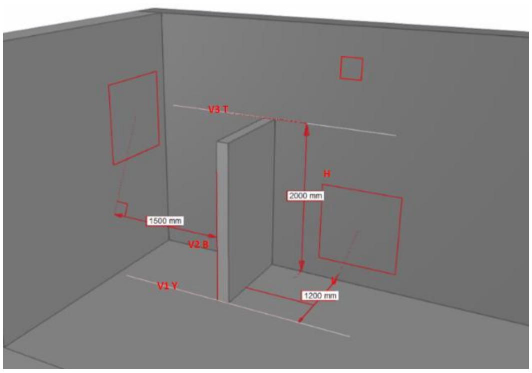

Figure 1. A digital layout of the test environment

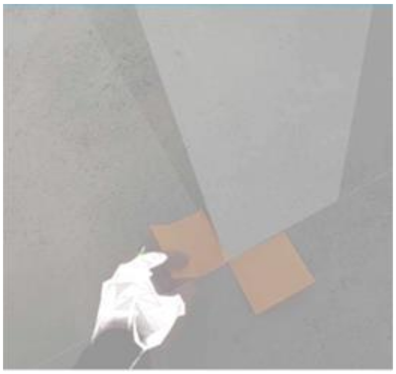

Figure 2. Placing the PostIts on the floor according to the digital representation of the wall

Microsoft HoloLens 2, Trimble XR10 edition with the Trimble Connect MR application was used to create the augmented reality experience. Three test persons were given the task to mark the new wall, represented the XR10, at five different reference points (H – Hight from floor, L – Length perpendicular from the existing wall, V1Y, V2B and V3T – lengths to wall from parallel existing wall) with the use of PostIts on the floor and the wall. This was done with the spatial alignment from the three different QR-codes that were placed accordingly from the Trimble Connect cloud platform. After the three sessions the markings were then physically measured with a tape measure and collected in a spreadsheet.

In the setup of the test environment for the data collection, the existing surroundings, and the spatial alignment through the QR-codes, may contain sources of errors. The levelness and true angle of the existing walls and floors were checked upon the start of the test, and so was the placement of the QR-codes.

3.3 FINDINGS

3.3.1 Precision versus Artisanal tolerances

The data collection contains 45 different measurements where only 5 were according to the Danish common tolerances of ± 3mm (DANSK INDUSTRI BYGGERI, 2023). The five acceptable measurements were generated by all three test persons. The five acceptable Measurements were also generated from all the placed QR-codes.

The test showed clearly that the placement of the QR-codes has a large influence in the deviation of the measurements. The M2 placement should align with the responding L (M2/L) measurement, the M3 should align with the V (M3/V) measurements and the M4 should align with the H (M3/L) measurement.

- The M2/L had a deviation of 0, 12 and -18 millimetres.
- The best M3V had a deviation of -5, -5 and 4 millimetres.

- The M4/H had a deviation of -3, -4 and 0 millimetres.

When we isolated examine the measurements where the QR-codes are compared with the responding sides, the technology is close to being able to deliver results that corresponds to the Danish tolerances. However, the test with QR-code M2 is an exception, which may have other reasons than precision in the technology and is dealt with later in chapter 3.3.2 Human Technology Interaction.

When we examine the measurements where the QR-code does not have a responsive side, the technology falls short. An example of a completely different level is M4/L. The measurements here have deviation of up to 60 millimetres, and none of the test subjects have been able to deliver measurements that are close to what was expected.

The summarized tolerances from the three QR-codes showed clearly that the placement on the floor would get the largest deviation in all other measurements than H.

3.3.2 Human Technology Interaction

Further investigation of the data collection shows that there is a difference in the test persons generated measurements on the same QR code. As an example, it can be mentioned that the difference in the measurement at M3/V2B has a difference of 17 millimetres (0, 10 and -7). It is not completely clear what the cause of such a deviation is, but the different test subjects are delivered with or perceive different kinds of information about the placement of the digital wall. Through the test and the test subjects' feedback, signs are seen that the fit of the helmet and thereby the position of the lens in relation to the eye can be instrumental in creating part of the basis for the mentioned differences in measurements. However, the HoloLens 2 uses eye tracking to align the hologram to the placement of the iris in the eyeball.

In relation to the above-mentioned problematic differences the development of deviating data can also be seen over time (from M2 to M4) for the three different test persons. The measurements are becoming closer and closer between the different test persons and the placement of the QR-codes the more the test persons use the technology. This can be seen as a sign of improving knowledge through experience in the use of the technology and thereby a better collaboration in the interaction between humans and the technology. between the different test persons and the placement of the QR-codes the more the test persons use the technology. This can be seen as a sign of improving knowledge through experience in the use of the technology and thereby a better collaboration in the interaction between humans and technology.

4. Discussion

4.1 TECHNOLOGICAL READINESS

The test showed clearly that the technology readiness of HoloLens 2 is deficient relative to the use case defined in this paper. The test showcased the limitations of the technology when the use case was driven to a point where the practical use does not relate to the context and structures of the real world. The use case was to make the layout of an interior wall, generated with the use of an augmented 3D model, to explore whether the technology could be a helpful artefact to make workflows more efficient and thus eliminate drawings on the construction site. It can be argued that together with the development of the technology in the market and more research in the field of the scope of this paper, the future may consist of using Augmented Reality to streamline information flow. More and more technology providers begin to develop Augmented Reality head mounted displays both as a consumer technology (APPLE , 2023) and as a market specific technology (XYZ REALITY LTD. , 2023). This will nevertheless drive the implementation and awareness of the future use of Augmented Reality in the construction industry.

Augmented Reality as a technology has left the Gartner Hype Cycle analysis in 2019 (GARTNER, 2019), maybe because it is overall ready to market. This analysis is done with a generic and broad perspective and not with the focus of the construction industry. If this analysis was to be done today it could be argued that Augmented Reality, in the context of this paper's use case, is at the Innovation Trigger phase and would reach the plateau of productivity in 5-10 years or more. On the other hand, if the overall use of Augmented Reality in the construction industry, analysed in a more generic context it could be evident that it could reach a plateau of productivity in 2-5 years or more.

4.2 HUMAN AND ORGANIZATIONAL ASPECT

The formulated use case and the test was an example of letting technology dictate how we humans perform tasks and completely rely on the technology. Technology has by itself created the reality that we solely rely on, and by that, not creating the different realities that we humans have by nature. In traditional artisanal working methods, it is the technologies that are the helping factor and artefact, where in the use case the roles were switched and we entered a function where we, unknowingly, where reduced to robots. In this meaning, the artisan will be as good as the used technology.

The core activity in the test was to place the wall based on the perceptions of the test subjects that made sense for them, where previous experiences from an analogue way of doing was used as framework of the task. The placement method was thereby plagiarized from an analogue method to a digital method using the HoloLens.

According to Yrjö Engeström (2001) and his work in the field of expansive learning, this will cause inconsistency in the outcome of a given activity, as the effects of the rest of the activity system, such as Community, Division of Labor, and Rules, have not been taken into account. By that means, it is not possible to believe that work methods, productivity, and human interaction with technology will be successfully implemented in the industry by only presenting a new technology that will replace already existing analogue work methods.

"Goal-directed individual and group actions, as well as automatic operations, are relatively independent but subordinate units of analysis, eventually understandable only when interpreted against the background of entire activity systems." (ENGESTRÖM, 2001, s. 136)

The test also showed that the boundary between technology and humans needs to be developed with a comprehensive and holistic manner to define where the authority is placed in the use of new technologies. This calls for a more human-centred way of using and developing future technologies, where the roles need to be defined and the focus on creating technologies that enhance professional competencies is at focus.

The discussion about how AR technology can be implemented as a use-full technology to enhance the information flow in the construction industry has a broader relevance than the topic of this paper. These elements in using and learning new technologies can also be used in creating a framework for future implementation strategies. The overall topic must be finding and creating a balance between technology and professional competencies. This development calls for more focus on knowing the different kinds of professional competencies and having technological competencies to create this kind of future framework where all aspects of the activity system are accommodated.

The strategy for the use of digitalization in the Danish construction industry (TRAFIK-, BYGGE- OG BOLIGSTYRELSEN, 2019) where the focus is largely on the aspects of using technologies in a better and more efficient way can be criticised. The strategy does not deal with the above-mentioned conflicts in using new technologies, where other, more human-centred aspects need to be taken in consideration. The strategy does not deal with these conflicts, where the context of the use of technology and the artisanal and professional competencies, by that meaning, elements in the activity theory system, is not changed. In other words, the other aspects of using digital technologies need to be revised or re-organized to fulfil the potentials in using new technologies in the construction industry.

5. Conclusion

The introductory purpose of this article was to examine the technology state of Head mounted Augmented Reality displays. Furthermore, create a specification of requirements and a concept to be able to use the technology to eliminate the use of drawings on the construction site. The preliminary test showed that the state of accuracy of the technology could not be aligned with the demands from the common standards in the industry. Therefore, a requirement specification and a concept will not make sense at this time as it will only be about the technology becoming technologically better.

The answer to the research question of this paper can summarised as: the current state of the technology does not align with the level of precision to facilitate a direct use of a projected holographic 3D model by an artisan to perform construction work.

Throughout the work with the technology in this paper, it is evident that there are other parts than the pure data collected in the test that can be drawn conclusions upon. The initial technological angle of approach was that the technology should work “out of the box”. Evidence from the test shows that human interaction with technology is taken for granted.

It has become evident that working with the current technology, training is necessary. Both in the use of the technology and in the understanding of what the technology contributes to and not contributes to. It arises that an understanding that we as humans must, of course, maintain a sound curiosity but especially, within that, a critical and reflective view of technologies, so the technology does not inadvertently take control and set the agenda. And by that means, as previously mentioned, turning humans into robots.

When we specifically gaze at Augmented Reality, where the technology is influential in creating a representation of a new reality, it is especially important that both the technology and the humans using it, are trained to be able to create a true understanding of reality.

The technological competencies of humans should encompass not only in-depth knowledge about the technology but also of the other shown activities in the test, both related to and in the use of technology.

6. Further work

As mentioned in the conclusion a further development of the technology where the spatial alignment of the holograms is taken into consideration. For this to happen, the large technology providers need to take action and by Apple's introduction of Vision Pro in 2024 (APPLE, 2023) there will undeniably be technological advancement in the future. The precision aspect of the technology could also be further supported by other kinds of technologies used on construction sites, such as Total Stations etc. The test in this article was done using a generic 3D modelled wall, and the level of detail of the geometry used for the holograms is an aspect that also needs to be taken into consideration and needs to be further examined.

The human factor in the test showed that there is more into getting understandable and legitimate data, that meets the eye. In the article the activity theory was used to give explanation of the human aspects in using the technology. Further development in this field could be done by examining the use in an Actor Network Theory context where all aspects of the interaction with the technology can be unfolded.

The use case formulated in the test was done with a very narrow focus of use, where it was solely focused on one work discipline in the construction industry. The most optimal use cases could therefore be examined, where other areas of the construction industry could be taken into consideration, including the manufacturing actors.

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DETERMINATION OF THE OPTIMUM INSULATION THICKNESS FOR DORMER ROOF DESIGNS: AN IRISH CASE STUDY

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Abstract. Improving the national residential building stock energy efficiency is an important step in meeting Irelands international obligations and EU commitment. Heat loss through a roof can accounts for up t0 30% of the building envelopes thermal energy losses. Substantial levels of insulation are required to mitigate against the building's energy losses. This study determined the optimum insulation thickness (OIT) for typical dormer roof designs in various regions around Ireland. Considering the investment costs associated with increasing the insulation thickness, retrofit measures for existing buildings will benefit from lower operational costs and a reduction in fuel consumption. The heating degree day (HDD) method was used to determine the building energy demand to maintain optimal thermal comfort levels in various locations across Ireland. This was paired with a p1-p2 life cycle analysis to assess combinations of insulation, heating energy systems and roof configurations based on their net savings. Each calculation produced figures on material payback periods, total costs, CO2 emission and heating demands. Results have shown a major difference in OIT and costs as HDD increases, over an insulation lifecycle, ensuring an increase in the annual cost savings potential and decrease in carbon dioxide emissions. Furthermore, there also exists regional differences in the payback periods and optimum insulation rates for each insulation type tested. Finally, a statistical analysis using analysis of variance (ANOVA) has also shown a significant difference between the mean and variance associated with OIT and costs of each group tested.

Keywords: Life cycle cost, Insulation, Roofs, Energy, Optimum insulation thickness.

1. Introduction

Since the 20th century, the effect of human activity through direct or indirect means has adversely contributed to the alterations in our planets climate patterns and systems. This means a change in our natural global atmospheric composition over comparable time periods through an increase in greenhouse gases (GHG) emissions caused by anthropogenic activities ("United Nations Framework Convention on Climate Change," 1992). To counteract the manmade catastrophe of climate change, various sectors of society have been targeted for energy reduction and as a consequence lower GHG emissions. In particular, the building sector in the European Union (EU) aims to reduce energy consumption of residential buildings through retrofit measures contributing to the 32.5% reduction in primary energy consumption (European Union, 2018). The built environment being the second largest energy consumer accounts for 40% of total energy usage and from a national perspective, the residential sector in Ireland accounts for a quarter of total energy consumption and CO2 emissions (Energy in the Residential

Sector 2018, 2018; International Energy Agency, 2021). Energy consumption in residential buildings occurs primarily through the use of lighting and appliances, cooking, domestic hot water, and space heating. The largest consumer of domestic energy is space heating at 67% (Energy in the Residential Sector 2018, 2018).

In order to achieve optimum energy conservation, adequate thermal protection is required to reduce the energy losses in building structures. The standards and building regulations underwent large changes in the 20th century right through to the 21st century, regularly refining home design to ensure an ever-improving thermal efficiency for national building stocks. While homes largely adhered to the building regulations of the times, the policies led to thermally inefficient buildings, especially in the pre-1978 era (Raushan et al., 2022). The pre-thermal building regulations did not provide for the addition of insulation in their building structure leading to high U values (W/m2K) for the roof, wall, and floor. On average for an uninsulated roof, up to 30% of the heat generated is lost to the environment (Muddu et al., 2021; NSAI: S.R. 54:2014&A1:2019 Code of practice for the energy efficient retrofit of dwellings, 2019). Subsequent to 1978, the post thermal era began albeit with varying levels of insulation resulting in very different U values based on the decade of construction.

At the time of writing, the world is experiencing excessively high energy prices for carbon-based fuels due to a multitude of global economic factors. The initial actions for deep energy retrofits involve increasing a dwellings insulation depth as a means to reduce energy consumption, improve thermal comfort conditions and lower CO2 emissions (Bolattürk, 2006). There exists a variation in the energy savings for insulation depending on the fuel type and construction assemblies. Bolattürk (2006) found various recommendations for the optimum insulation thickness (OIT) depending on fuel type, insulation type, wall configuration and energy transmission loads. Where the latter is modelled in life cycle costs (LCC) using the well-known degree day (DD) concept. This approach was used by Sisman et al. (2007). To investigate the optimum OIT and energy savings at ceiling level, albeit with a concrete roof. In Ireland, Muddu et al. (2021) found OIT increased as DD increased and varies regionally by up 30%. Numerous studies have focused on OIT for walls but less so on OIT for insulation at the ceiling or rafter level (Al-Sanea and Zedan, 2002; Cyrille Vincelas and Ghislain, 2017; Rosti et al., 2020).

Therefore, the LCC associated with installing additional insulation in an existing dwelling with a dormer conversion must be examined. Dwellings with dormer attics account for approximately 5% of the national housing stock in Ireland but have been excluded from energy efficiency improvement schemes as the capital costs of retrofit can far outweigh the savings from increased energy efficiency (i.e., the cost optimal model) (Ó'Riain and Harrison, 2016; "Warmer Homes Scheme | Midlands Warmer Homes | SEAI," 2020). The room in the roof restricts the space for insulation to the depth of the rafter resulting in a high U value. Moreover, a 50mm air gap is required to prevent condensation in this space, further restricting the insulation depth. This study will also examine the savings over 20 years used by Collins and Curtis (2017) when examining value for money associated with energy retrofits rather than the 10 years used by Muddu et al. (2021) for wall configurations considering the material lifespan is closer to the former. Additionally, OIT was examined using fuel and insulation costs based on peak 2022 market rates and compared with an average 5-year price. Thus, determining the savings accrued today and with a price that is not subjected to the current volatility of the market.

2. Methods

The DD method was used to determine the annual building heating transmission loads required to maintain optimal thermal comfort levels in various locations across Ireland. DD assumes that the outdoor temperature (To) directly effects the indoor (Ti) through a proportional relationship between the former and a specified threshold temperature (Th), in this case of 15.5°C and is modelled with:

$$DD = \sum_{days}(T_h - T_o)^+ \quad (1)$$

Muddu et al. (2021) found that DD ranges from 1900-3300 across the island of Ireland with an average of 2793 and these figures were used to evaluate the LCC. Upon configuration of the energy demands using the DD method, the next step is to determine the heat loss through unit surface area of a building fabric section such as roof or wall and is expressed through heat flux (ql) as:

$$q_l = U(T_i - T_0)$$
(2)

And the resistance of an existing as-built multi layered roof (Roof, as-built) is expressed as:

$$U_{as,built} = \left(\frac{1}{h_0} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \ \dots\dots + \frac{x_n}{k_n} + \frac{1}{h_1}\right)^{-1} \quad (3)$$

Where h0 and h1 are the heat transfer coefficients for the inside and outside surface respectively, kn is the thermal conductivity of individual layers and xn their corresponding thicknesses. Although it should be noted that there exist multiple conditions for an as-built multi-layered roof where the room design follows the slope of the ceiling, an uninsulated (RF1, U = 2.3 W/m2K) and partially insulated configuration as shown in Figure 1. The latter as built design with existing insulation is to be modelled with a depth of 75 mm (RF2, U = 0.5 W/m2K) and 125 mm (RF3, U = 0.35 W/m2K) currently installed.

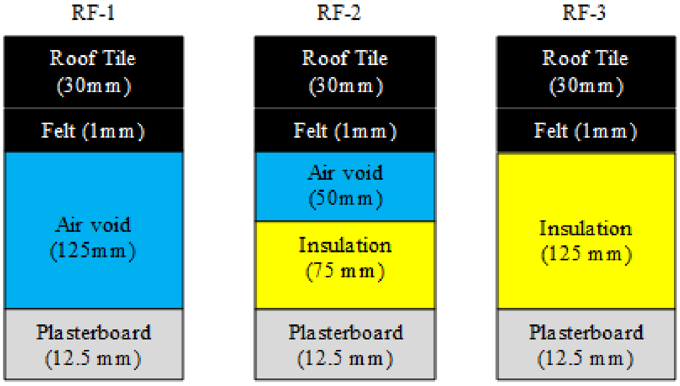

Figure 1. Pre-retrofit roofing configurations. Note: Post retrofit would include a vapour control barrier on warm side of insulation and insulation either laid perpendicular to rafters for RF-1 or internal wall insulation for RF 2 and 3.

The three roof configurations were taken from the recommend U values for insulation thickness based on their period of construction outlined by Raushan et al., (2022). Neither meets the current stipulated building regulations U value for existing dwellings but these values were chosen as a rafter on average is 125mm deep and the 75mm insulation for RF-2 incorporates the required 50mm air gap. Whilst RF-3, is an unventilated roof space and is not regulated for in Ireland but exists in practice. In addition, Liu et al. (2023) examined the impact of reduction ventilation gap, finding a negligible effect where the 50 mm is not adhered to, although the unventilated condition requires further examination. Therefore, three roof designs with different U values based on their level of insulation currently installed were analysed, assuming a limitation where only the 2D plane between the rafters is assessed. Both partially insulated roofs will have additional insulation added to internal walls of the dormer structure and/or to the rafter space for the uninsulated where the material assembly thermal resistance is now expressed as:

$$U_{tot,ins} = \frac{1}{R_{roof,as-built} + R_{ins}} = \frac{1}{R_{roof,as-built} + \frac{x_{ins}}{k_{ins}}} \quad (4)$$

Three insulation materials typically used for rafter insulation were chosen for assessment based on their thermal conductivity and costs per m3. An expensive polyisocyanurate with extremely low thermal conductivity (PIR-E, k=0.019 W/mK and 470 €/m3), standard polyisocyanurate (PIR-S, k=0.023 W/mK and 298 €/m3) and rock wool (RW, k=0.044 W/mK and 155€/m3). The annual heat losses (QAhl) can be determined by adjusting Eq. (2) from daily heat losses to annual with DD as the transmission load and accounting for the corresponding fuel efficiency (η) from Table 1 results in the annual heating demand:

$$E_{Ah} = \frac{Q_{Ahl}}{\eta} = \frac{86400UHDD}{\eta} = \frac{86400HDD}{(R_{roof,as-built} + \frac{x_{ins}}{k_{ins}})\eta} \quad (5)$$

C_F is the unit price of fuel (unit/kWh), which is determined by the product of the fuel costs per unit (C_f) and annual fuel consumption (m_{af}) and LHV is the lower heating value in (MJ/kWh, MJ/Kg or MJ/m^3):

$$C_F = C_f m_{af} = \frac{86400 HDDC_f}{LHV\eta(R_{roof,as-built}+\frac{x_{ins}}{k_{ins}})} \quad (6)$$

Where the heating fuels assessed are electricity (E), heating oil (HO) and gas (G) whose fuel parameters including LHV, η and fuel costs are assessed in Table 1. In addition, the CO2 emission for each fuel is considered through emission factors of 0.435, 0.257 and 0.209 kg/kwh for E, HO and G respectively. A reduction in a dwelling's energy consumption is inherently tied into the insulation material, thickness and boundary conditions. Improving a building envelopes U value through the addition of insulation materials with low thermal conductivity also requires an economic assessment in order to evaluate OIT.

TABLE 1. Fuel parameters be assessed for OIT in this study.

HF	LHV	η	5-year average	2022 cost
			€/kWh	
E	3.48	1	-	0.438
HO	44.2	0.9	0.083	0.155
MG	34.8	0.9	-	0.146

As the insulation thickness increases, at some point the increase will no longer be economically viable and balance must be ascertained. In effect, a cost analysis using the P1-P2 LCC method is to be used as this has been employed extensively for multi component walls/roofs (Al-Sanea and Zedan, 2002; Bolattürk, 2006; Cyrille Vincelas and Ghislain, 2017; Muddu et al., 2021; Rosti et al., 2020). P1 is the life cycle energy shown in Eq. (7) which is used to calculate the present worth factor (PWF) in order to evaluate the current worth of the total investments and net energy savings. P1 is based on the market discount rate (d), inflation rate (i), economic analysis period (n) and C accounts for the income or non-income producing dwellings. A 8% inflation was used based on the current economic climate and as previously mentioned n was taken to be 20 years and a market discount rate of 10% was used and also adapted from this study (Collins and Curtis, 2017). In the case of the latter variable, this considers rental income on the dwelling where C=0 for owner occupied and C=1 for rented buildings. Only the former is considered as approximately 70% of dwellings are owner occupied in Ireland and is expressed as:

$$P_1 = (1-C)PWF(n,i,d) = \sum_{j=1}^{n} \frac{1+i^{j-1}}{1+d^j} = \begin{cases} \frac{1}{d-1}\left[1-\frac{1+i^n}{1+d}\right], i \neq d \\ \frac{n}{1+i}, i = d \end{cases} \quad (7)$$

Additional capital investment on top of the initial investment is determined through the ratio of the life cycle expenditure (P2). Muddu et al. (2021) found that P2 is highly variable across the different dwelling types, economies, resale, state of the housing market etc. and also suffers from a lack of data availability. Hence, additional capital investment is typically not considered and P2 is taken as unity (Bolattürk, 2006; Muddu et al., 2021; Sisman et al., 2007). The total annual costs (Ct) of the energy consumed in the rooftop is expressed through P1 and P2 as:

$$C_t = P_1 C_F + P_2 C_I = PWFC_F + C_{ins}.x_{,ins} \quad (8)$$

C_{ins} is the cost of insulation per unit thickness. The net energy savings *(S_{net})* accrued is the difference between the energy usage costs pre and post retrofit:

$$S_{net} = \frac{86400PWFHDDC_F}{LHV\eta}\left(\frac{1}{R_{roof,as-built}} - \frac{1}{(R_{roof,as-built}+R_{retrofit,ins})}\right) - C_{ins}.x_{ins} \quad (9)$$

In order to calculate the payback period (PBP) of the investment the S_{net} in Eq. (9) is set to zero, such that:

$$PBP = \frac{C_I}{\frac{S_{net}}{PWF}} \quad (10)$$

And setting the partial derivative of Eq. (9) with respect to x to zero, OIT can be obtained with:

$$x_{opt} = 293.94\sqrt{\frac{(HDD\ C_F\ k_{ins}PWF\ )}{LHVC_{ins}\eta}} - k_{ins}R_{as\_built} \quad (11)$$

3. Results

3.1. INFLUENCE OF INSULATION ON OIT FOR VARIOUS AS-BUILT ROOFING CONFIGURATIONS

The LCC methodology used here is designed to optimise the insulation thickness in order to maximise the reduction in the life cycle energy costs. Greater levels of insulation reduce the energy losses and by extension fuel costs, but the capital investment on insulation must be at a minimum to maximise the return on investment. The results from Figure 2 detail the impact of the total costs associated with the fuel consumption and insulation costs for the PIR-S as the thickness increases. OIT was found to be larger for RF-1 at 0.076 m compared to OIT of 0.042 m for RF-2 and 0.024 m for RF-3. OIT occurs when the minimum total costs are determined as shown Figure 2 where the slope of the total costs trendline is equal to zero. Moreover RF-1 minimum lifecycle costs at the OIT amounts to 48 €/m^2, RF-2 is 38 €/m^2 and RF-3 results in 32 €/m^2. These minimum values are related to the impact of increasing insulation thickness and its impact on decreasing fuel costs. However, once the insulation thickness passes the point where the minimum lifecycle costs occur, the increase in costs of the insulation now starts to negatively impact the return on investment by increasing the total costs.

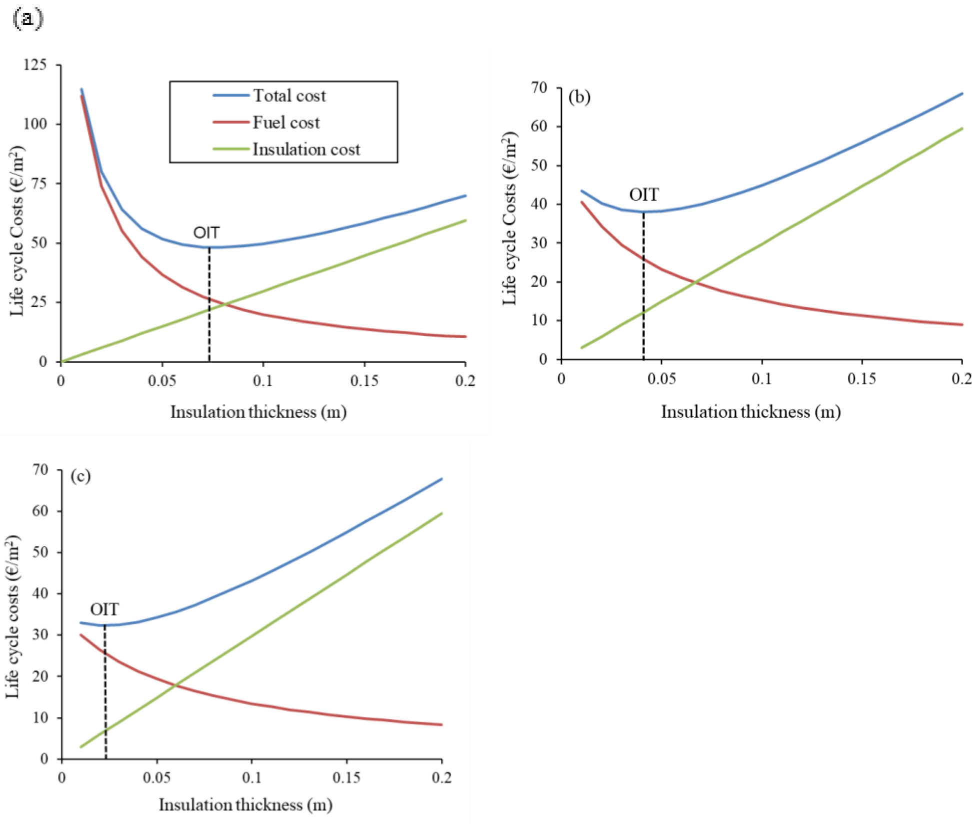

Figure 2. Effect of the insulation thickness for PIR-S insulation with a DD of 2793 and using a 5-year average oil price for (a) RF-1 (b) RF-2 (c) RF-3.

OIT also varies across insulation type and based on the magnitude of the required heating transmission loads as illustrated in Table 2. For example, PIR-E, PIR-S and RW ranged from 0.044-0.061 m, 0.061-0.084 m and 0.12-0.164 m respectively over a DD range of 1900-3300 for RF-1. OIT gets larger with increasing DD for all insulation types and smaller as the insulation thermal conductivity increases. Alas, this results in higher PBP for the more efficient insulation, as it is typically more expensive to manufacture materials with ever reducing thermal conductivity. At the average DD of 2793 for RF-1, the PBP of the RW is 1.93 years which extends to 2.1 years for PIR-S and 2.88 years for the most expensive insulation PIR-E. Furthermore, applying the same analysis to RF-2 and RF-3 where insulation is currently installed rather than uninsulated, OIT reduces for all insulation types and their PBP exceeds the life cycle analysis period due to the low energy savings and high capital costs.

TABLE 2. Impact of DD on OIT and payback period for each insulation and roof type.

Ins	DD		RF-1	RF-2	RF-3
PIR-E	1900	OIT	0.044	0.014	0
		PBP	2.88	43.9	0
	2793	OIT	0.055	0.025	0.009
		PBP	2.32	23.1	92

	3300	OIT	0.061	0.031	0.015
		PBP	2.1	18.31	64.31
PIR-S	1900	OIT	0.061	0.027	0.008
		PBP	2.4	25.8	131
	2793	OIT	0.076	0.042	0.023
		PBP	1.93	16.3	43.6
	3300	OIT	0.084	0.049	0.03
		PBP	1.78	13.7	31.54
RW	1900	OIT	0.12	0.051	0.013
		PBP	2.46	27.1	175
	2793	OIT	0.149	0.08	0.043
		PBP	1.99	16.81	45.85
	3300	OIT	0.164	0.095	0.057
		PBP	1.81	14.26	33.8

This variation in the annual energy cost savings between each rooftop in Figure 3 is attributed to the existing insulation in RF-2 and RF-3. Whereas pre-energy retrofit, RF-1 is completely uninsulated leading to high energy losses and the subsequent post retrofit incurs much larger energy savings irrespective of the insulation thickness. More importantly, RF-2 and RF-3 only result in low levels of energy savings due to the existing insulation and is typically only effective at thinner insulation thicknesses. For example, the former roof type, has no energy saving beyond 0.12 m and the latter 0.05 m. Whereas RF-1 substantial energy savings are consistently positive regardless of insulation thickness.

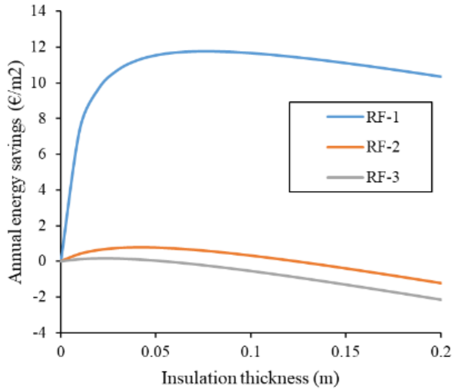

Figure 3. Annual energy savings comparison between the rooftop configurations across a range of insulation thicknesses.

3.2. IMPACT OF FUEL TYPE COSTS IN 2022 ON OIT FOR VARIOUS ROOFING CONFIGURATIONS

The last section used a 5-year averaged HO price for analysis, but recent events have driven fuel prices to an exceptionally high level of cost. The price of HO in 2022 is nearly double the averaged five-year price and therefore an analysis on the impact of fuel prices on energy savings was performed in Figure 4 to ascertain the impact of the energy crisis. Heating a residential dwelling with E results in the highest energy savings compared to the other fuel types as the cost per kWh is far greater. Whereas G was somewhat cheaper than the HO, and it returned similar energy savings as the LCV is greater for the latter. Whilst RF-1 and RF-2 consistently had positive energy savings with today's prices, insulation thickness above 0.15 m resulted in a loss of investment for RF-3.

Contrasting this with the 5-year averaged HO price shows that the volatility of the fossil fuel market can have a significant impact on the energy savings accrued after the installation of additional insulation. Up to 60 €/m^2 energy savings can be achieved with RF-1 when E is the primary energy supply for space heating. This drops to approximately 20 €/m^2 for HO and G heated dwellings. A significant drop then occurs for RF-2 and RF-3 ranging from 1-2 €/m^2 and 0-1 €/m^2 for HO and G respectively. Again, the E heated dwellings have a higher return on investment at 8 €/m^2 for RF-2, dropping to approximately 4 €/m^2 for RF-3.

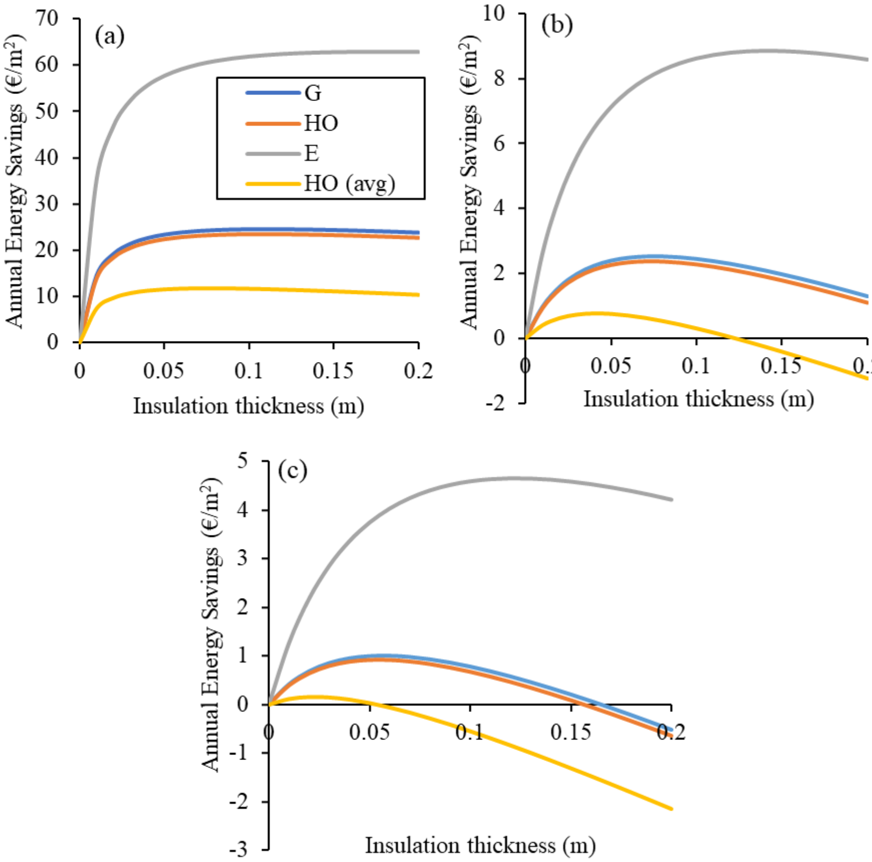

Figure 4. Influence of fuel type on energy savings with PIR-S and DD of 2793 for (a) RF-1 (b) RF-2 (c) RF-3.

Outside of the economic savings, retrofitted insulation results in a lower operational carbon emissions from the fuel sources as the insulation thickness increases. This is illustrated in Figure5a where the CO_2 emissions are 34.8, 44 and 67 Kg for the G, HO and E respectively lowering to ≤ 11 kg with a minimum addition of 50 mm PIR-S insulation. Contrasting this with Figure5b for HO dwellings, the difference in CO_2 savings is not as substantial for RF-2 and RF-3 as the insulation thickness increases. Finally, the impact and change in CO_2 is not as consequential past the addition of 100 mm insulation.

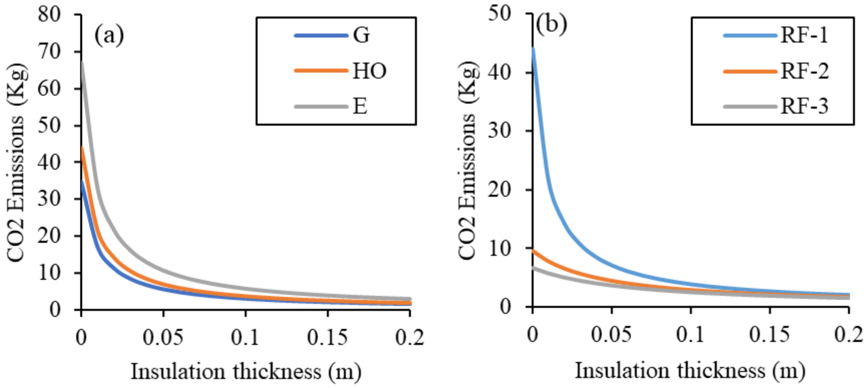

Figure 5. Assessment into the impact the addition of insulation has upon the CO_2 emissions from (a) each fuel type with RF-1(b) roof type with HO.

4. Discussion

4.1. REGULATED U VALUE VS OIT

The LCC methodology seeks to minimise the investment in insulation while maximising the financial returns but does not consider the stipulated building regulations U value for a roof. In other words, the OIT for each insulation may not necessarily adhere to the minimum regulated U value. Using the average HO price and a DD of 2793; U values with their corresponding OIT rounded to the nearest 10mm of 0.06 m (PIR-E), 0.08 m (PIR-S) and 0.15 m (RW) for RF-1 amounts to a U value of 0.28 W/m^{2}k, 0.25 W/m^{2}k and 0.26 W/m^{2}k. The current Irish building regulation Technical Guidance Document L Conservation of Fuel and Energy – Dwellings requires a U value of 0.25 W/m2k, thus only PIR-S meets this threshold (Building Regulations 2022 Part L: Conservation of Fuel and Energy – Dwelling, 2022). Lowering the DD to 1900 results, in all the insulation types and their respective OIT incurring U values that exceed the building regulations. On the opposite end of the spectrum at a DD of 3300, the U values for both RW and PIR-S OIT lead to U values lower than the building regulations. Whilst the most expensive insulation with the lowest thermal conductivity when using its OIT never meets the building regulations. A balance between the type of insulation used based on their cost and efficiency must therefore be sought when considering the appropriate retrofit measures.

4.2. IMPACT OF BUILDING WORKS AND LABOUR COSTS

It should be mentioned that the application of insulation in a dormer attic will require other remedial work that will drive up the initial capital costs. Labour costs were not considered and are typically neglected in these studies (Al-Sanea and Zedan, 2002; Bolattürk, 2006; Cyrille Vincelas and Ghislain, 2017; Muddu et al., 2021; Rosti et al.,

2020) due to the variation dwelling to dwelling and across locations. The addition of plaster, paint and re-fixing of electrical devices will be required in most retrofit scenarios, but the cost will be highly variable depending upon the building size, type, and location. The large energy savings for RF-1 which is uninsulated, post energy retrofit would be lessened with extra costs but still expected to be financially viable. In addition, the number of government grants that are available for roof and wall insulation retrofit measures would more than offset the extra costs, if added to the national retrofit schemes.

4.3 INFLUENCE OF RISING FUEL COSTS ON OIT

The results have shown that there is a significant impact on the energy savings achieved when taking into account the volatility of the worldwide energy markets. As fossil fuel prices rise, the energy savings increase with the addition of insulation to the dormer attic making the potential for retrofit more financially advisable. This is especially true for uninsulated rooftop when compared with its partially insulated counterpart. Although the other roof configurations where insulation is currently installed might not result in a return on investment due to the low energy savings. Long payback periods and the remedial works might wipe out the slight positive returns. In their case, the thickness needs to be increased to meet the building regulations by adding PIR-S panels internally to the dormer room and the return on the investments is minimal. Although the introduction of the dormer dwelling to government retrofit programmes would help alleviate fuel poverty and lead to a better thermal comfort for the occupants.

4.4 IMPACT OF INSULATION RETROFITTING ON A PROPERTIES AVERAGE PRICE PER M^2

The addition of insulation internal to the room in order to improve the roof structures U value has two knock-on effects. The first relates to a system that measures the energy performance of households using building energy rating (BER) or known internationally as energy performance certificates (EPCs). The alpha-numeric EPC system grades the energy efficiency of a building on 15-point scale with A being the most efficient and G the worst. A deep energy dwelling retrofit can incur multiple benefits where Curtis and Pentecost (Curtis and Pentecost, 2015) found that every 1-point increase on the BER scale in Ireland coincides with a 1.6% reduction in energy expenditure. In addition, dwellings with excellent BER ratings on today's property market increases the value of the property depending on location, existing condition of the dwelling (i.e., levels of insulation and renewable technology) and the scale of the upgrades (Hyland et al., 2013). Hurley and Sweeney (Hurley and Sweeney, 2022) found that increasing a dwelling from a G grade to an A on the BER scale could increase the value by 13 %. Most studies focus on the impact of the BER rating on the property value, but a negative effect not typically considered when retrofitting internal insulation is the loss of the dwellings value based on the average property price per m^2. Installing insulation in the loft space will reduce the liveable floor area and thus the value of the house. Although the magnitude of the loss is dependent on the location. A three-bed semi-detached home in rural Ireland such as county Longford, the average price per m2 is less than 1000 € and over 5000 € in certain areas of urban Dublin (Lyons, 2017).

4.5 ASSESSMENT INTO THE STATISTICAL SIGNIFICANCE OF THE FUEL AND INSULATION TYPE ON THE ROOF CONFIGURATIONS

A statistical analysis was also conducted examining the statistical significance between the 2022 fuel types, roofing configurations and insulation types for the energy savings. For an analysis of variance (ANOVA) to be used, the datasets were checked for a normal distribution and homogeneity between the group's variances. The datasets were found to have a non-normal distribution and a heterogeneity of the variances. Therefore, a non-parametric ANOVA was chosen known as Kruskal-Wallis one way ANOVA and a post hoc pairwise comparison to identify the groups that are significantly different. Three different scenarios were tested with a significance of 0.05, examining the following groups: insulation to fuel and roof type, fuel to roof and insulation type and roof configuration with respect to fuel and insulation.

For each of these tests, the results showed a significant difference for all three scenarios. The post hoc test was subsequently employed to determine which groups were significantly different. Taking the first scenario which involved analysing the differences between insulation types. The results found there were significant differences comparing PIR-E and PIR-S for each case study except for E-RF-1. When comparing PIR-E and RW, only G-RF-2, G-RF-3, O-RF-2, O-RF-3 have significant differences between these insulation types. And PIR-S vs RW led to a significant difference when electricity is used but not HO or G for each roofing configuration across the insulation types. The next group examined was the variation in the energy savings when comparing fuel types. There was no significant difference for any of the insulation rooftop pairings between the oil and gas but a significant difference when contrasting the E with either HO or G across all groups. The final analysis looked at the roofing configurations and found all groups when pairing insulation and fuel types were significantly different across the roofing configurations.

5. Conclusion

In conclusion, the OIT was found for several different types of insulation with a PIR-S insulation type resulting in the optimum financial outcomes. This insulation was found to more cost effective than it's more expensive counterpart and require less space than RW. This is especially important for dormer attics where space is limited. Furthermore, PIR-S OIT typically resulted in a thickness that would lead to an adherence to the building regulation U value for roofs. Examining the energy saving for an uninsulated RF-1 and roofs partially insulated but not meeting regulations (i.e., RF-2 and RF-3), resulted in a large difference. RF-1 incurred savings of 20 €/m^2 using the average HO price compared to approximately 0-2 €/m^2 for the latter roofing configurations. Although fuel type and cost have a major impact on the level of energy savings. The 2022 oil and gas prices generated similar savings as per ANOVA but the more expensive energy source, E, had nearly three times the savings. Finally, the addition of insulation to an uninsulated attic space also massively lowers the CO_2 emissions through fuel reduction usage. This also occurs for the other roofing configuration, but the reductions are much less. In other words, meeting the building regulations through OIT is cost effective and lowers the operational carbon emissions of a building. Further analysis should be conducted using a 3D whole building model on the impact of embodied carbon, hygrothermal conditions and LCC of different building archetypes, post retrofit.

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HOW ARTIFICIAL INTELLIGENCE WILL CHANGE THE HOUSING RETROFIT PROCESS

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Abstract. The operation of the housing stock in the UK is reported to contribute 18% of the total carbon emissions. The UK is required to achieve net zero emissions by 2050. As 80% of the housing stock of 2050 is already built, retrofitting the existing housing stock to meet sustainability requirements is critically important. However, due to various reasons, the progress of housing retrofit in the UK is stagnated. Artificial Intelligence (AI) has been a buzzword in technology for a long time. Recently there has been considerable progress. It is believed that AI will influence a lot of areas in different aspects. However, the full potential of AI is yet to be identified. Considering these aspects, the paper tries to identify the potential change brought about by AI to housing retrofit. The study has been conducted as a selective literature review, followed by a CATWOE analysis. The findings of the study show that the designing process and project management functions as the clear beneficiaries of artificial intelligence. Further, the government and the construction companies as the owners will also have a considerable influence. Mainly, the processes applicable to housing retrofit will be optimised with artificial intelligence. The findings of the study mainly benefit policymakers, homeowners, retrofit professionals and construction companies. However, this study will show only the possible directions of AI towards housing retrofit. The revolution of artificial intelligence is now a documented reality. Accordingly, the synergy of housing retrofit, and AI is an important opportunity to move the industry forward.

1. Introduction

1.1. HOUSING RETROFIT

Housing retrofit can be identified as improving housing performance by installing various measures. Although the housing retrofit is mainly viewed from an energy efficiency perspective, a retrofit can be considered in many aspects. E.g., Structural performance (Cao et al., 2022) or seismic performance (Dauda and Ajayi, 2022). A general housing retrofit project will ideally contribute to improving energy efficiency as well as health, comfort, aesthetics, and durability (UKGBC, 2021; Passivhaus Trust, 2021). The housing retrofit is quality controlled under PAS 2030;2019 and 2035;2019 frameworks by the British Standards Institution (The Retrofit Academy, 2021). The retrofit process has several steps, according to BSI (2019). They are the assessment, strategy, design and specification, installation, handover, and monitoring/evaluation. First, the house is assessed for retrofit requirements by the retrofit assessor. The retrofit co-ordinator shall decide and agree the retrofit measures and their order. The retrofit designer shall design the retrofit measures. Retrofit installers can install the retrofit measures according to the design. Once the project is handed over back to the client, the retrofit evaluator should evaluate the performance.

Housing retrofit is something that needs to be accelerated for the next three decades in the UK for net zero in 2050 (DBEIS, 2021). The retrofit progress in the UK is currently below 200,000 per year. This should be increased to at least 1,200,000 per year to meet net-zero targets (Parliament UK, 2021). According to IEA (2021), the progress of housing retrofit is extremely poor. Without a significant turnaround in the way of driving retrofit, the trajectory of retrofit completion will not meet 2050 net zero targets.

1.2 ARTIFICIAL INTELLIGENCE REVOLUTION

Artificial intelligence is a discipline that blends computer science with extensive data sets in order to solve problems, that usually need human intervention. It includes sub-disciplines like machine learning and deep learning, which are often mentioned alongside AI. These fields are composed of algorithms designed to build skilled systems capable of making predictions or classifications based on input data (IBM, 2023). Artificial intelligence is the science involved with computer systems which can learn, reason and act like humans. This is a multi-disciplinary science which has roots in computer science, statistics, data analytics, linguistics, etc. AI is mainly based on technologies such as deep learning and machine learning (Google Cloud, 2023).

Akinsola et al. (2022) refer to artificial intelligence as the most prominent technology which revolutionizes the world. They call AI a disruptive technology that changes how consumers, businesses and industries behave. Agreeing with this, Lazzeretti et al. (2022) propose that artificial intelligence is still an emerging topic. Most literature on AI was published after the year 2020. Accordingly, artificial intelligence can be considered to be in an earlier stage of its application. In the future, more significant developments are to be expected. Although the possibilities of artificial intelligence are still uncertain, there can be a considerable influence from AI on the way of doing retrofit. Accordingly, this study looks at how artificial intelligence will influence the retrofit processes and address retrofit challenges.

The concept of artificial intelligence first came into conversation when Alan Turing answered the problem of “Can machines think?” in 1950. He used an example test called “Turing Test”. This debated the field for some time. However, the term “Artificial Intelligence” came into the vocabulary in 1956 at an Academic conference on AI. After different levels of progress in the AI field, 2023 showed a considerable boom in the AI field with AI language models such as ChatGPT (IBM, 2023). According to Bill Gates, there are two breakthrough phenomena that he has witnessed in his lifetime. One is the graphical user interface (GUI) in 1980 and the other is the Artificial Intelligence in 2022. An AI program was able to score 59 out of 60 MCQ in the advanced biology examination in the USA while scoring A Plus for the essay part.

Accordingly, the world is witnessing a dramatic change in the way computers are operated (Gates, 2023).

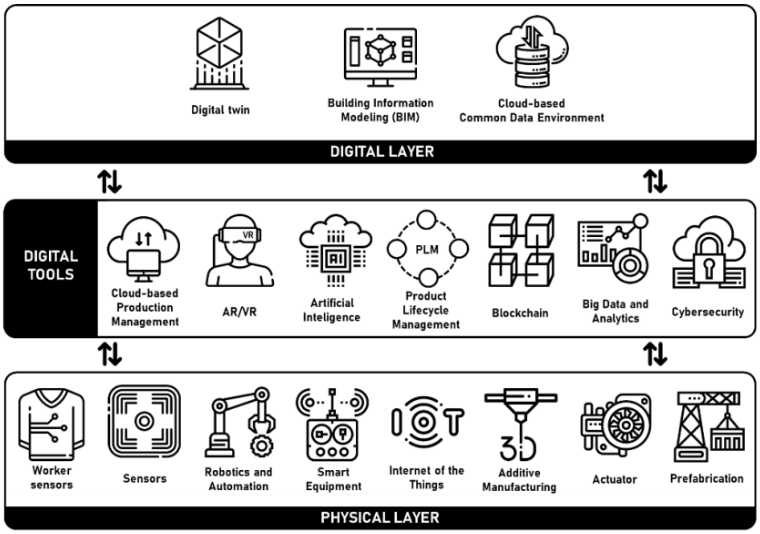

Figure 1: Interaction between AI & construction (Sawhney et al., 2020)

According to Sawhney et al. (2020), artificial intelligence comes as a tool between the physical layer and the digital layer of construction. The challenges of construction 4.0 can be suggested as resistance to change, uncertainty over the value proposition, higher initial costs, low level of research, skill shortages, industry fragmentation, lack of standards, data security issues and legal uncertainties. When artificial intelligence is discussed, construction 4.0 must be considered as a related parallel development. Construction 4.0 is considered as the situation of digitalising the construction industry plus the industrialisation of the construction processes (Forcael et al., 2020).

1.3 OBJECTIVE

The objective of this study is to identify the potential change of housing retrofit due to artificial intelligence with the different stakeholders involved.

2. Methods

Housing retrofit can be identified as improving housing performance by installing various measures. Although the retrofit of housing is mainly viewed from an energy efficiency perspective, a retrofit can be considered in many aspects. E.g., Structural performance (Cao et al., 2022) or seismic. Data was collected by way of a selective literature review. The articles published in peer-reviewed journals were chosen for this purpose. A selective literature review was chosen over a systematic review due to the low availability of articles with both AI and housing retrofit together. Accordingly, articles studying AI influence in the construction industry were used for this study and they were adapted for housing retrofit. The literature review gathered data about the potential of AI technologies in the construction industry under five topics: natural language processing, computer vision, machine learning, robotic process automation and optimisation. Finally, a soft system analysis under CATWOE model was done to identify the big picture of artificial intelligence and housing retrofit from the stakeholders' perspective.

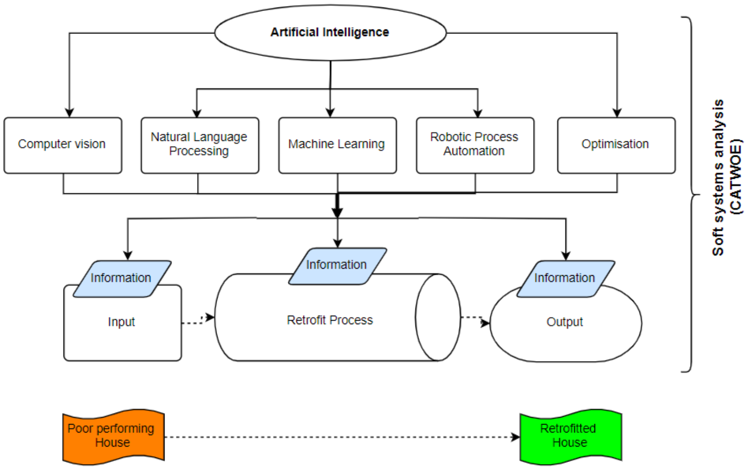

Figure 2: Conceptual framework for methodology

3. Findings

3.1 CAPABILITIES OF ARTIFICIAL INTELLIGENCE

As far as the literature is reviewed, literature is found mainly in the field of construction. Journal articles are lacking in the area of housing retrofit, which have studied the influence of different AI technologies on housing retrofit. In this situation, the following selective literature is consisting of the findings of journal articles about different AI technologies and their influence on general construction industry sections. The next section is dedicated to doing a soft system analysis of how these AI technologies will influence housing retrofit. For this purpose, the housing retrofit industry is specifically focused on.

3.1.1 *Computer vision*

TABLE 1: Summary of computer vision

AI category	Example capabilities
Computer vision	1. Managing safety in construction (Khan et al., 2022) 2. Making intelligent buildings with higher energy efficiency (Tan et al., 2022) 3. Managing construction waste (Lu et al., 2022) 4. Monitoring the progress of construction (Reja et al., 2022). 5. Identifying defects in buildings (Ai et al., 2023)

Computer vision is the acquiring and processing of images for visual simulation. Accordingly, computers can sense the visual environment (Tan et al., 2022). Khan et al. (2022) have proposed the use of computer vision for safety management in construction. By placing CCTV cameras in the workplace, an AI model is used to identify and alert unsafe behaviour of the workers. The accuracy was 98%. In another case, Tan et al. (2022) have studied the use of computer vision AI in intelligent buildings for controlling lights. The accuracy was 95.15%. Lu et al. (2022) used computer vision to identify and segregate construction waste. The AI model is useful for managing construction waste in real-life and complex scenarios. Using computer vision for progress monitoring in construction sites was discussed by Reja et al. (2022). Another study has looked at using computer vision AI to identify cracks in civil infrastructure. Computers can analyse images or videos more effectively than humans (Ai et al., 2023).

3.1.2 *Natural language processing*

TABLE 2. Summary of Natural Language Processing

AI category	Example capabilities
Natural language processing	1. Analysing text to improve construction project intelligence (Ding et al., 2022) 2. Reviewing project specification (Moon et al., 2022) 3. Automating the compliance check of designs (Zhang & El-Gohary, 2016) 4. Facilitating smart construction (Higher performance and productive construction) 5. Dispute resolution support (Hassan et al., 2021) 6. Bridging the humans and buildings interface (collecting occupancy data to machine readable data) (Panchalingam & Chan, 2019)

According to Duduka et al. (2022), natural language processing (NLP) AI models help humans to be involved with complex tasks of software with simple language. The input doesn't have to be perfect. There are two potentials of AI identified by Zheng et al., (2022). One is text classification and the other is the management of content. This can be further improved by optimising the model with a better amount of data. Ding et al. (2022) Suggest that with Construction 4.0, NLP can be highly used in the construction industry. NLP will be important to analyse texts to create construction project intelligence. Moon et al. (2022) suggest the importance of NLP for construction specification review. Zhang & El-Gohary (2016) have evaluated the potential of using NLP for automated construction regulatory compliance checking. Another study has studied the potential of NLP for smart construction. AI will be useful in improving information extraction, integration, and decision-making help (Wu et al., 2022). The potential of NLP to screen legal documents and contracts to help resolve construction disputes is proposed by Hassan et al. (2021). The objectivity of interpretation by AI can be the key point when it comes to artificial intelligence. Panchalingam & Chan (2019) highlight the difficulty of getting occupants' data related to the buildings and the potential use of NLP as an interface between humans and buildings.

3.1.3 Machine Learning

TABLE 3: Summary of Machine Learning

AI category	Example capabilities
Machine learning	1. Performance prediction of composite materials (Khambra & Shukla, 2021) 2. Quality management in industrialised manufacturing/off-site construction (Siebert et al., 2021) 3. Estimation and prediction of building construction cost (Alshboul et al., 2022) 4. Predicting and mitigating workplace accidents/ improving health and safety (Koc et al., 2022) 5. Project delay prediction and estimation (Gondia et al., 2020)

In machine learning, the computer makes decisions using a large amount of data. However, how the decision is made is not visible (Siebert et al., 2021). Khambra & Shukla (2021) talk about using machine learning in fly ash concrete. As the use of fly ash for concrete is more sustainable, AI can help to predict the performance after construction. Another study has evaluated using AI for managing quality in industrial processes. Quality measurement is one of the main aspects in industrial cases. Further, when it comes to prefabrication, most items are manufactured off-site. Siebert et al. (2021) used machine learning for quality management in concrete manufacturing. Alshboul et al. (2022) use machine learning to predict cost of the green buildings. With machine learning, the accuracy of the cost estimate can be improved. Koc et al. (2022) suggest that the use of machine learning can be helpful in predicting and mitigating workplace accidents. Further, Gondia et al. (2020) have used machine learning algorithms to predict and estimate project delays. Construction project delays are highly critical in managing the project to the objectives.

3.1.4 Robotic Process Automation

TABLE 4. Summary of Robotic Process Automation

AI category	Example capabilities
Robotic process automation	1. Construction with robotic automation with BIM (Wong Chong et al., 2022). 2. Improving the processes of automating prefabrication (Xiao et al., 2022; Feldmann, 2022) 3. Improving construction productivity and safety (Onososen & Musonda, 2022) 4. Automated masonry construction with robotics (Bruckmann & Boumann, 2021) 5. Health and safety benefits due to automation of manual works (Aghimien et al., 2022)

Robotic automation can be simply defined as the physical motion of things for performing various tasks (Xiao et al., 2022). A study suggested that the use of robotic automation in construction together with BIM is 39 times faster than usual (Wong Chong et al., 2022). Xiao et al. (2022) further suggest that prefabrication, collaboration, and automation have potential with robotic processes. Onososen & Musonda (2022) predict a higher level of potential for robotics in construction, especially in improving productivity and safety. Further, Feldmann (2022) shows the potential of robotic automation in improving modular construction and prefabrication.

Another research team has published their work on cable-driven robots for masonry construction of walls (Bruckmann & Boumann, 2021). Aghimien et al. (2022) suggest that the implementation of robotic automation is obvious in the future. One benefit of this is the enhanced safety levels due to the automation of manual human work.

3.1.5 Optimisation

TABLE 5. Summary of Optimisation

AI category	Example capabilities
Optimisation	1. Process optimisation 2. Product optimisation 3. Tools optimisation 4. Solution optimisation

Generally, optimisation can be defined as an equilibrium between the benefit and the risk. It is not getting something more than necessary or something less than necessary. Further, it also focuses on what must be sacrificed to achieve the required level of value. According to Sayers (2022), artificial intelligence and meta-heuristics have powerful capabilities of multi-objective optimisation. These technologies will be able to handle highly complex problems in construction as well as solve the current optimisation issues. Berk Ekici et al. (2022) have studied the potential of artificial intelligence in optimising self-sufficiency in high-rise buildings. The brief insight of the study is that artificial intelligence is highly useful in the optimisation of different aspects of construction (Abioye et al., 2021). It is hard to list them all as the list is exhaustive. Generally, processes, products, tools, and solutions can be given as examples.

3.2 CATWOE ANALYSIS

This is an analysis to identify the potential change in a business, as suggested by Peter Checkland under soft System Methodology. According to the author, this can be used to prompt ideas about business problems and solutions with regard to change. CATWOE analysis uses a stakeholder perspective when looking at the change and it expects to see the big picture of the situation (Newbert, 2023).

TABLE 6: Definition of CATWOE analysis (Basden & Wood-Harper, 2006)

	Term	Definition
C	Customer	Parties influenced by the system
A	Actors	Parties who carry out the transformation
T	Transformation Process	The way the current situation is transformed into the desired situation
W	Worldview	The big picture of the transformation
O	Owner	The decision maker
E	Environmental constraints	Restrictions that will impede the transformation

In this section, a CATWOE analysis is done for the inputs to the retrofit process. Accordingly, the analysis will show how AI will change the retrofit process inputs. Only the above-shortlisted AI technologies are considered for this purpose. The literature findings about AI capabilities are not specifically for the retrofit industry. However, they were adapted to the retrofit industry characteristics for the purpose of this analysis.

TABLE 7: CATWOE analysis

	Term	Application	Description
C	Customer	Homeowner and tenant	The homeowners or/and the tenants of the house are the parties who are affected by the change
A	Actors	Retrofit professionals	Retrofit professionals such as project managers (coordinators), designers, engineers and energy assessors are some examples of professionals
T	Transformation Process	Using AI for retrofit processes	The AI will be adopted in retrofit to change the industry for the better
W	Worldview	Better project delivery	The expectation is to make the retrofit project delivery better
O	Owner	Government and construction companies	The government and/or the construction companies involved in retrofit should make the decision.
E	Environmental constraints	Resistance to change, High initial costs.	There are several potential constraints. Some of the examples are given.

4. Discussion

The discussion is aimed at relating the AI capabilities to the CATWOE analysis. CATWOE analysis was done for housing retrofit while the selective literature review about AI capabilities was done in the general construction industry. Accordingly, the purpose of this discussion is to find out how AI capabilities influence change in housing retrofit.

4.1 CUSTOMERS

With the retrofit process, there are two possible influenced parties. One is the homeowner who owns the house. The other is the tenant, ideally living in the house under a rent agreement. One of the important aspects of housing retrofit for the customer is energy efficiency. According to Tan et al. (2022) computer vision can be useful in making intelligent buildings with higher energy efficiency. In addition, NLP can be helpful in resolving disputes between the customer and the contractor (Hassan et al., 2021). Further, NLP can be used to collect occupant data and understand their behaviour (Panchalingam & Chan, 2019). In general, the use of AI will be able to help the retrofit experience better with improved transparency, more personalised and more intuitive.

4.2 ACTORS

Actors are the stakeholders who bring the change. Accordingly, retrofit professionals are the people who should introduce the use of AI in retrofit deliverables. It can be noted that most of the AI capabilities are directly influencing the way of working of retrofit professionals. Mainly, project managers' and designers' stakes are discussed.

From the perspective of the project managers, improved health and safety (Aghimien et al., 2022; Koc et al., 2022; Khan et al., 2022), progress evaluation (Reja et al., 2022)., dispute resolution (Hassan et al., 2021), quality management (Siebert et al., 2021), cost estimation (Alshboul et al., 2022), time estimation/ delay prediction (Gondia et al., 2020) and automated construction with robotics (Bruckmann & Boumann, 2021) can be noted.

From the designers' perspective, designing more intelligent buildings (Tan et al., 2022), reviewing project specifications (Moon et al., 2022), automating the compliance check (Zhang & El-Gohary, 2016), performance predicting composite materials (Khambra & Shukla, 2021) and optimising the solutions can be noted.

4.3 TRANSFORMATION PROCESS

This involves the rules, interactions, procedures, and all the activities within the change. In the context of the AI influence on housing retrofit, this includes changing the retrofit process from a state without AI to one with AI. However, the important aspect is to what level AI can be adopted. For this purpose, a maturity analysis model of AI in a retrofit context will be ideal. It will be out of the scope of this study. This study is expected to signpost the directions of changes involved with AI adoption in the retrofit industry.

4.4 WORLDVIEW

The general worldview about the use of artificial intelligence can be suggested as positive in terms of the above selective literature. However, this can be argued as biased as the literature is selected, not systematic. Further, the worldview could be ideally obtained through empirical data collection through interviews or questionnaire surveys.

4.5 OWNER

From the owner's perspective, the change is expected to improve the achievement of their objectives. The government and the contractors are considered the owners of this change as they will be the key decision-makers in bringing about the change. When the government is considered, managing health & safety (Khan et al., 2022: Koc et al., 2022), managing waste (Lu et al., 2022) and improving the overall productivity and efficiency of the retrofit can be given as examples. As the construction companies are considered, their motivation shall include all of the above. However, in addition to them, the main objective of the construction companies will be profit. In order to maximise profit, it is important to reduce cost, maximise productivity and reduce risk. This is when the optimisation comes into play. It is expected that AI technologies can optimise the existing processes, tools, products, and solutions which will contribute to higher project value.

4.6 ENVIRONMENTAL CONSTRAINTS

As far as the environmental constraints are considered, the true challenges of bringing AI to the retrofit industry are yet to be researched. It can be suggested that the usual challenges of Construction 4.0 are also applicable here, as described by Sawhney et al. (2020). For example, resistance to change, unclear value proposition, additional costs, lack of expertise, legal uncertainties, data security issues, etc.

5. Conclusion

This study focused on how artificial intelligence will change the retrofit process in the big picture. For this purpose, a selective literature review was conducted under five key themes of artificial intelligence. These five themes can be noted as computer vision, machine learning, natural language processing, robotic process automation and optimisation. However, the literature review was conducted in the general construction industry as the housing retrofit industry lacked relevant literature. As the next step, a CATWOE analysis was done to suggest the potential change from artificial intelligence adoption to housing retrofit. Finally, a discussion was carried out to suggest the potential change of artificial intelligence to housing retrofit processes.

It can be concluded that the main influence of artificial intelligence on the housing retrofit will be improving the action of the retrofit professionals. Retrofit project managers' and retrofit designers' work scopes are mainly identified. The designing process and project management functions are the clear beneficiaries of artificial intelligence. Further, the government and the construction companies as the owners will also have a considerable influence. Mainly, the processes applicable to housing retrofit will be optimised with artificial intelligence. The government will be able to drive housing retrofit more rigorously. Construction companies will be able to reduce their direct costs and overheads through AI optimisation. However, there will be challenges in adopting artificial intelligence, which was not covered under the scope of this study. Further, the maturity of artificial intelligence in the retrofit industry is also not studied.

This study has been done as an eye-opener to draw attention towards adopting artificial intelligence for improving housing retrofit processes. It is recommended that further studies be conducted to establish the true potential of AI in the context of housing retrofit. Further, it will be highly beneficial to evaluate AI maturity models in the retrofit industry for better positioning of this disruptive technology in a progressive trajectory.

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CONTINUOUS MOISTURE CONTROL OF BUILDING MATERIALS

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Abstract. With the increasing moisture content due to climate change, we may need to monitor our wood and other biological building materials that are moisture sensitive continuously. This is now possible with the new technology that displays the results and provides alarms at selected limits continuously via the Internet and wireless connections, which provides easy assembly and monitoring, as well as providing good documentation in both the construction phase and the maintenance phase. A test shows us, that we maybe are going to use some new meteorological data for the future calculations of moisture proof.

Keywords: Moisture control, Moisture plan, continuous moisture measurement, Woodsense, moisture control plan, Flat roofs, climate change.

1. Introduction

An increased use of bio-based materials and an increased rainfall/moisture load due to climate changes make a moisture strategy extremely relevant in the construction planning. A short test measurement over a summer and a winter are indicating that the climate date we are using now for moisture calculation are not sufficient for the future, where we will become more moisture over the year.
Moisture, with the non-sensitive materials we use, is already considered to be the main cause of damages in our buildings. Moisture can also cause odour nuisance and health problems. Finally, high moisture content within building materials will reduce their insulating ability by Build instruction SBI Guide no. 227-229. The consequences are difficult and costly replacements of structures, and in some cases moulds in the indoor climate, with demands for rehousing of the residents. According to the Building Damage Fund May 2022.

2. Legislation in Denmark requirement

When a building is handed over, it is undertaken as a formal delivery, where the executor hands over several documents to the developer. These documents show, among other things, that the building complies with the requirements of the building regulations for the building in question and the requirements that were set in connection with the building legislation. This material shall include, inter alia, quality assurance contractor, which should contain at least information on precautions against wetting materials and buildings during construction, including control plans and moisture measurements.

Documentation of the moisture conditions is important to manage construction cases and prevent damage due to building moisture. In connection with disputes about defects in completed construction tasks, documentation of the moisture conditions may be decisive for the outcome of the case. The documentation must consist of all relevant material for the construction work, including assumptions, overall descriptions, drawing material, calculations, test results, measurement results, etc. The documentation shall clearly state who has carried out the moisture measurements, where and when the measurements were made, with what type of instrument, at what temperature and with what result.

In connection with the measurements, it may also be appropriate to note weather conditions, especially if it concerns precipitation periods for buildings with interim covers. Bad weather is no excuse for poor cover. The information can help facilitate the interpretation of the results and thus a possible clarification of the cause. In the delivery situation, the reason is irrelevant to the developer and authorities, but if the reason is clarified, it can help to point out conditions that should be changed to prevent new humidification elsewhere in the construction if the delivery is made in stages.

The above listed is a normal a very manual process with hand meters that is time-consuming, unprecise, and uncertain, likewise the documentation is a time-consuming process.

3. Methodology

Figure 1. Example of measuring with an insertion moisture meter from Prexiso

Moisture is normally measured in wood and similar materials with an insertion meter which measures the resistance in the material, and which transfer this measurement to absolute moisture content in the material. The measurement depends on where it is possible to measure, and the moisture varies depending on where on the wood you measure.

3.1 AUTOMATION OF A PART OF THE PROCESS

For this documentation, we can use an existing technology that makes it possible to detect humidification automatically and via alarm limits get alarms and stop any damp elements, as well as find the time and thus cause of humidification before installation, as well as get error messages in case of construction defects that come after the installation of the materials.

Figure 2. Example of measuring with a insertion moisture meter from Woodsense

The test meter from Woodsense works according to the same principle with resistance measurement, but with a temperature and humidity meter built-in, and precipitation times and amounts are obtained from meteorological institute. The meter is placed strategically by an impartial person and will measure in exactly at the same place throughout the lifetime of 10 years. Reading is done via a wireless signal to a hub connected to the internet. The hub sends data to a woodsense server on the Internet from where data can be retrieved and alarms for SMS alerts can be set up. The meters are calibrated in our laboratory and have a deviation of approx. 2% on the moisture parameter.

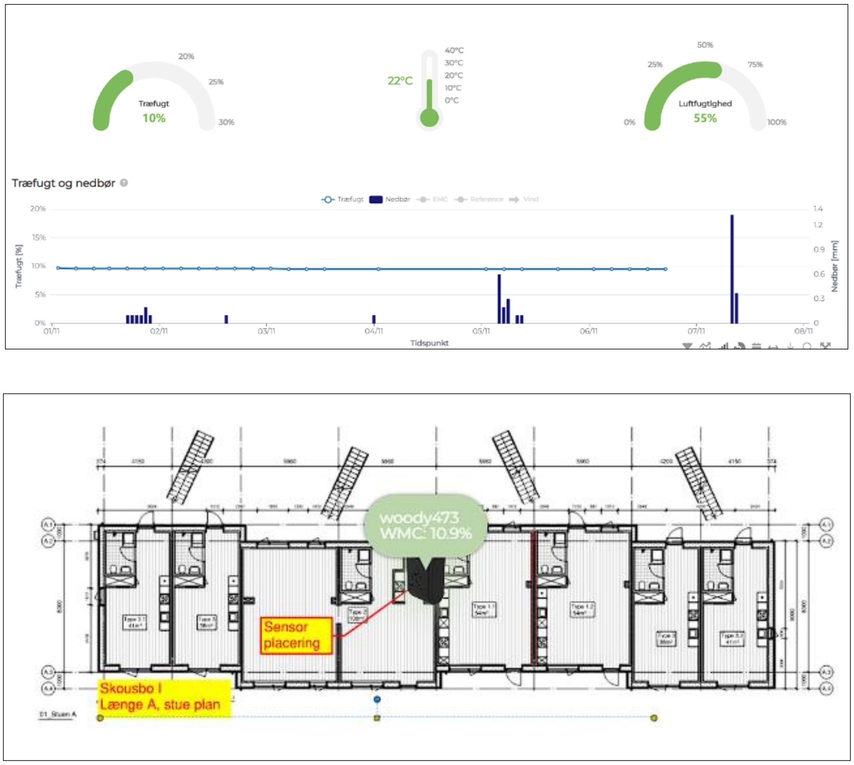

Figure 3. Reading from the Woodsense meter – shows wood moisture, temperature and air humidity in the columns at the bar and rainfall and time. Placement of the sensor shown on a plan.

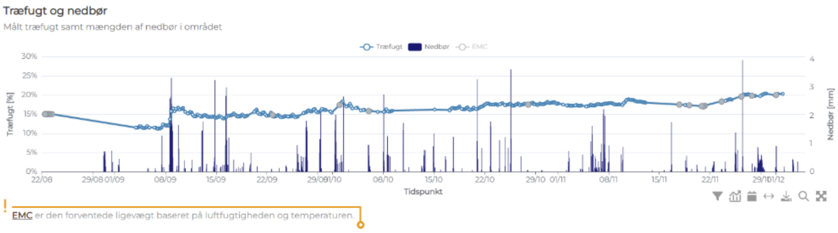

Figure 4. Example of measuring a wooden wall from setting up 13% residual moisture in the wood, where it is seen how the wood is humidified with each rainstorm (the vertical columns with amount of rain) until the residual moisture is up to 21% residual moisture in the wood – which is at the limit for mould growth.

Figure 5. Relative humidity in the surrounding air is also continuously measured, compared to residual moisture in the wood, so that it is seen how the wood moisture balances itself in equilibrium with the room moisture according to time.

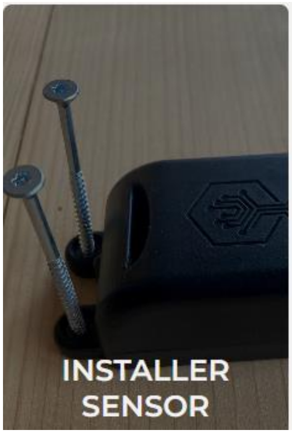

Figure 6. Woodsensor with the screws that are measuring humidity by resistance - by Woodsence.

3.3 RISKS

Under Construction:

- Storage of building materials without rain and condensation risk
- Are the building materials dry or are they allowed to dry out.
- Closure of the building
- Is the building closed and the materials are wetted during transport to the construction site.

Moisture measurement of the risk areas during operation can be the following:

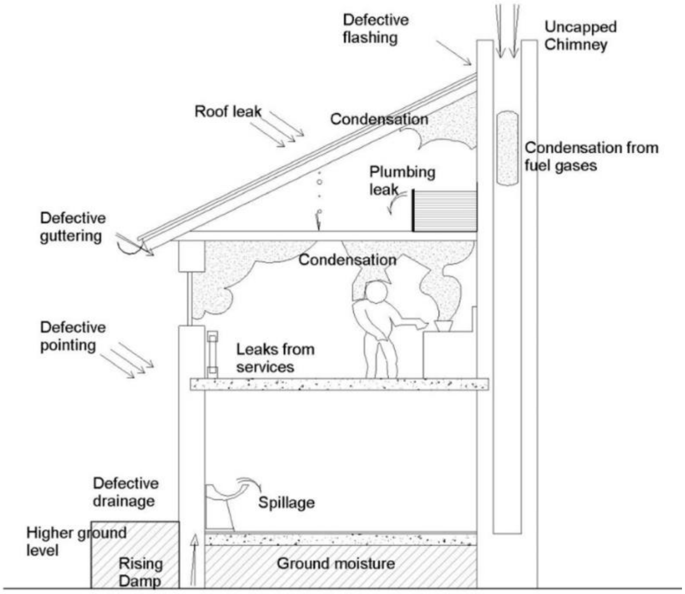

Figure 9. Risk areas from Woodsense brochure and SBI 224 fugt I bygninger

3.3 Moisture Measurement Flat Roofs: a critical area

The challenge with flat roofs is that it is almost impossible to avoid cracks where water can find its way in. And when it gets through the membrane and into the building, then the water can fall somewhere completely different, which means that locating the point error always becomes very expensive.
With a widely used roof surface, locating the damage only becomes more expensive, as it means removing the green roof or solar panels before looking into the insulation to find out where the water is coming from.
In general, the later the damage is discovered, the harder it will be to locate and the more widespread the damage, which means that the repair will be up to 100 times more expensive than if you had found the damage within a few days. By Woodsense

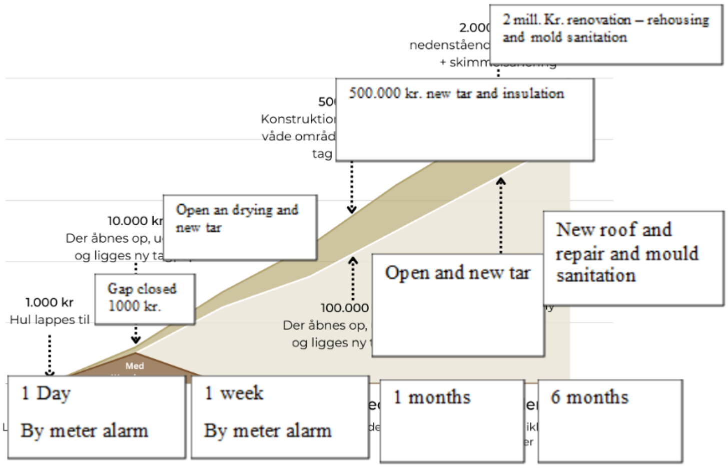

Figure 10. Picture of value loss over time of water damage – by woodsense

The sensors are sent mounted on a small piece of timber 5x10x2 cm. The sensors are placed in vulnerable areas around the roof (during penetrations, roof downspouts, mounts, etc.); ideal for covering every 30-60 m2. The sensors are placed above the concrete and bottom membrane, but below the insulation. A hole must be cut in the insulation to fit the sensor. If water enters the upper membrane and runs down through the insulation, then the wood will absorb the water, and the sensors will detect an increase in the moisture content and humidity of the wood. The building owner will receive a notification and be able to repair the damage immediately.


Figur11. Measurement on roof with a wood block under the sensor - by Woodsence

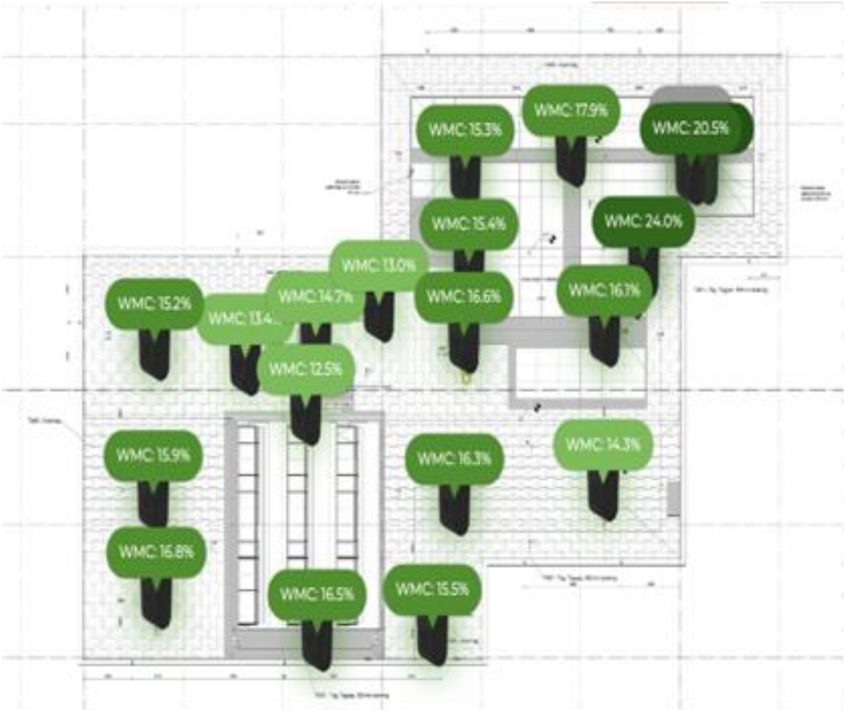

Figure12. Flat roof plan with sensors - by woodsense

3.4 A SMALL CASE STUDY

Figure 13. Small wooden house for measurements

We have installed moisture meters on both the outer wall and the inner wall of an uninsulated log house in 40 mm pine walls without any vapor barrier at the inside and only Lin oil at the outside. When setting the house up during a dry and hot summer, the residual moisture in the wood was about 13% and during a wet winter the water content in the wood rises to 21%, which is above the mould green of 20%. Unfortunately, as expected, there were black traces of mould on the front of the house during the spring, even though a surface treatment with linseed oil with fungicide had been given, where the oil was supposed to prevent some of the wetting. The pine beams were placed radially, and the door hole was increased from 2,100 m to 2,1035 m– approx. 3.5 cm in 2 m, or approx. 1.7%

which fits with the theory of a length expansion of 0.3% tangent to per 1% change in residual moisture. The change in residual moisture increased from 13% to 21% - 7% x 0.3% = 2.1% - which is close to the measured 1.75%.

A WUFI calculation was made on the wooden wall based on Danish reference years over the last 100 years, with locality location in southern Denmark.

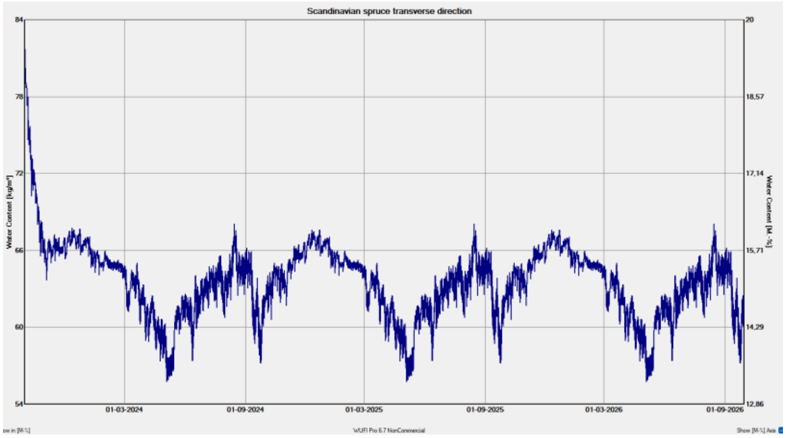

Figure 14. WUFI calculation of water content over 2 years – by a normal year

As can be seen from the calculation – the residual content did not exceed 17% residual moisture in a normal year. In the real test we reached 21 % moisture, over the mould limit at 20 %. This is due to the fact that this winter has become approximately. 2°C warmer and significantly more precipitation has fallen than the average of the last 100, which has fallen 422 mm compared to 374 mm in a normal year – where 70 mm has fallen in January compared to a normal January of 36 mm of water. The average temperature has also risen by about 1.2 °C in January (Source: DMI)

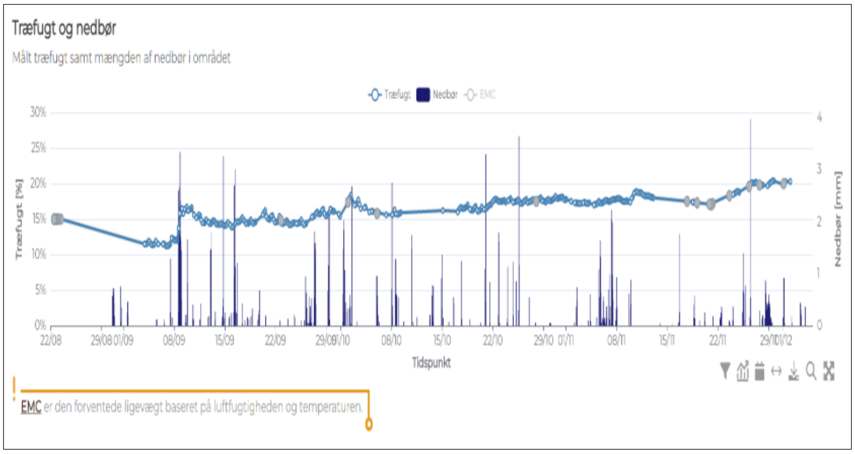

Figure 15. Wood moisture from 15 % at 21 % humidity – and rainfall each day

4. Conclusion and reflection.

In the future, there will be greater demands for continuous moisture control, a short measurement in one place does not give any significance, as the climate will become more humid and hotter, and create greater problems with moisture/mould especially in the bio-based constructions, which we will use more of in the future.

Using a continuous moisture measurement throughout the construction process will provide better buildings and the opportunity to correct errors and upcoming errors in time, without the large expenses a total renovation will require.

Automatic alarms can prevent or reduce construction damage from too much moisture and subsequent mould and too little moisture and consequently excessive shrinkage cracks and provide a better construction in the future.

Our small measurement/test shows us that we cannot depend on the previous climate data over the last 100 years, as we do now in our calculations, as shown in the WUFI calculation made on the DRY data (Danish reference year by SBI Denmark). We are going to use data from the future climate instead.

We have calculated in WUFI that the maximum wood moisture would be 17 % and we achieved 21 % which is over the limit at 20 % moisture in wood, and we could see the mould at the front of the house.

The small test shows us the some of the constructions, that we use now as a moisture proof construction, will not be moisture proof in the more warm and wet future.

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A COMPARISON OF ENERGY-EFFECTIVE WALL TYPOLOGIES

A Comparison of low impact embodied energy wall alternatives for an extension to an existing building

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Abstract. 44% of European energy consumption is attributable to the built environment, as modern buildings are required to perform at a high level. This can be environmentally unsustainable, and as a result, the European Directive (Energy Performance of Buildings Directive) requires all buildings to progress toward a low energy standard to achieve ideal cost-performance levels for significant renovations. The embodied energy of a low-energy structure during its full life cycle may exceed 30% of the total energy consumed. The existing building referred to in this paper was the Galway Bay Sailing Club. This was a medium-sized building established in the 1950s at Renville Oranmore, County Galway, in the West of Ireland, located approximately ten kilometres from Galway City. The secondary research was conducted up to May 2022. This paper analysed and compared the various wall assemblies, determining the most practical alternatives and construction fabrics involved, and analysed the environmental consequences and life cycle of each material. This paper investigated renewable and sustainable materials in depth, which led to a passive and environmentally sustainable wall extension by informing the material choices to optimize the wall's low embodied energy rating. In this paper, five low-impact materials were evaluated. Three were wall assemblies, while two were insulations alone: Hempcrete, Rammed earth wall, Cob, Cellulose, and Mineral wool. Although the materials are low-impact owing to their embodied energy, they were required to fulfil the Technical Guidance Document L Energy Conservation 2022 and attain a Passive House U-value wall standard of 0.15 W/m2K in the wall extension. Using a combination of research, interviews, calculations, and case studies, it was determined that, despite the need for additional research, Hempcrete appeared to be the most suitable low-impact material option with the lowest embodied energy and the smallest contribution to global warming when meeting Passive House standards and was most suited for an extension to the existing building.

Keyword: Passive House; Low Embodied Energy; Environmental Impact; Hempcrete; Life Cycle Assessment; Carbon Emissions; Rammed Earth Wall; Cob; Cellulose; Mineral Wool.

1. Introduction

One of the essential parts of the construction process is deciding on an appropriate choice of materials and products (Cotgrave & Riley, 2013). Choosing the right materials is key to the performance of the building over its lifetime. The environment, however, may be substantially impacted in terms of energy and carbon with each negative decision made in the construction phase.

Buildings today exhibit noticeably rising energy performance levels. As a result, there is a growing number of negative impacts with a raw material's extraction, processing, transportation of materials, assembly and usage are increasing. This is known as embodied energy, the energy taken to manufacture all these materials used in construction. Natural and renewable structure and insulating materials such as hemp, cellulose, wood, straw, wool, cob, and earth walls cultivated and sourced locally can help mitigate the negative impacts.

Energy-related alternatives have become more imperative in this current era of increased environmental concern for sustainable architectural design. Environmental impact takes and converges countless varied questions and focuses them on the real materiality of buildings. The question of scale comes up when assessing the origin of materials. The issue of environmental effect varies from resource extraction, material transformation, human work, and transportation to the scale of a single material.

When comparing the environmental impact of materials, time also comes into question. What was the duration of its' manufacture and transportation to site? How frequently will it require maintenance? How often will it need to be replaced? For example, the environmental impact of materials such as metal and reinforced concrete have a comparatively higher environmental impact than stone, timber, and straw. To understand why low energy materials are beneficial to medium-sized structures mainstream building construction, it is important to describe what the materials are and to compare them to others, including traditional construction typologies of the Irish vernacular.

2. Aim

This paper seeks to investigate and evaluate low impact wall assembly options and thermal products for medium-sized buildings and to calculate comparisons of low impact embodied energy solutions for an extension design.
The selection of low embodied energy wall types stems from the diverse array of products available for thermal options and wall systems.

Bearing in mind this abundance, it is prudent to acknowledge that not every product within these options will be addressed in this report. Consequently, this paper will concentrate on in-depth discussions on carefully chosen products within this framework.

2.1 OBJECTIVES

1. Evaluate and compare low embodied energy and thermal options for wall typologies suitable for an extension.
2. Investigate low impact materials for medium-sized buildings.
3. Calculate environmental impact and embodied energy of the study findings.
4. Integrate the study findings into the case study.

3. Secondary research

The secondary research aims to use an existing background of data from other sources, such as books and articles, to pursue a research interest that distinguishes itself from the original work. This section of the report investigates embodied energy factors, and the effects materials and products have on everyday life, discussing their impact on sustainability results. The materials to be discussed in this report are low-impact natural resources such as Hempcrete, Cob-walls and Rammed earth walls and insulation options like Cellulose and Mineral Wool. Insight into these materials and a brief life cycle analysis will support the results.

3.1 WHAT IS CONSIDERED A LOW IMPACT EMBODIED ENERGY MATERIAL?

Low impact materials are materials from a sustainably managed source local area within 56 Kilometres (Low impact materials, 2007). These materials are characterized by a low environmental footprint, signifying their reduced adverse impact on the environment, meaning they are not as detrimental to the environment and are derived from other materials such as hemp, straw, lime, and sand. Since embodied energy varies greatly between materials, the choice of materials and construction process can substantially impact the quantity of energy embodied in a building. In addition, different materials can be recycled in different ways, which can assist the recovery of the embodied energy at the end of a building's life (Crawford, 2020).

Building materials such as timber, hemp and straw consume less energy in manufacturing since they require significantly less processing and much lower use of chemical resources (Woolley, 2013).

TABLE 1: ICE Embodied Energy Figures 2011 (Woolley, 2013)

Examples of embodied energy figures Based on Inventory of Carbon and Energy (ICE) 2011		
Materials	**Embodied energy MJ/kg**	**Embodied carbon $kgCO_2/kg$**
aggregates	0.083	0.0048
aluminium (general)	155	8.24
Portland cement	5.50	0.93
glasswool	28	1.54
rock wool	16.8	1.05
wool recycled	20.9	NA
flax	33.5	1.7
straw	0.24	0.01
polyurethane foam rigid insulation	101.5	3.48

3.2 ATMOSPHERIC CONDITIONS

The medium sized building is at the west of Ireland and the east coast of County Galway in Oranmore, and with the building being by the sea, it creates a set of climate conditions that the selected materials would have to confront. The west of Ireland is occasionally wet and humid, with abundant rainfalls occurring. This may increase the moisture build-up of the building due to the proximity of the sea. In addition, because of the orientation of the building, the wall extension for this building, constructed to the southwest of the building, is completely exposed to the prevailing winds that are correspondingly driven from the exact location.

According to the Climate Statement of Winter 2020 released by Met Éireann, the western regions of Ireland experienced an average monthly rainfall ranging between 300mm and 500mm. The wall material chosen would be exposed to the winds and the possibility of harsher rain with sea salt, which also appears. Technical Guidance

Documents A, B, and C discuss the building regulations and requirements the materials compared would have to meet concerning the proper structure and moisture resistance. Options such as overhangs, and thicker walls may be an option but may increase that material's overall embodied energy.

3.3 LIFE CYCLE ASSESSMENT

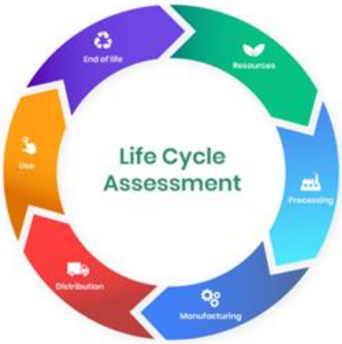


Figure 1. Stages of Life Cycle Assessment (One Click LCA, 2021)

Life Cycle Assessment is a method for determining a material or product's environmental and resource impact over its entire life (Kilbert, 2013). All energy and materials resources and air, water or land emissions are charted over the entity's life cycle. The life cycle, or period considered in this evaluation, can span from the extraction of resources, the manufacturing process, the installation in a building and the item's final disposal (Kilbert, 2013). This assessment also considers the resources required to transport components from extraction to disposal shown in figure 1 (One Click LCA, 2021).

3.4 HEMPCRETE INVESTIGATION

Hempcrete, a renewable building material, has low adverse energy requirements. It is made of lime and hemp shivs, a hemp waste product (Sparrow & Stanwix, 2014). Hempcrete is lightweight, reducing emissions associated with transporting heavy materials. Industrial hemp can be grown in a variety of climates and soils, making it a viable local building material option (Roberts, 2020).

Hemp has started being grown in Ireland for farmers under license from the Health Products Regulatory Authority (Allen, 2020). Hemp, however, finds a situational end, which is the lack of processing plants for it in Ireland and for it not being readily available (Kennedy, 2021). The shipment of Hempcrete would face the issue of locality if it were to be incorporated into the upgraded wall for the medium-sized building. This can raise overall capital expenditures by requiring imports from another country or limiting options owing to a lack of resources (HempBuild, 2021). This could be an increasing factor due to the club's location. Hempcrete may have a lower heat conductivity than concrete. When Hempcrete construction is perfected, it can better retain thermal energy. When tested, a denser hempcrete had a lower conductivity than a stronger hempcrete ((Elfordy, et al., 2008).

Hemp is naturally fire and mould resistant, giving it benefits on sustainability maintenance (Roberts, 2020). Displayed on the table below are the key components of hemplime in construction, along with their respective energy capacities. This provides valuable insights into its carbon emissions.

Another study also showed that the embodied energy of hemp resulted at 0.10MJ/kg (Latif, 2020) for environmental attributes. However, Hempcrete is not loadbearing, making it fall in that category (Sparrow & Stanwix, 2014).

Meaning it cannot be used as a foundation structure due to its low compressive strength, being 1/20 of a concrete block. This would have to be paired with a timber frame to provide structural support, increasing the overall running and construction expenditure. Despite its structural deficiencies against concrete, Hempcrete redeems itself in thermal properties and a low embodied energy (Bedliva & Isaacs, 2014) (Sutton, et al., 2011).

Although possessing various advantages, Hempcrete also exhibits certain drawbacks that hinder its optimal suitability as a construction material. Notably, the porous nature of Hempcrete diminishes its mechanical strength while augmenting its propensity for water retention (Madhura Yadav, 2022).

TABLE 2: Embodied Energy of Hemplime Construction (Reilly & Kinnane, 2017)

Constituent	MJ/kg	CO_2e (kg CO_2e/kg)
Cement (avg CEM I)	5.5	0.913 – 0.95
Cement with 21-35% GGBS (CEM II/B-S)	4.77 – 4.21	0.77 – 0.65
Lime	5.3	0.78
GGBS	1.3	0.067 – 0.07

3.5 COB INVESTIGATION

Cob, a building material extracted from the earth, is used primarily to construct walls (Libnam, 2015) and is another comparable low impact material. Cob is a mixture of straw soil, clay, water, and sand (Weismann, 2010). As it is used in natural structures, buildings that emphasise sustainability, renewable resources, architectural design, and inexpensive construction cost (Sumerall, 2015), Cob would be recognised for its beneficial environmental impact.

It is believed that while calculating the embodied energy, assuming if working with a mechanical digger, 1 gallon of diesel equalled the extraction per ton of Cob (Libnam, 2015). This would reduce its carbon footprint as it is sourced locally, a material being mined from or near to site (Sumerall, 2015). Research has shown that buildings with Cob can indefinitely last for long periods if constructed correctly and protected, with many Cob buildings reaching 500 years old (Goodvin, 2011).

This provides a viewpoint on whether an old low impact embodied energy material, with a natural resource building option, has a place in today's construction world where energy efficiency and affordability (minimal transport cost and emissions) are primary themes.

Compared to Hempcrete, when mixed in correct proportions, Cob can be used to replace bricks due to it being as strong and durable as concrete (Vannice, 2018), creating an argument here on which is a better alternative. This calculation of the natural resource of Cob compared to other materials is shown in the graph below. With embodied energy as the emphasis for the table below, a study (Loftness, et al.,

2017) discovered that traditional Cob had a low embodied energy value of 0.065 MJ/kg compared to other conventional materials.

TABLE 3: Embodied energy and carbon per kg of Cob in comparison to other building (Loftness, et al., 2017)

Material	Cob	Brick	Limestone Brick	Cement	Soil Ce-ment	Steel	Timber
embodied energy: MJ-eq/kg	0.065	3	0.85	4.6	0.85	24.4	8.5
embodied carbon: kgC/kg	0.036	0.06	--	0.23	0.038	0.48	0.12

3.6 RAMMED EARTH WALL INVESTIGATION

Rammed earth walls consist of aggregates such as gravel, sand, silt, and clay being rammed together from a sturdy and long-lasting construction block. It increases the strength and durability of the block by adding small amounts of cement (5-10%), giving it an idea of being a "weaker concrete". As of this addition, built rammed earth buildings do not require any sort of reinforcement or framing, saving the cost and excess materials required (Downton, 2013). Rammed earth can be sourced or grown locally.

However, it is not as popular in Ireland compared to the other mentioned materials and nations. Due to the type of soil found in Ireland, there are not many Rammed earth buildings or materials on display (Madsen, 2014). In addition, the topic of the locality may cause conflict as the transportation to this building would increase the overall embodied energy results due to workers importing it. However, if it were to grow in popularity. It would be readily available material, having a low energy intensity, from recyclable materials and typically available locally within a short distance from the construction site if dug correctly.

Despite its lack of locality, the earth wall would still positively impact due to its energy and low-cost options. Rammed earth wall is a known energy-efficient alternative to load-bearing walls due to load carbon emission (Reddy & P. Prasanna Kumar, 2010), compared to a primary timber frame building that uses large amounts of insulation (Pérez-Lombard, et al., 2008). In addition, the embodied energy of Rammed earth is low to moderate (Downton, 2013). A study (Reddy & P. Prasanna Kumar, 2010) showed a Cement Stabilised Rammed Earth wall at a thickness of 155mm.

With various densities and cement contents applied, a total embodied energy of this earth wall resulted in between 0.04–0.05 MJ/kg. Conversely, it should be noted that although the material alone could be low cost, the labour costs associated with rammed earth construction can be substantial. Moreover, the inherent energy efficiency of rammed earth in isolation remains relatively modest, needing a high level of skill on-site for successful implementation thus increasing the cost.

3.7 THERMAL OPTIONS: CELLULOSE

Cellulose is a natural thermal insulation material produced from recovered paper fibres, with recycled newsprints and cardboard as primary elements. Due to its environmental impact and high thermal efficiency, it is often known as 'The Green of the Green' (CIMA & CIMAC, 2019). This insulation implemented into the building would portray a positive impact on the environment as well as fire resistance and it being a thermal insulator with a lambda value of 0.035-.04W/m2k (Greenspec, 2022) is extremely energy efficient in manufacturing.

Cellulose has the lowest embodied energy status compared to Hemp and Mineral Wool, and other insulations. A case study on Cellulose revealed a calculation of 0.045MJ/kg (Greenspec, 2022). It is said that fibreglass takes up to 10 times more embodied energy than Cellulose due to it being complex and requiring longer shipping distances, and spray polyurethane foam insulation has up 60 times more embodied energy (CIMA, 2011). Given the building's proximity being right by the sea and overall cost, the insulation is breathable yet not fully waterproof; it has a resistance to a degree. It is a loose-fill product with fibres that may become wet and increase the weight unnecessarily. This reduces its thermal conductivity significantly.

In an enclosed area, Cellulose absorbs water, resulting in prolonged drying durations. The water could travel through the insulation to the exposed structures resting against it. As a result, the insulation being right by the sea highlights the subject of tangibility when compared to the other insulations. Cellulose has the potential to fall short.

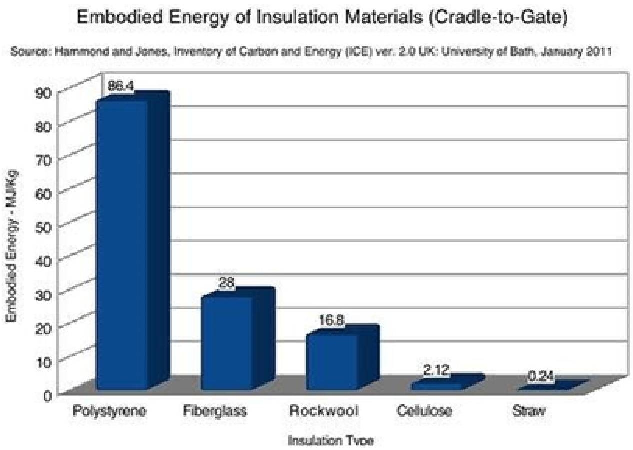


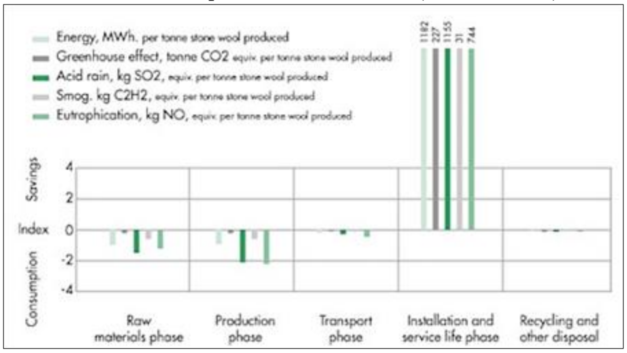
Figure 2. Embodied Carbon and Operational Carbon (Naditz, 2016)

3.8 THERMAL OPTIONS: MINERAL WOOL

Mineral wool (also known as rock wool) is a versatile product with numerous attributes. It is a non-metallic, inorganic material with thermal, fire safety and acoustic qualities. It is manufactured from a selection of materials such as stone, slag (industrial waste), or molten glass spun to form fibres such as wool and then packaged into rolls or slabs (InsulationSuperstore, 2022).

Compared to alternative insulations (other than Cellulose), a life cycle analysis of Mineral Wool insulation revealed that the material has a lower embodied energy than most non-mineral wool products such as sheep or glass wool (MIMA, 2022). For example, mineral wool investigated in one study had an embodied energy calculation of 16.6MJ/kg (Latif, 2020). In reference to the building content, mineral wool shows a significant advantage in the water resistance category due to it being hydrophobic (Truini, 2017), making it a more viable option for this sea design building. Its terms of locality and cost, the construction cost can vary greatly. It is also costly to produce causality. Its transportation is extensive.

TABLE 4. Impact of Mineral wool (MIMA, 2022)



The table above depicts the fundamental environmental impact of mineral wool in terms of energy usage and carbon emissions throughout its lifetime instalment in a building. It has been demonstrated that the life cycle approach reveals that this material provides a variety of environmental benefits.

4. Overview of Secondary Research

The secondary research addressed two of the four objectives. To investigate low impact materials for medium-sized structures as evidenced by qualitative study on selected materials and evaluate and compare low embodied energy and thermal choices for wall typologies suited for an extension. Secondary research provided information on all the materials chosen, including Hempcrete, Rammed Earth Wall, Cob, and thermal materials like Cellulose and Mineral Wool.

5. Methodology

The primary research implemented both on quantitative and qualitative data acquired by the researcher. A case study analysis of the selected materials was conducted by using sites such as the materials datasheets and other third-party software, in this case, ICE database and Ubakus.

The qualitative method took the form of semi-structured anonymous interviews with three individuals who work in sustainability and have substantial knowledge of the discussed materials. 10 questions were asked to each interviewee through online interviews about the environmental Impact of the chosen materials.

1. Interviewee 1: A Northern Irish architect and professor who specializes in retrofitting and energy-saving bio-based materials.
2. Interviewee 2 – A Lead Director for Irish Green Building Council, who has focused on whole-life carbon, life analysis, material budgeting, and data analysis for years.
3. Interviewee 3: A natural builder who has built Cob and Hempcrete buildings.

6. Discussion & Results

6.1 INTERVIEW FINDINGS

Question 1. How many years of experience do you have in the field of sustainability, and do you know much about embodied energy?

Interviewee 1 has been interested in sustainability "since the 80s really" and is "pretty dubious" about embodied energy calculations. Interviewee 2 mentioned their five-year-old masters and dissertation on whole-life carbon and sustainability. Interviewee 3 graduated from environmental science in 2003 and had some sustainability knowledge.

Question 2. In your opinion, what is the highest factor to consider while building a sustainable home?

All 3 interviewees had opposing viewpoints. Interviewee 1 said health is the most important consideration in sustainable house selection. Interviewee 2 stated that whole-life carbon is the "key" thing to consider, while interviewee 3 mentioned finance and the spending high-performing low-cost materials are people choices.

Question 3. Which of these materials have you heard of being constructed into a building?

All three responders said they had heard each material being built. Interviewee 1 said clients and builders like Cellulose, but they personally disagreed that choice. Interviewee 2 said their university had UK's highest rammed earth walls. Interviewee 3 said they never used rammed earth in natural building projects.

Question 4. Did you have an opportunity to use these materials in your projects? If yes, then what is your opinion about the material/s?

Interviewee 1 said they always recommend Hempcrete to clients because of its benefits. Interviewee 3 agreed. Interviewee 2 said they have used all products and would recommend them all in appropriate situations because one may not work in a particular environment. Interviewee 3 chose Hempcrete and Cob for their breathable self-builds.

Question 5. Do you think contractors or companies in the current climate take the embodied energy of materials into account or prefer that the building remains high?

All three respondents shared an agreement that contractors and companies disregard the overall embodied energy of materials.

Question 6. How do you think we can reduce embodied energy in the construction sector?

Each respondent expressed different views, with Interviewee 1 explaining bio-based materials being the most efficient way of reducing energy. Interviewee 2 believing that regulations are the most constructive method for a positive environmental impact. and Interviewee 3 recommended materials selection and waste minimization to reduce embodied energy.

Question 7. Which (of these) thermal options do you think is the most suitable for a building near the coast? Hempcrete, Cellulose or Mineral Wool? What insulation solution would you recommend for a wall extension?

All three responders preferred Hempcrete for thermal performance over concrete wall insulation mix. Interviewees 1 and 2 also noted Hempcrete's moisture resistance in a damp climate.

Question 8. Is there anything complicated about any of these material aspects mentioned that you dislike and why?

Interviewee 1 criticised Cellulose and Mineral Wool's moisture-insulating capabilities. Interviewee 3 said they would avoid Mineral Wool insulation if possible due to health risks. Interviewee 2 noted that each material had its own advantages and had no issues with them.

Question 9. Which of these materials and insulation do you think has the most positive environmental impact, in your opinion?

Interviewees 1 and 2 chose Hempcrete due to its long lifespan, but they also mentioned that earth buildings might require more maintenance and that Mineral Wool has a more positive impact than Cellulose due to its chemical properties. Interviewee 2 said Hempcrete can be utilized as insulation and an outer wall, decreasing waste. Interviewee 3 chose Cob because it can be excavated anywhere, lowering its Embodied Energy.

Question 10. If you were designing a low embodied energy wall, what would be your choice of materials and for what reasons?

All three responders recommended Hempcrete for building's low Embodied Energy wall. Interviewee 1 preferred Hempcrete but said Mineral Wool would be chosen if the customer wanted another thermal alternative off the coast. Interviewee 2 and 3, who both chose Hempcrete, additionally shared their personal choice, Interviewee 2 chose a timber frame structure with straw to meet passive house standards, while Interviewee 3 described a straw bale Cob hybrid with clay paster that is low cost and very insulated.

Narrative for Interviewee 3.

Interviewee 3 was given specific questions to why they favoured Cob above others. Interviewee 3 discussed the material's intricacy and benefits, mentioning the risk of cracks if the clay to sand ratio is wrong and how easy and aesthetically pleasing is to work with. They answered only positively on the material's embodied energy and renewability. Interviewee 3 compared LCA and moisture resistance of the material. They stated that they would remain with Cob and that it was their preference. They were then asked about the microclimate, buildup, upkeep, and heating of their Cob building, which they built. These questions also ask if it can be built into a building near the coast in terms of U-value and moisture and if the researcher can integrate the design into their case study wall build-up analysis and compare it to other materials. Interviewee 3 stated that the building has a low R-value but a high thermal mass, keeping it at a pleasant temperature.

6.2 CASE STUDY ANALYSIS

Each wall construction displayed its U-value, thickness, and materials. There were two separate comparisons, but only one was selected, given that there were three wall assemblies and two insulation options. Because of this, each wall used GUTEX Wood-fibre, for its green credentials and it being completely breathable, low embodied energy in transit due to location, and no bias against the two insulation choices that was also be evaluated. Based on the matrix table below, the Wood-fibre insulation received the highest score in an earlier assessment across five pillars (Environmental, Quality, Economics, Performance, and Social).

TABLE 5. Individual Element Matrix for External Wall Insulation

SUPPLIER	PILLAR HEADINGS AND SUBHEADINGS	MATRIX TABLE - FIVE PILLARS OF CONSTRUCTION																TOTAL SCORE
		ENVIRONMENTAL 20%			QUALITY 25%				ECONOMICS 20%				PERFORMANCE 25%			SOCIAL 10%		
		LIFE CYCLE ASSESSMENT	CERTIFIICATION	WASTE MANAGEMENT	ROBUSTNESS	DURABILITY	AESTHETICS	CERTIFICATION	INITIAL COST	REPLACEMENT	MAINTENANCE	INSTALLATION	THERMAL CONDUCTIVITY	FIRE RESISTANT	MOITSURE/VAPOUR RESISTANCE	LOCALITY MATERIALS	HEALTH SAFETY	
	Subheading % Splits	10	5	5	5	10	3	7	5	5	5	5	12	8	5	5	5	100
MINERAL BASED																		
ROCKWOOL	MINERAL WOOL	8	5	5	1	8	3	3	4	5	3	5	10	8	2	1	5	73
FOAMGLAS	RIGID FOAM	8	5	4	1	10	3	3	2	5	3	3	10	7	5	1	2	69
PETROCHEMICAL																		
KORE	EPS	7	2	1	5	10	3	7	4	5	5	4	10	3	5	1	1	73
Xtratherm	XPS	5	2	1	5	9	3	7	2	5	5	4	9	5	5	1	1	69
Kingspan	PHENOLIC	2	2	1	5	9	3	7	2	5	5	5	8	6	5	3	1	65
ORGANIC BREATHABLE																		
GUTEX	WOODFIBRE	9	5	5	4	8	3	7	3	0	5	4	7	5	2	1	5	75
ISOHEMP	HEMPCRETE	7	4	2	3	9	3	4	5	0	5	4	5	6	5	5	4	71

Wall-build up Specification:

Internal

- 15mm Plasterboard
- 35mm unventilated service cavity with 35x38mm treated battens @ 600mm c/c
- Airtightness Layer
- 150mm ISOhemp (Hemp and lime) Hempcrete block with timber studs @ 600mm c/c
- 180mm Gutex Woodfibre External Wall Insulation λ = 0.40 W/mK.
- Breather Membrane
- 50mm Ventilated service cavity with 50x50mm treated timber battens at 600mm c/c
- 8mm fibre cement rain-screen cladding fixed back to timber battens

External

Achieving a U-value of 0.142 W/(m²K)

Overall thickness: 438mm

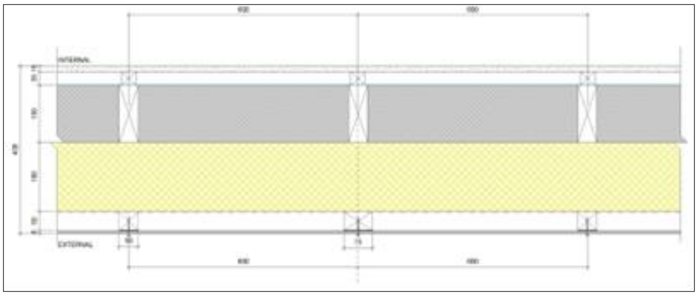


Figure 3. Hempcrete Wall Build-up

Wall-build up Specification:

Internal

- 15 mm of airtight gypsum plaster
- 300 mm of Rammed earth mixture (by the structural engineer)
- 240mm Gutex Woodfibre External Wall Insulation λ = 0.040 W/mK
- Breather Membrane
- 50 mm ventilated service cavity with 50x50mm treated timber battens at @600mm c/c
- 8 mm fibre cement rain-screen cladding fixed timber batten

External

Achieving a U-value of 0.147 W/(m²K)

Overall thickness: 613mm

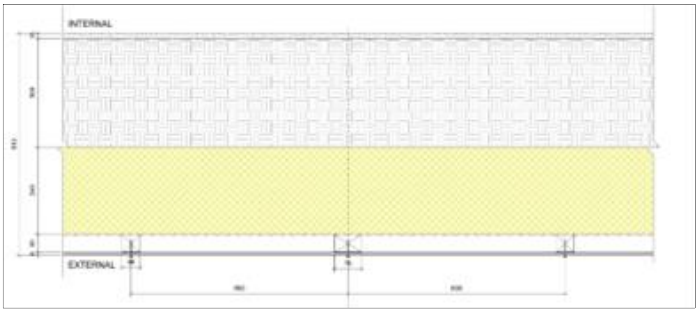


Figure 4. Rammed Earth Wall Build-up

Wall-build up Specification:

Internal

- 15 mm of wet plaster to achieve airtightness
- 400 mm of Cob wall
- 240mm Gutex Woodfibre External Wall Insulation λ = 0.040 W/mK
- Breather Membrane
- 50 mm ventilated service cavity with 50x50mm treated timber battens at @600mm c/c
- 8 mm fibre cement rain-screen cladding fixed timber batten

External

Achieving a U-value of 0.143 W/(m²K)

Overall thickness: 713mm

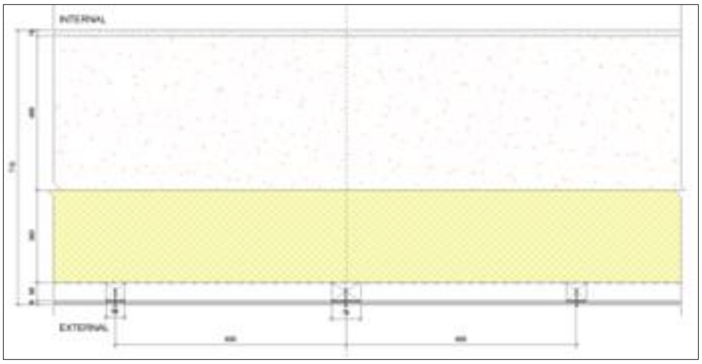


Figure 5. Cob Wall Build-Up

Wall-build up Specification:

Internal

- 15mm Plasterboard
- 35mm unventilated service cavity with 35x38mm treated battens @ 600mm c/c
- Airtightness Layer
- 75mm Dense Ecocel Cellulose Fibre Insulation
- 200mm Ecocel Cellulose Fibre Insulation with timber studs @ 600mm c/c λ = 0.032 W/mK.
- 30mm unventilated service cavity with 30x38mm treated battens @ 600mm c/c
- 15mm Horizontal Oriented Strand Board
- Breather Membrane
- 50mm Ventilated service cavity with 50x50mm treated timber battens at 600mm c/c
- 100mm medium density masonry block wall
- 15mm Silicone External Render Finish

External

Achieving a U-value of 0.145 W/(m²K)

Overall thickness: 531mm

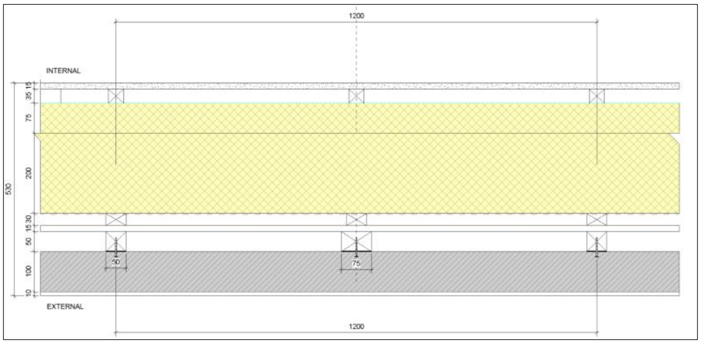


Figure 6. Timber Frame Cellulose Build-up

Wall-build up Specification:
Internal
- 15 mm of wet plaster to achieve airtightness
- 200 mm of concrete wall (by the structural engineer)
- 8mm Adhesive Layer
- 220 mm Rockwool External Wall Insulation λ = 0.036 W/mK.
- Reinforcing Mesh
- 10mm Render Basecoat
- 7mm Silicone Render Finishing Coat

External
Achieving a U-value of 0.149 W/(m²K)
Overall thickness: 462mm

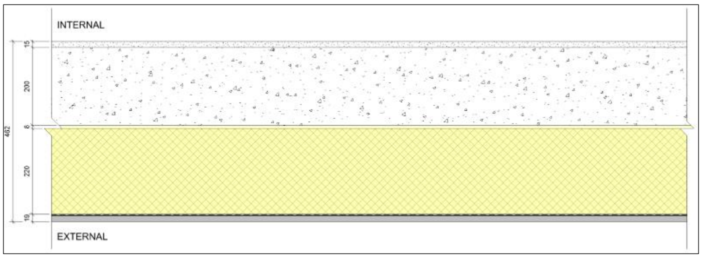


Figure 7. Mineral Wool External Wall Build-up

6.7 MOISTURE AND TEMPERATURE ANALYSIS

Every material's moisture and condensation resistance required testing under external and internal humidity conditions. Oranmore, County Galway, experiences an average humidity of 83% (Weather and Climate, 2022) externally and 50% internally. The Ubakus program's case study involved a comparison of materials' moisture content. Saturation is represented by blue, while humidity is indicated by black. The following figures depict the buildup of each material alongside its respective humidity and moisture analysis.

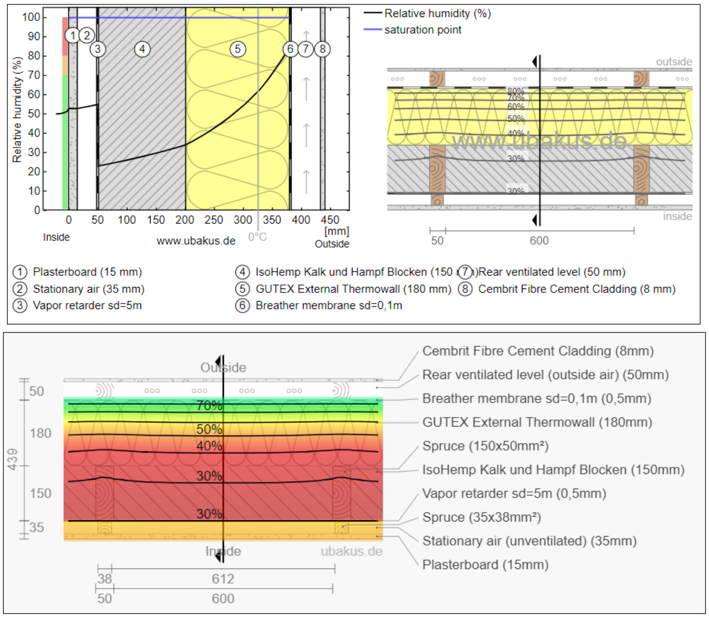


Figure 8. Moisture Analysis of Hempcrete Wall

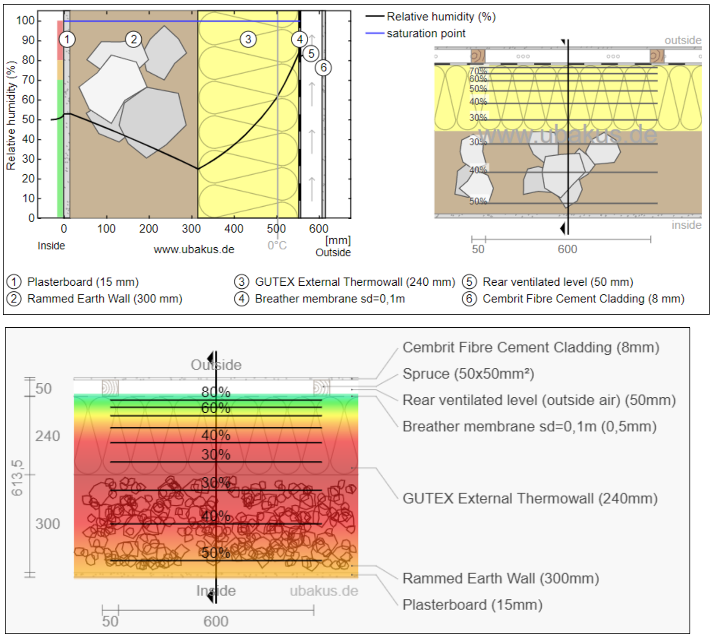


Figure 9. Moisture Analysis of Rammed Earth Wall

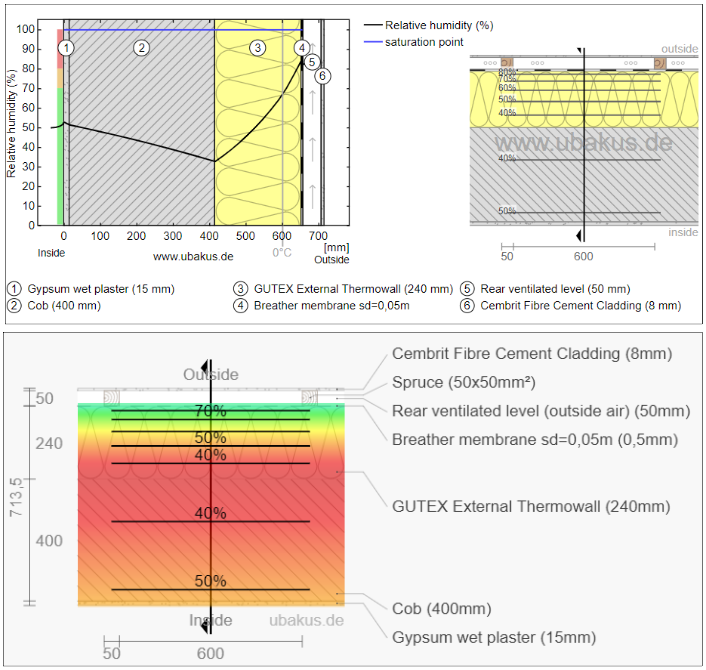


Figure 10. Moisture Analysis of Cob Wall

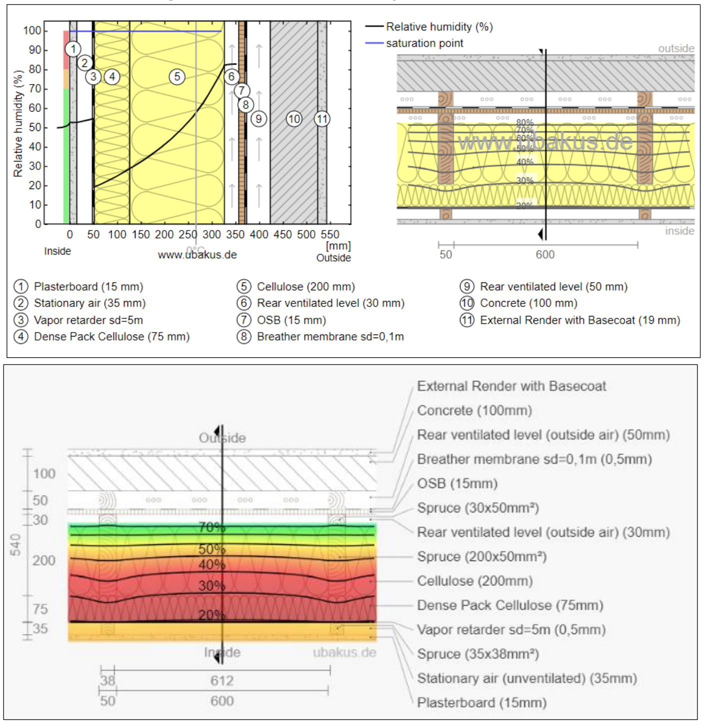


Figure 11. Moisture Analysis of Cellulose

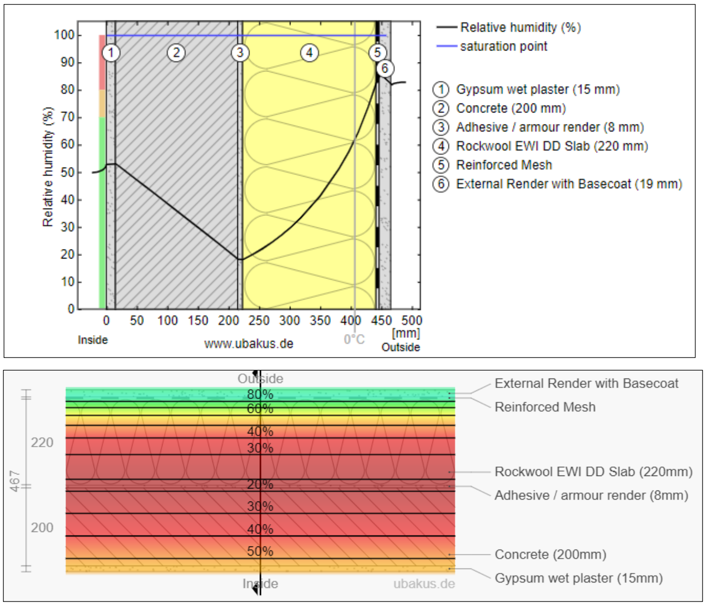


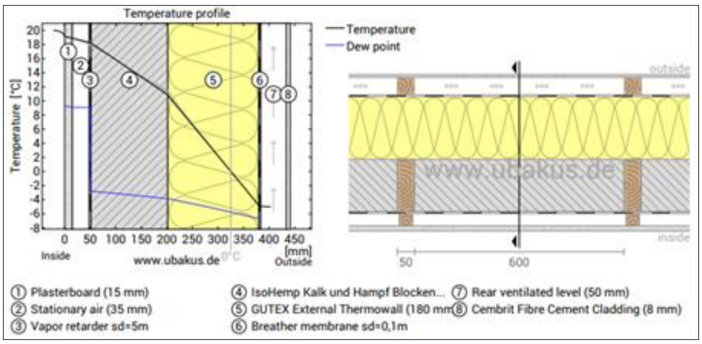
Figure 12. Moisture Analysis of Mineral Wool

6.8 MOISTURE RESULTS

As shown in all figures, for the calculation of the amount of condensation water, the component was exposed to the following constant climate for 90 days: inside: 20°C and 50% Humidity; outside: -5°C and 83% Humidity, all wall components are free from condensation under the given climate conditions.

6.9 TEMPERATURE

The dewpoint indicates the temperature at which water vapour condensates. If the temperature of the component is everywhere above the dew point, no condensation occurs.



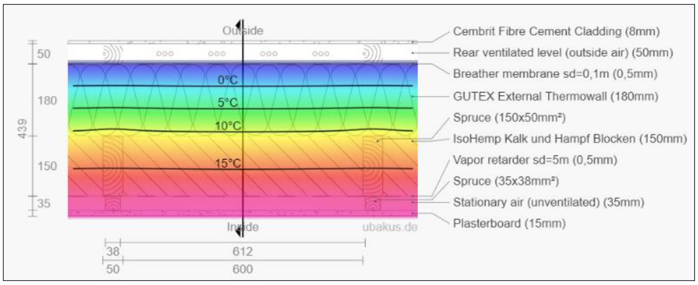


Figure 13. Temperature of Hempcrete Wall

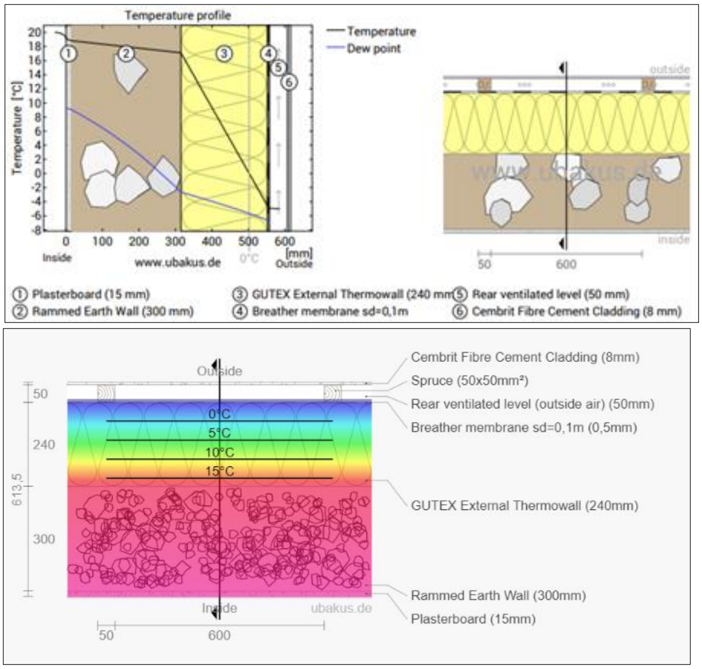
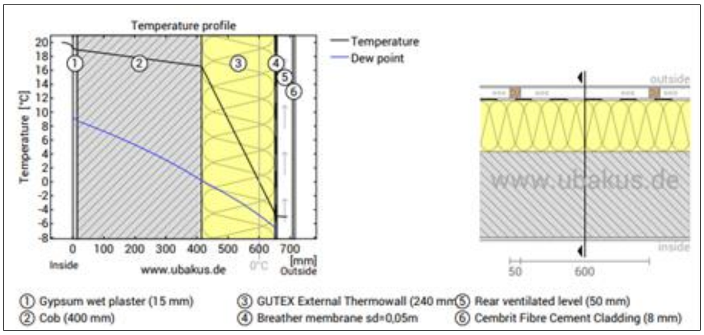


Figure 14. Temperature of Rammed Earth Wall



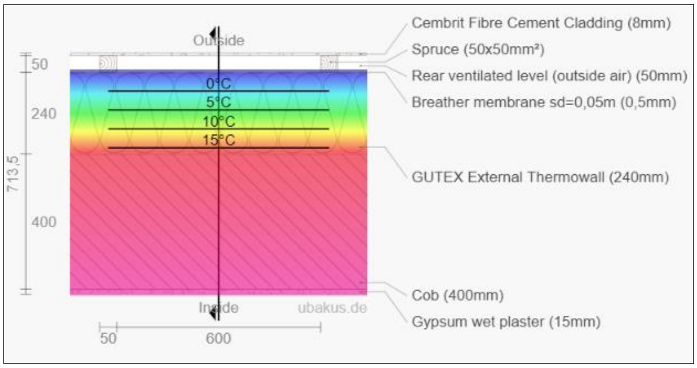


Figure 15. Temperature of Cob Wall

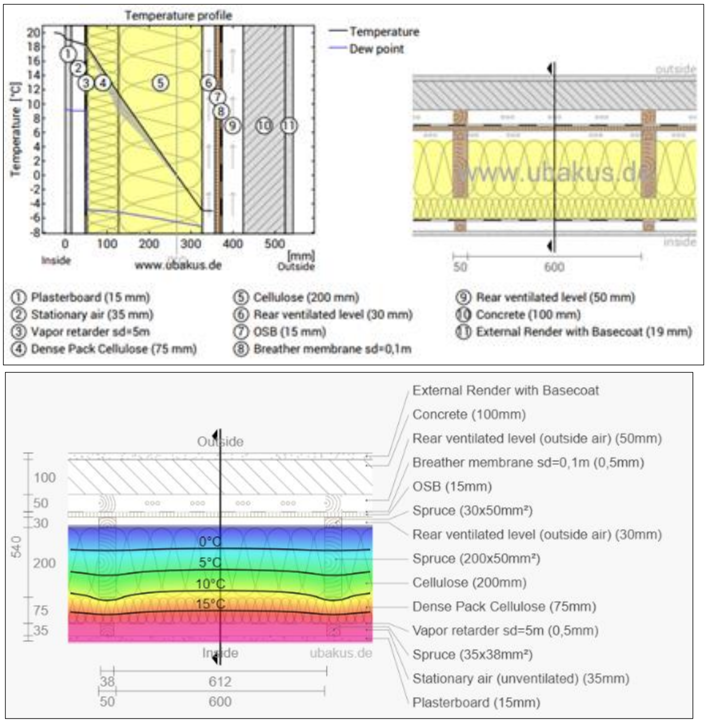
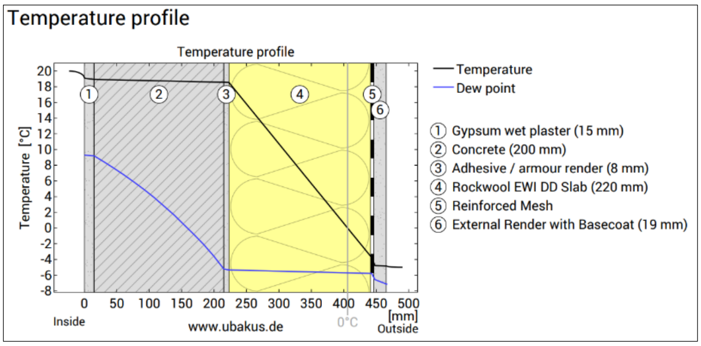


Figure 16. Temperature of Cellulose



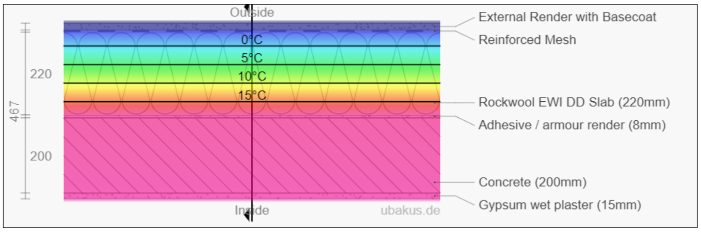


Figure 17. Temperature of Mineral Wool

6.10 TEMPERATURE RESULTS

All figures showed that the temperature and dew lines do not intersect. Therefore, all wall components were free from condensation under the given climate conditions.

6.11 HEAT PROTECTION ANALYSIS

A room's heat protection is mainly affected by direct solar radiation through windows and overall heat storage capacity (floor, internal walls, and furniture). Different component temperatures are displayed. Brown lines at 3pm, 11am, and 7am. The outer (red) and inner (blue) surface temperatures are at 7 pm, 11 pm, and 3 am. The arrows indicate the location of the maximum temperature values.

Note: For wall phasing, the blue line, representing interior temperature, stays straight due to good insulation.

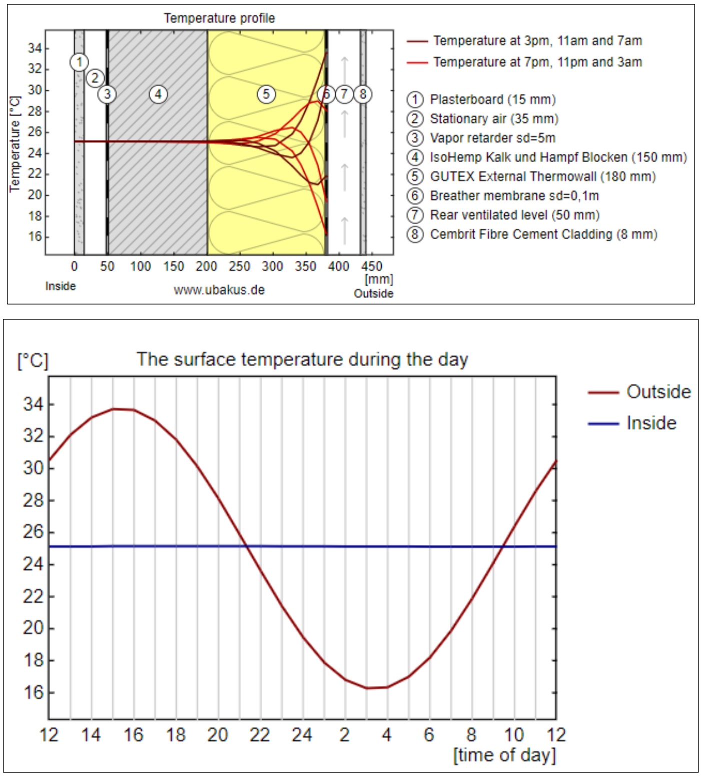


Figure 18. Heat Analysis of Hempcrete Wall

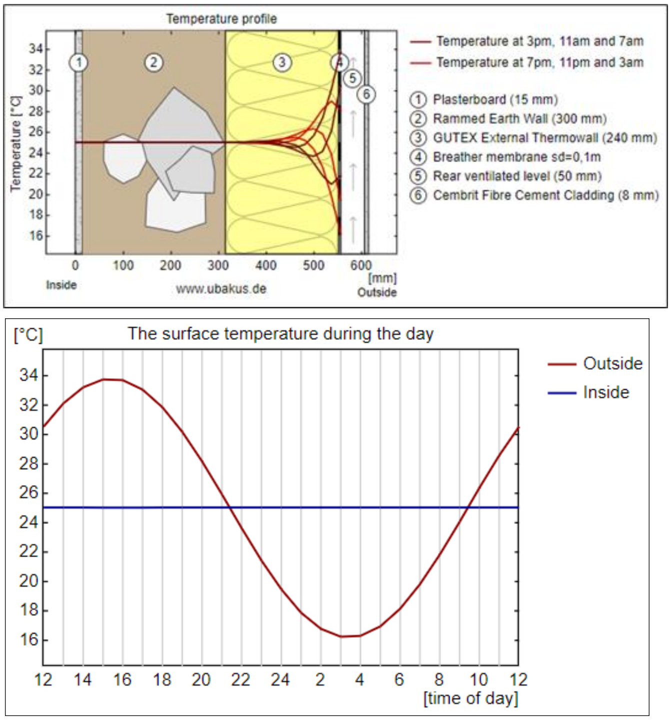


Figure 19. Heat Analysis of Rammed Earth Wall

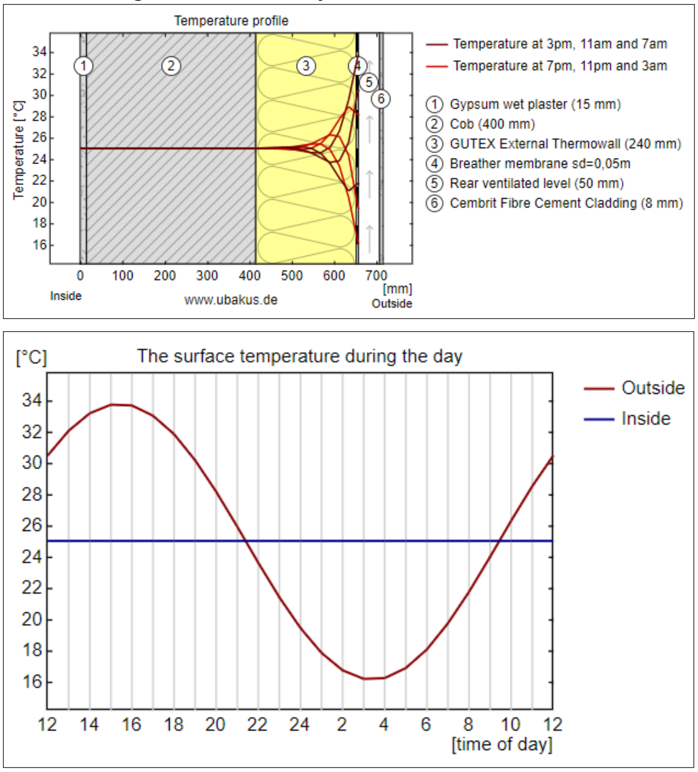


Figure 20. Heat Analysis of Cob Wall

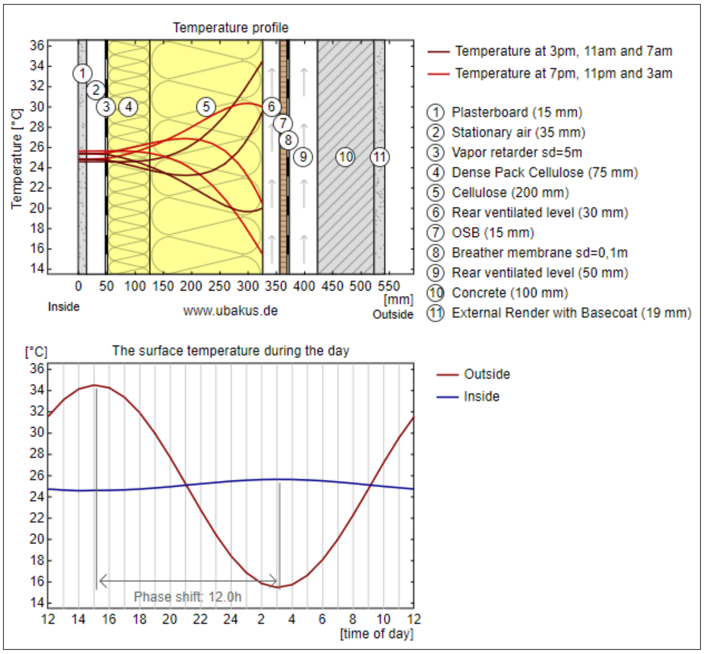


Figure 21. Heat Analysis of Cellulose

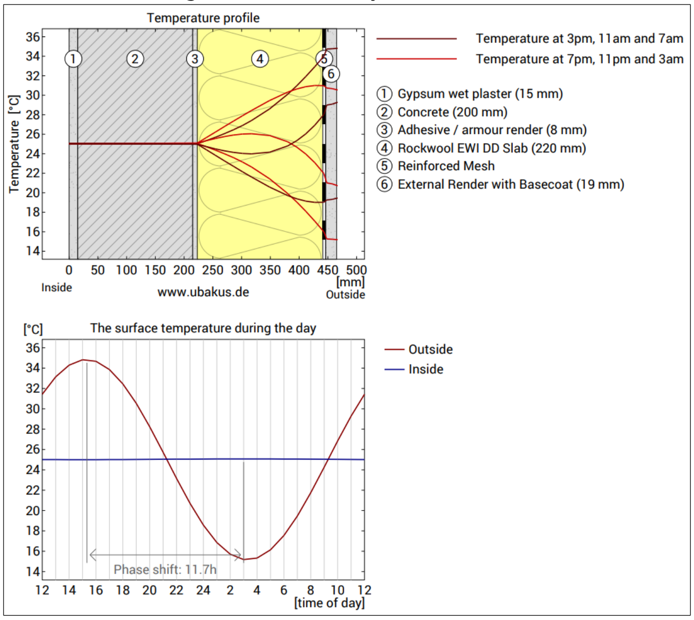


Figure 22. Heat Analysis of Mineral Wool

6.12HEAT RESULTS

A heat and phase investigation revealed that the heat passage through all walls takes over 24 hours to reach the core region. All wall styles offer high protection and phase change, which can be advantageous in Ireland due to faster heat retaining. For thermal options, the Cellulose wall showed to retain heat slightly higher.

TABLE 6. Heat Phase Shift

Wall Type	Phase Shift (h)
Wall type 1 – Hempcrete Wall	Over 24
Wall Type 2 – REW	Over 24
Wall Type 3 – Cob Wall	Over 24
Thermal Options	**Phase Shift (h**
Thermal Option 1 – Cellulose	12
Thermal Option 2 – MW	11.7

6.13 LIFE CYCLE ANALYSIS

This component's heat loss per square metre during heating. Heat loss from internal and solar gains exceeds heating demand. New construction materials were made using non-renewable primary energy ("cradle to gate"). Therefore, more greenhouse gases were removed from the environment than were emitted during construction material manufacturing.

The calculation is based on monthly average temperatures further using the Ubakus software. Ideally, the Life Cycle Assessment should also include the disposal of building materials after their end of life. With lifetimes of 30 or more years, however, it is not foreseeable today what kind of damage or benefit the disposal would pose. For this reason, the disposal is not considered here.

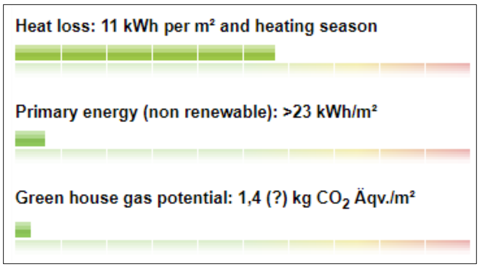


Figure 23. Life Cycle Assessment of Hempcrete Wall

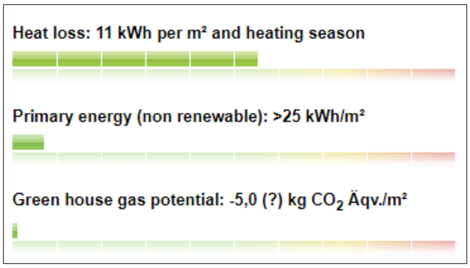


Figure 24. Life Cycle Assessment of Rammed Earth Wall

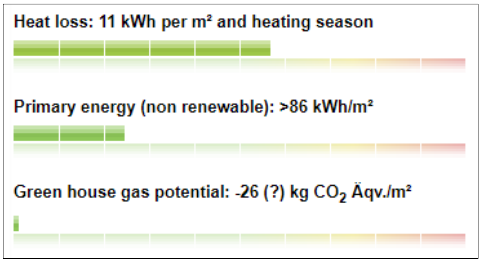


Figure 25. Life Cycle Assessment of Cob Wall

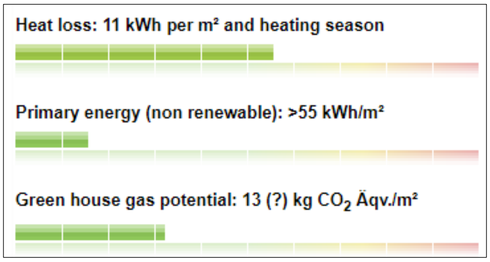


Figure 26. Life Cycle Assessment of Cellulose

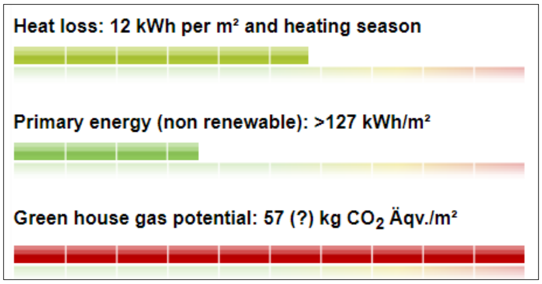


Figure 27. Life Cycle Assessment of Mineral Wool

6.14 LIFE CYCLE ASSESSMENT RESULTS

In terms of wall types, wall type 1, the Hempcrete, performs slightly better than both the Rammed earth and Cob wall in relation to LCA. Due to it acting as both a primary structure and thermal option. However, Cellulose shows to excel farther than all other options.

6.15 LOW IMPACT LIFE CYCLE COMPARISON

A comparison was conducted on LCA, which was split into four phases, including the topic of embodied energy. A wall type was assessed with different options of construction types for these elements. This section aims to determine the environmental impact and embodied energy of the recommended material and wall assembly, one of the report's four main objectives.

A brief embodied energy calculation specific to the low impact materials was conducted using the Bath University's Inventory of Carbon and Energy, the manufacturer's Environmental Product Declaration and datasheets and other third-party websites, and a wall build calculation comparison from 3.2.3 using the Ubakus software due manufacturer limits as mentioned in the limitations, figures were only calculated from manufacturing stage.

TABLE 7. Low Impact Life Cycle Comparison

Materials	Low Impact Life Cycle Comparison				
	Declared Unit	EC (in GWP) kg CO2-Equiv	Declared Unit	EE of materials MJ	Source and Comments
Material 1 – Hempcrete	Kg	-9.63E+01	MJ per m^3	4.30E+01	ISOHemp Hempcrete EPD A1-3
Material 2 – Rammed Earth	Kg	9.36E+00	MJ per m^3	1.27E+02	Oekobaudat - Restricted Information from third party site (Due to limitations)
Material 3 – Cob Clay:Soil:Sand:Straw:Water 2:1:4:1:1	Kg	8.02E+00	MJ per m^3	9.10E+00	GWP Modelled with ICE DB V3. EE calculated from journal article. Due to limited material information, the result may be incomplete ICE DB also doesn't consider waste rate and EE.
Material 4 – Cellulose	Kg	3.49E+00	MJ per m^2	1.69E+02	Ecocel Cellulose EPD A1-3
Material 5 – MW	Kg	5.46E+00	MJ per m^2	8.37E+01	Rock Wool MW External Wall Insulation EPD A1-3

Wall Types	Declared Unit	Ubakus Greenhouse Gas potential g CO2 Äqv./m²	Declared Unit	Ubakus Primary Energy (Non-Renewable) to achieve a U-value of 0.015W/m²k	Source and Comments
Wall Type 1 – Hempcrete	Kg	-5.00	MJ per m^3	9.00E+01	Ubakus software – Primary energy tab converted from KWh/m² to MJ/ m^3
Wall Type 2 – Rammed Earth	Kg	1.40	MJ per m^3	8.20E+01	Ubakus software – Primary energy tab converted from KWh/m² to MJ/ m^3
Wall Type 3 – Cob	Kg	13	MJ per m^3	1.98E+02	Ubakus software – Primary energy tab converted from KWh/m² to MJ/ m^3
Thermal Option 1– Cellulose	Kg	-26	MJ per m^3	3.09E+02	Ubakus software – Primary energy tab converted from KWh/m² to MJ/ m^3
Thermal Option – MW	Kg	57	MJ per m^3	4.57E+02	Ubakus software – Primary energy tab converted from KWh/m² to MJ/ m^3

6.16 RESULTS

Interviews were conducted with three respondents who gave their distinct understanding of the topic and discussed the environmental impact of the materials. Each showed a similar interest in Hempcrete being their preferred option due to its qualities.

All material options were designed in the modelling software Revit in a build-up to achieve passive house standards of 0.15 W/m²K, which is standard if being applied to the medium sized building's wall proposal. The materials were then evaluated in terms of U-value, moisture analysis, temperature profile, heat phases shifts and an LCA. It is necessary to clarify that each was deemed suitable for the building, having no risk of condensation and little impact on carbon footprint without its complete assembly.

This information was considered when determining the most optimal low impact option; however, in terms of sustainability, wall thickness and overall LCA, Hempcrete (Wall type 1) was more favourable than the other selected materials. Likewise, Rammed earth has similar results; however, it's wide thickness to achieve the minimum U-value would require more energy to be constructed, thus increasing its embodied energy.

7. Conclusion and Recommendations

This paper assessed the favourable and complicated features of various materials. Following the calculations, results, and comparison of each material, this analysis concluded that Hempcrete was the best low-impact alternative for the project. When meeting the Passive House standard and being suited for the building, the embodied energy and global warming contribution are the lowest. Nevertheless, it is crucial to acknowledge that each material possesses its own set of advantages and disadvantages. While Hempcrete demonstrates suitability for medium-sized constructions, it may not match the overall weather resistance exhibited by Cob and Rammed earth shown in the studies despite all three types exhibiting condensation-free properties and having slightly lower heat retention compared to cellulose wall types.

The report investigated and evaluated low impact thermal products and wall assembly options; it is recommended that more in-depth research on low-impact sustainable manufactured materials, such as strawbale, cellulose mineral wool, and timber, seeking more data on Hempcrete, Rammed Earth Wall, and Cob manufacturers in Ireland, be conducted. As a result, EPD datasheets and other requested material for this report were not obtained.

It would be interesting to develop new strategies for improving that component in current building as companies and contractors do not consider embodied energy and more sustainable solutions. The topic of modern construction and sustainability is undoubtedly an area of further research.

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I would like to express gratitude to the interviewees for their time and expertise in their respective fields.

I am grateful to my friends and family for their support, appreciation, encouragement. Above all, I dedicate my work to God Almighty, as this study would not have been possible without him.

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THE POTENTIAL FOR DIGITAL CONSTRUCTION TECHNOLOGIES TO ENHANCE FIRE EVACUATION PROCEDURES

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Abstract. In recent years digital construction processes and emerging technologies have had a huge impact on the construction sector, advancing the design, construction, operation, and maintenance of buildings. As an area of potential advancement, it is essential to recognise the extent of the benefits associated with fire evacuation procedures without disregarding traditional approaches which have been drawn upon in studies to date. This study aims to present the concept of linking a QR code to Building Information Modelling (BIM) to deliver a 3D fire evacuation animation in Twin motion based on the location of the building occupant. The concept developed in this study considers current studies investigating Bluetooth Low Energy (BLE) sensors and Real Time Location Systems (RTLS) before proposing a solution in the form of an instructional escape video, which aims to encourage users to use a safe escape route from their origin to reach a fire assembly point. The navigation video uses wayfinding, graphics, and directional arrows which collectively address aspects of colour psychology and cognitive affordance which can be linked to how an individual responds in an emergency within an unfamiliar space. Results show the potential for professionals within the Architecture, Engineering, and Construction (AEC) industry to incorporate BIM authoring software into the workflow using a Revit model and the Twinmotion add-in to develop a virtual evacuation demonstration as part of the building's fire strategy. Future work in this area may consider formulating a real-time fire evacuation management system that aligns with the 3D wayfinding animation to allow for the QR code to be updated. To extend the BIM module, further research could determine how this system may incorporate real-time information and respond to information from smoke detectors to provide alternative escape routes for occupants during a fire evacuation. This paper demonstrates the progressive nature of this concept, by leveraging twenty-first-century technologies to create a 3D fire evacuation video using BIM, which paves the way for developing indoor location-based AR evacuation experiences.

Keywords: QR code, Fire Evacuation, BIM, Wayfinding

1. Introduction

A fundamental principle in the profession of an architectural technologist is to provide technical building solutions through detailing, and so, fire safety design and appropriate material specification are at the heart of safe practice which influences this study. Today, fire evacuation procedures are announced verbally, supported by hand gestures guiding the audience's attention toward the nearest fire evacuation route based on their location within a space. It proves viable to disrupt traditional fire evacuation procedures in the twenty-first century and utilise the new and emerging technologies that are widely available. Informative studies have been conducted in recent years utilising the functions of BLE sensors and RTLS collaboratively with a "smartphone module" and BIM to direct individuals to a point of safety during a fire evacuation (Zhang et al. 2019). The success of these studies paves the way for the QR code and escape animation concept developed in this paper, as it advances the familiarity between individuals and their environment by targeting colour psychology using modern-day technology. The 3D animation developed in this paper presents a hypothetical fire evacuation scenario in an education facility, intending to exhibit the opportunity to introduce this concept into the building fire and safety management protocol. The objective is to improve the awareness of building occupants of their surroundings by utilising this concept during a fire drill to enhance their understanding of the methods of escape in the event of a hypothetical fire.

Professionals within the Architectural, Engineering, and Construction (AEC) industry are frequented with Health and Safety procedures supporting safe evacuation, especially at Continuing Professional Development (CPD) courses, which take place on premises that individuals tend to be unaccustomed to. The study in this paper recognises the lack of engrossment linked to traditional Health and Safety procedures, which are limited in their approach and often fail to captivate the audience which has an influence on exit choice in an evacuation. In the late '90s, Pires (2005) investigated human cognitive behaviour using "people evacuation models" to determine the response of occupants in acknowledgement of the type of building and the context of the emergency at hand. The results obtained revealed that "to represent the decision-making process of people during an evacuation, the model must incorporate a way to simulate the occupant's behaviour", which is addressed in this study by the creation of a 3D escape animation that adheres to the criteria of Pires' findings.

Building upon the work carried out by Pires in 2005, Nilsson (2009) outlined how the choice of an exit route for building occupants in fire emergencies is established around environmental factors, one's "familiarity with the route, personal associations connecting safety to the colour green and danger to the colour red, and social influence" all concerning the Theory of Affordances by Gibson (1978). Nilsson exhibits the purposeful effect that passive (static e.g., emergency signage) and active (dynamic e.g., wayfinding) measures have on advancing safe evacuation. These findings have informed the escape animation created as part of this study, it complements passive and active measures in the building through visual representation of emergency signage, relatable colours, and directional arrows to directly target human cognitive behaviour. More recent studies conducted in 2018 relate to the 3D visualisation modelling abilities of BIM (Chen et al. 2018) and the proposition of a controlled "fire evacuation management framework" using BIM (Zhang et al. 2019). Pires (2005) conducted an assessment method to consider human cognitive behaviour in this respect. The analysis concluded clear findings that relate to this current study: "In educational occupancies (i.e., universities, schools, etc.), where the occupants are familiar with the place and subject to discipline and control during an emergency, the way-out selection might not take too long". On the contrary, he concludes that "unfamiliarity with a space and especially an escape route retards occupants' movement in an escape" (Pires, 2005).

In the event of a fire prevailing throughout a high-rise building, every second counts to ensure a quick and safe escape for building occupants (Stančík, 2019). Recent findings on escape path planning in high-rise buildings using BIM applications to navigate endangered occupants to a safe space in a fire, prove successful in buildings with a high capacity (Wang et al. 2020). However, the shortcomings surrounding the implications that the obscuring properties of smoke generate, create opportunities for developing a better escape path in conjunction with BIM visualisation (Wang et al. 2020). By familiarising building occupants with the given environment by incorporating digital technology and smartphone devices to maintain evacuation plans, the evacuation procedure should become more straightforward (Zhang, 2019). Research advancements demonstrate the competence of BIM and its correlation with 3D visualisation modelling to alert endangered occupants in the event of a fire, by incorporating the Dijkstra algorithm to facilitate the "process of dynamic fire escape path planning method" aided by the smartphone (Wang et al. 2019). Stančík (2019) concludes by studying the parameters of BIM, and the feasibility of maintaining fire evacuation plans using add-on applications.

This study is extremely relevant as it proposes a dynamic concept which allows for building occupants within a given space to scan a QR code using their smartphone device, which automatically projects a hypothetical 3D escape animation onto the device screen, ultimately taking them on a step-by-step path out of the building to a designated fire assembly point. The overarching aim of this study is to produce an 'accessible for all' concept which can be accessed by scanning a QR code to enhance existing fire and safety management procedures by improving their impact factor – especially in unfamiliar settings – through animation and colour. This study has been informed by the previous research and findings revealed in this paper and assisted by the maturing technologies available such as Autodesk Revit and Twin motion.

2. Technology and Fire Management

In the last decade, fire safety and BIM have become emerging topics in the Architecture, Engineering, and Construction (AEC) industry. More industry professionals have recognised that the functionality of BIM implementation in retaining and maintaining building data and information in a common data environment (CDE), entails a massive opportunity for improving emergency evacuations. Historically, fire-related protocol has not actively encouraged technology which has the potential to retain mass amounts of building information however, this concept encourages escape evacuations to become more effective than before by grasping the opportunity for continual improvement by creating an instructional escape video based on the occupant's origin using technology. Currently, fire evacuation protocol follows a regimented structure by which rapid safety information is verbally directed towards individuals to retain. The issue with this form of direction is that it is adhered to within the first few moments that an individual enters a space when one is not fully attentive, which may leave a significant amount of time between the point in which they first retain the information and the point in which they may need to implement it i.e., during a fire evacuation, creating a higher possibility of one forgetting the original information. Other fixed forms of fire evacuation procedures include '5-point fire evacuation notices' found fixed to internal walls beside fire extinguishers, or emergency evacuation plans which are often fixed to the back of internal doors. The presentation of this fire evacuation literature may easily go unnoticed, and the overall appeal is lacking in most cases primarily due to the location where it is placed, or the text size used to outline the action required.

The introduction of new technologies especially those concerning BIM creates a realm of possibilities for digitising traditional fire evacuation procedures. BIM is the way that "digital information" about the built environment (physical building and infrastructure) is represented and organised (ISO 19650). BIM in the modern era has been utilised by the construction industry to make the labour sector more competitive, whilst meeting the demands of a growing, ageing, and urbanising population at a lower cost. More emerging research from years 2019-2021 focuses on the technological advances related to BIM and human cognitive behaviour to enhance rescue operations, concerned primarily with how data extraction from smartphones can inform Bluetooth sensors, which track spatial configuration, generating safe evacuation in the form of 3D navigation models tailored to an individual building occupant (Zhang et al. 2019). Despite the implementation of digital technology and smartphones already linked to improving fire evacuation in the form of fire safety apps, from the previous literature reviewed, there would appear to be a shortage of studies relating to QR code incorporation within a technological framework.

If all visitors and occupants to the building receive introductory training as part of the fire safety protocol, this strategy could disrupt traditional workflows by forming new possibilities for fire evacuation procedures using technology to revolutionise building design and life cycle. The escape animation concept accessed through scanning a QR code, is an accessible approach that builds on new and previous studies to compose a modern-day advancement on traditional approaches with the safety of building occupants as a prime focus.

Evidence collected in studies dating back to 2008 highlights the lack of fire prevention and control measures that lie within high-risk buildings, identified primarily as complex high-rise, highly concentrated structures, prove an ongoing problem with fire management in buildings of all scales (Yong, 2008). More recent findings produced by the Home Office UK in the Fire and Rescue Incident Statistics England Report 2021, highlight a 6% increase in fire-related fatalities in high-rise and domestic dwellings between the year ending June 2020 and June 2021, as the fatality rate escalated from 235 to 249 (HM Government, 2021). These statistics produced following the data provided by the Fire and Rescue Service (FRS) England reveal that building fires occur most regularly, especially during operation and maintenance periods which contributes to the research undertaken in this paper (Wang et al. 2021). Wang (2021) and the Grenfell Tower Inquiry: Phase 1 Report, 14th June 2017 (HM Government, 2019) confirm the ongoing validity of research into fire risk assessment and consideration of the building occupants' behaviour in response to the circumstances of a potentially life-threatening event (Ma and Wu, 2020).

2.1 TECHNOLOGICAL FRAMEWORK

The method formulated by Jinyue Zhang 2019, "proposes a fire evacuation management framework which takes advantage of a 3D model and a Bluetooth low energy (BLE)-based indoor real-time location system (RTLS)". Successful outcomes demonstrate the viability of incorporating smartphones into the RTLS module to calculate an evacuation route based on the Bluetooth Fire Detector Status and BIM Fire Safety Information to guide building occupants to a safe space. Zhang (2019) reiterates the effectiveness of developing a competent model comprising Fire Safety data from up-to-date guidance documents, relating to the identification of material fire ratings. This method validates the benefits of the "proposed fire evacuation management framework" using case study examples in an office building but, poses further research into the authentication of improved interaction between building occupants and their environment using a smartphone module (Zhang et al. 2019).

Elaborating on previous studies, (Ma and Wu, 2020) and (Wang et al. 2021) have trialled Dijkstra's algorithm within intelligent BIM systems incorporating Bluetooth technology. This method involves an animation appearing on the building occupants' smartphone device which demonstrates a visual representation of the room in which they are located, including directional arrows and a floor plan layout which indicates safety distances in metres. This approach is innovative in pushing the boundaries of technology but does not fully comply with the Theory of Affordances by Gibson (1978). The advancement in research led to the determination of the most efficient escape route by maintaining connections between nodes comprising Dijkstra's algorithm within differing proximities to obtain the most efficient escape path based on travel distances, which analysed the shortest escape path through the interpretation of the fire information data input into the BIM system.

In 2020, Ma and Wu (2020) validated the ineffectiveness of proposing a rigid evacuation strategy that fixates on limiting factors, as opposed to accounting for a culmination of alternative responses described "in the form of a fire emergency management" operation system – which allows for informed decisions to be made through the 3D model responding to the occupants' location, irrespective of the spatial layout of the building. The crux of existing findings reveals the practicality of utilising innovative technology (Wi-Fi fingerprint identification and an e-building platform), to enhance the speed of evacuation rates from buildings through 3D modelling and visualisations interpreted using a smartphone device. This concept demonstrates how an internal evacuation route can be displayed on a building occupant's smartphone device indicating the escape route which improves the relationship between the building occupants and the space. Advances combining location information using cellular data within an advanced BIM integration system, produce the smooth transferral of precise information throughout an e-building platform by transferring the evacuee's exact positioning into a PC, enabling an audio response to be returned to the smartphone device, with the advantageous outcome being an informed evacuation path directing the user to safety using intelligent monitoring (Ma and Wu, 2020). Despite each fire breakout being unique in its height of blaze and potential, it is pertinent to bear in mind that the solutions conferred in this paper and others researched are not completely accomplished (Zhou et al. 2019). The practicality of conducting a further study into optimising BIM and safer evacuation strategies with QR codes to a new extreme proves very viable on the basis that the potential limitations outlined in Section 5.0 are investigated.

"BIM and Computer Vision framework systems for fire evacuation" developed at a later stage by Deng, (2021) focuses on the performance and integration of BIM in generating a virtual escape route based upon individual co-ordinations delivered by a geometry network module (GNM) within the context of a campus building. The results concluded by Deng (2021) suggest that continual development is needed to formulate a system that uses the data incorporated within BIM more innovatively to design a strategy that accounts for the safety and functionality of the escape route by utilising advanced technology to address the safety and reliability of the proposed evacuation route.

2.2 QR CODES

QR codes are accessible, widely used, and versatile, as they can be scanned with the built-in camera on modern smartphones. QR codes are highly integrated into society today for several applications, but within the AEC industry, one use case for QR codes involves the displaying of QR codes on hoarding surrounding building sites as a tool to assist with promotional purposes. After the QR code is scanned, the user may be prompted to the company's webpage, and it is then that a link is established between the user and the company's identity. QR codes are convenient on-site, often Architects' drawings will include a QR code within the title block. Once scanned, the individual on-site executing the design may be directed to an enlarged technical detail at a larger scale than what has been presented on the sheet. In modern higher education facilities, QR codes have been identified within teaching rooms, and on door handles to restrict and manage the occupancy in reduced access rooms such as a board room setting. QR codes do not appear to be becoming outdated and still hold relevance today which supports the concept developed in this paper.

In the event of a fire in a building, occupants' exit choice behaviour is often dictated by the direction in which they need to move towards to reach safety. By creating a highly dynamic fire evacuation strategy, more value is placed upon functional affordance during a fire evacuation (Nilsson, 2009). It is believed that by introducing an interactive 3D evacuation video in the form of a QR code, building occupants will have an improved cognitive affordance of the space in which they are, obtained by technical design features and colours which carefully create relationships between building occupants' sensory affordances and the building environment, intending to increase the rate at which building occupants respond in a fire evacuation, ultimately improving the likelihood of occupants reaching an area of refuge. For the proposed strategy to be successful, occupants need to trust the developed design which will stem from a streamlined interactive concept in the form of an evacuation animation, to strengthen building occupants' cognitive and sensory affordances through distinctive fire-related visuals (e.g., signage) and colour associations (Nilsson, 2009).

3. Methodology & Data Collection

This research investigates how digitally enhanced evacuation plans could improve the emergency response reaction time of building occupants, with the outcome of better-informed evacuations through addressing the affiliative behaviour of building occupants in the form of a fire evacuation management framework. To make the QR code application in response to fire safety, it was pertinent to find out information on human movement and behaviour in fire evacuations to develop the pathway for an intelligent evacuation system. To acquire the desired data, a combination of data collection methods in Figure 1 was applied to reach the objectives of this paper. A case study approach was utilised to facilitate a well-informed evacuation animation, which was achieved using BIM. Step 1 involved acquiring information on the current protocol within the higher education building. The navigation video proceeds from a meeting room in an education facility, the evacuation path from this room was identified and mirrored in the 3D model (Step 2). Once the escape route was determined using the existing protocol, the Twinmotion add-in for Revit was applied (Step 3) and the navigation video was designed and linked to a QR code by the author

(Step 4). All steps were completed in numerical order (Figure 1) to ensure a smooth-flowing process, with the end outcome as the generation of an interactive escape animation.

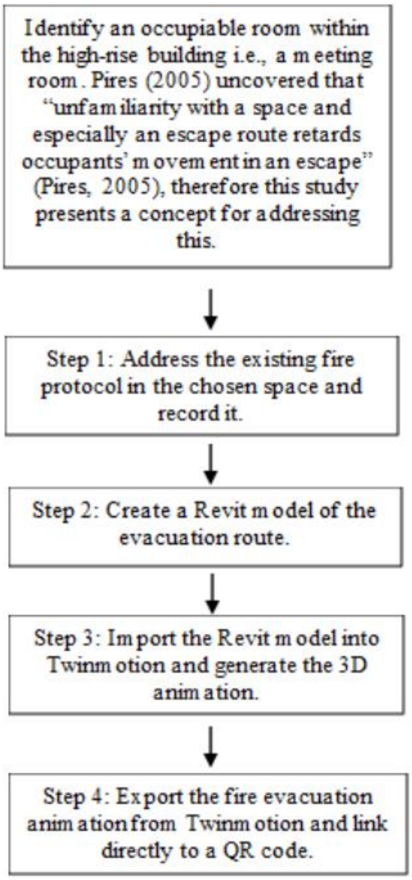

Figure 1. The concept of integrating a 3D evacuation plan.

4.0 Case Study

An occupiable room was chosen for this case study as opposed to a habitable room. The evacuation animation has been based on the escape route from a meeting room, the reasoning resonated with affiliative behaviour and how occupants react during emergencies in unfamiliar environments. Step 1 involved making a visit to the meeting room to investigate the existing fire evacuation protocol already in place such as smoke alarms, audio speakers, emergency lighting etc. and taking a photographic record of those in place (Figure 2). The 3D navigation video enhances the established fire evacuation protocol, by methodically taking the user on the escape route from their place of origin to an area of refuge via the stair core.

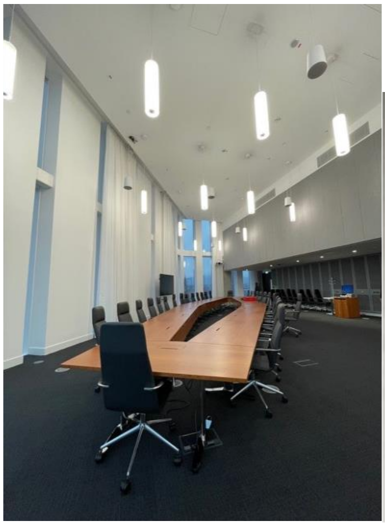

Figure 2. Meeting room and existing fire safety devices.

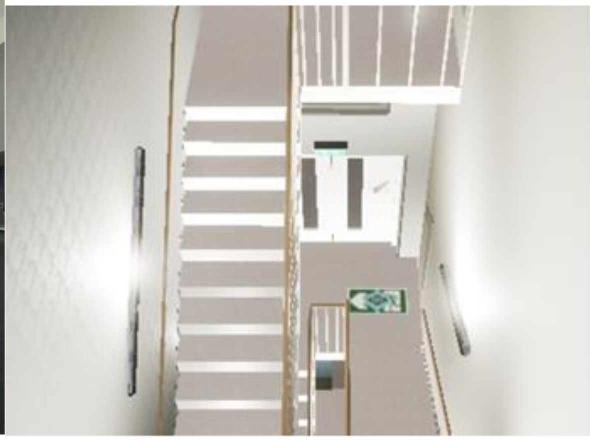

Figure 3. Stair core.

Step 2: Involved in creating a 3D Revit model of the stair core for the execution of this paper. The stair core shown in Figure 3 was modelled in Revit by the author (Step 2) and imported into Twinmotion where the animation was created (Step 3) before it was exported and linked to a unique QR code (Step 4).

Figure 4. Twinmotion renders from 3D evacuation animation.

Once exported, the 3D animated evacuation path from the meeting room to the refuge area was executed using the visual data imported from the Revit model. A virtual walkthrough of the evacuation route (Figure 5) from a meeting room was created and exported as an MP4 file (Step 4). Having created the Revit model, realistic visual details were achievable, permitting the most realistic animation demonstration to be obtainable. To demonstrate the positioning of the QR code in the meeting room, a prototype was superimposed on an evacuation plan next to the fire exit door (Figure 5). Please scan the QR code below.

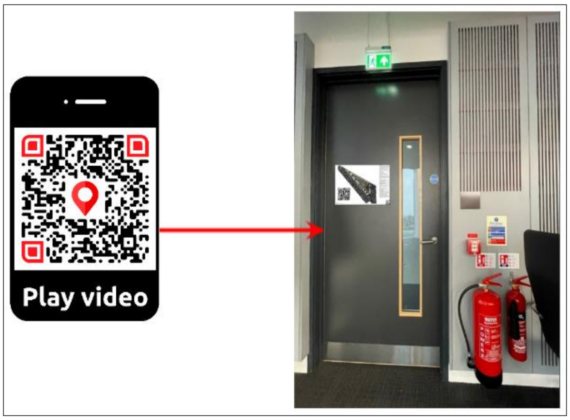

Figure 5. QR code prototype.

5.0 Discussion

The findings in this paper prove the actuality of incorporating a 3D animation into an existing evacuation plan to aid ease of escape for building occupants. The safe evacuation video developed as part of this paper uses visual aids to provide safer evacuation. The video footage demonstrates how one may obtain a safe escape from the setting using a walkthrough generated in Twinmotion. The evacuation video shows the potential for professionals within the AEC industry to incorporate an extended technological framework into the workflow when producing 2D fire evacuation plans. The possibilities of technology are more pertinent than ever, and it is up to professionals within the AEC industry to use those available to them to evolve existing 2D fire evacuation plans. To build upon the success of the method developed within this paper, one may consider the idea of continual improvement by formulating a real-time fire evacuation management system that aligns with the 3D animation to allow for the QR code to be updated. To make the concept more stable, especially in the event of a power outage, a backup generator or other standby power supply will need to be included in the design of the building. Other design considerations include adaptive evacuation system control units with integrated battery-supported power supplies for passive controls and phone signal amplifiers. Given that one cannot presume building occupants will be carrying a smartphone with sufficient battery health / cellular data at all times of the day, further development of a safety briefing upon entry to the building will bring one’s attention to the importance of having sufficient battery health to acquire the benefits of the QR code. To extend the BIM module, further research into how this system may incorporate real-time information and respond to information about smoke detectors could be included in the framework to provide alternative escape routes for occupants during a fire, for example, if a route has been blocked off or if a route is congested. Further investigations into Big Data may affirm the relationship between human cognitive behaviour and the proposed method to highlight the reality of how effective building occupants would respond to the animation as opposed to gravitating towards following the crowd or making choices based on the natural tendency to not think rationally in an emergency. Inclusive design principles are an area for further development which needs to be factored into the proposed concept to make it more universal within the AEC industry, by addressing the needs and behaviours of a variation of building occupants including those who carry disabilities, particularly visually impaired individuals, and wheelchair users.

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AN INVESTIGATION OF THE PHYSICAL AND THERMAL PROPERTIES OF IRISH HEMP FIBRES AS A LOOSE-FILL INSULATION PRODUCT

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Abstract. Construction and built environment sectors account for approximately 37% of Ireland's carbon emissions. Of this 37%, 14% of the emissions consist of embodied carbon emissions from the construction materials from the production to the end-of-disposal of buildings. The construction industry can reduce its embodied carbon by using materials with a lower embodied carbon. Hemp fibre batt insulation is an example of a bio-based material and a lower embodied carbon alternative to conventional insulations. The existing hemp fibre batt insulation is typically composed of hemp fibres with a polyester binder. These polyester binders have higher embodied carbon while also being a non-biodegradable material which has negative implications the end-of-life disposal. There is a lack of knowledge on how hemp fibres can be used independently as a loose-fill insulation. In this research, loose hemp fibre insulation specimens with varying fibre density were produced using locally grown Irish hemp. The effect of density, fibre orientation and fibre length on thermal performance was investigated using the hot box test procedure. The obtained test results were validated against polyisocyanurate insulation. These test results indicated how hemp fibre insulation in a loose state should be installed within a loose-fill insulation system to optimise thermal performance.

Keywords: density, fibre length, fibre orientation, hemp fibres, hotbox, insulation, thermal conductivity

1. Introduction

To mitigate the negative effects of climate change there is a significant emphasis on the role of embodied carbon within the construction sector (Joint Committee on Housing, Local Government and Heritage, 2022). A report from the Joint Committee on Housing, Local Government and Heritage, Government of Ireland (2022) estimates that roughly 37% of Ireland's carbon emissions are created from the construction and built environment sectors. Of these 37%, 23% are operational emissions connected to the building's energy consumption, while the remaining 14% consists of embodied carbon emissions connected to the production and disposal of these buildings' materials. Thus, there is motivation for the development of sustainable construction materials with a lower embodied carbon.

Sustainability within the construction industry is essential to consider in today's climate emergency and has led to the introduction of hemp-based insulation as an alternative to achieve a more sustainable insulation material (Dlimi et al. 2019;

Gaujena et al., 2020). Bio-based insulations, such as hemp-based, are competitive with conventional insulation material's thermal performance while maintaining a lower embodied carbon and are therefore simultaneously reducing energy use and GHG emissions (Dlimi et al., 2019; Donatelli et al., 2017; Al-Homoud, 2015; Kosiński et al., 2017). Hemp-based insulation has a more sustainable manufacturing process compared to synthetic insulation (Hussain et al., 2019; Scrucca et al., 2020). This results from the hemp plant's ability to sequester carbon during its growth phase, storing carbon within hemp-based materials resulting in a lower overall embodied energy material (Hussain et al., 2019; Scrucca et al., 2020; Ingrao et al., 2015; Zampori et al., 2013).

Ekolution Hemp fibre batt insulation (Ekolution, 2023) is an example of existing hemp-based insulation, which is typically composed of hemp fibres with a polyester binder to give the insulation rigidity to improve workability. The use of these polyester binders, however, gives the hemp fibre batt insulations a higher embodied carbon value. According to Donatelli et al. (2017), more than half of the energy consumption to produce hemp fibre-based insulation batts comes from the use of these polyester binder supports. It is identified that a reduction or elimination of the polyester binder material would decrease the total energy used for production and decrease the embodied energy (Donatelli et al., 2017). The use of plastic-based insulations can cause environmental issues due to the consumption of non-renewable materials and disposal phases of end-of-life products (Asdrubali et al., 2015). This motivated this research to explore the use of hemp fibres without a binder to eliminate the embodied carbon resulting from these synthetic polyester binders.

2. Literature Review

The concept of using hemp fibres as loose fill insulation has been explored by Kosiński et al. (2017) where they present results of raw hemp fibre obtained from a polish hemp crop of the Białobrzeskie variety. Kosiński et al. (2017) investigated the thermal conductivity (TC) and air permeability of raw hemp fibres in relation to bulk density as shown in Figure 1 below (Kosiński et al., 2017).

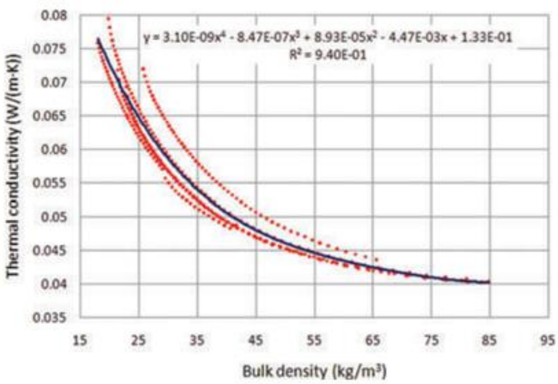

Figure 1. Thermal conductivity of hemp fibres in the function of material density (Kosiński et al., 2017)

The thermal properties of hemp fibre as an insulation material were dependent on the density of the hemp fibre (Kosiński et al., 2017), which is why research in this area is particularly useful. Kosiński et al. (2017) also confirmed that the lowest TC achieved by the hemp fibres in their study was 0.04W/mK with a density of 85kg/m³ as shown above. Their research confirmed that an increase in the density of the fibres caused a reduction in the TC.

A survey conducted in 2015 by Giesekam et al. (2105) on a sample of working professionals within the construction industry suggested that the construction industry is reluctant to use "low-carbon" building materials, including hemp-based, due to a lack of knowledge on the material itself. Furthermore, the author of this investigation noted a dearth of information regarding the most optimal way to use hemp fibres as a loose-fill insulation material.

Leading on from this, the main aim of this research is to develop knowledge about hemp fibre insulation used in loose-state and as a result, to encourage the construction industry to use bio-based materials such as hemp-based insulation.

The objectives for this research include:

1. Conduct desktop research to investigate how hemp fibres are processed from hemp plants, to then process fibres which are required for testing.
2. Identify the optimum density of hemp fibres for TC as an insulation material.
3. Determine the influence of hemp fibres orientation and fibre length on hemp fibres TC as an insulation material.
4. Conduct research which will add new information to the database and encourage the construction industry to install hemp fibre as a loose-fill insulation material.

3. Material and Methodology

3.1 MATERIAL

Hemp plants, of the FINOLA variety, were supplied by a representative of the Irish Hemp Farmers Association (IHFA).

Teagasc (2022) notes this dual hemp variety of the plant has only recently been introduced to Ireland. They can grow to a height reaching 1.5m compared to the standard 3m heights of typical hemp plants. They are grown primarily for seed production, but the fibre from these plants' stalks can still be used for construction materials (Teagasc, 2020). A limited amount of hemp fibre was obtained in this investigation due to the lack of resources in Ireland.

3.1.1 How to obtain hemp fibres from the hemp plant

Dried hemp plants were supplied for this research. Thus, the hemp stalks needed to be processed to obtain the hemp fibres. Desktop research was conducted to investigate the methods used to process hemp stalks for their fibres. There are machines manufactured which process the hemp stalks to separate the bast fibre. These machines are used to break and "comb" the stalks. This type of processing machinery is available in the United States but not in Ireland as there are no hemp processing facilities. For this research, smaller-scale versions of these processing machines were manufactured by the author. This included a "break" and a "comb". These machines were made using waste and salvaged materials.

3.1.2 The "break"

A break is a tool which is used initially to break up the hemp stalks to separate large parts of the woody core called the "hurd" from the fibre as shown in Figure 2.

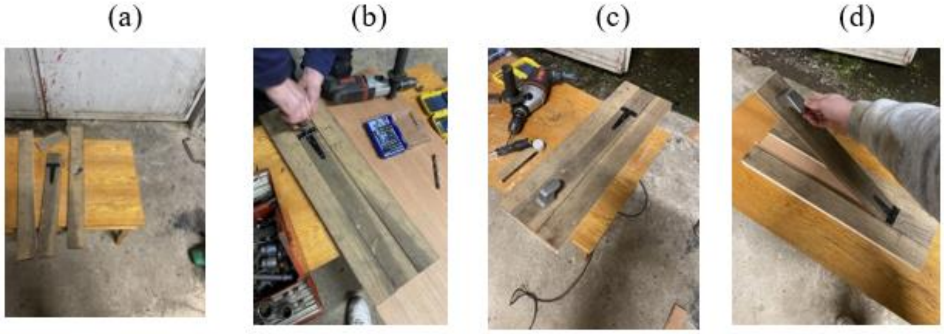

Figure 2. Manufacturing *process of* a "Break"

Unused floorboards from a renovation project were sourced and cut to create the break shown in Figure 2a. Three pieces of wood were fixed to a plywood base. Then, a board was fixed in the middle of the base, shown in Figure 2b, using a metal door hinge and screws. This was to create a freely moving board to move up and down to break the stalks. Finally, to make the breaking process easier for an operator, a handle was fixed to the moving piece shown in Figure 2c. The base beneath boards acted as a collector for "Hurd" which broke away from the stalk. The completed "break" is shown in Figure 2d.

3.1.3 The "comb"

The comb was made by using a waste piece of MDF board which was cut to size using a band saw. This piece of MDF was then marked to have screws placed within it and then the screws were screwed through shown in Figure 3a and Figure 3b, and the comb was ready to be used as shown in Figure 3c.

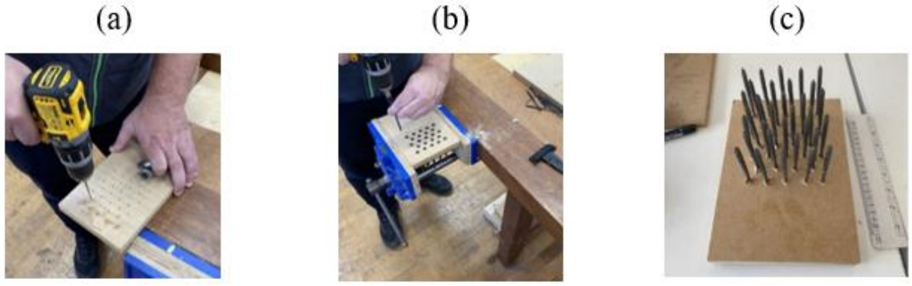

Figure 3. Manufacturing of a "Comb"

3.1.4 Processing the hemp stalks for fibre

Firstly, the parts of the plant which usable fibre could not be obtained from were cut from the plant as shown in Figure 4a and Figure 4b. Next, the "break" was used to begin the process of removing the larger woody "hurd" part from the stalk shown in Figure 4c. After the stalk had been sufficiently broken up to the point where the stalks were no longer rigid, the stalks were passed through the "comb" to remove the broken up "hurd" parts that were stuck shown in Figure 4d. Once the stalks had passed through the "comb", the bast fibres were left with minimal "hurd". The fibres were then cut to the desired sample lengths shown in Figure 4e.

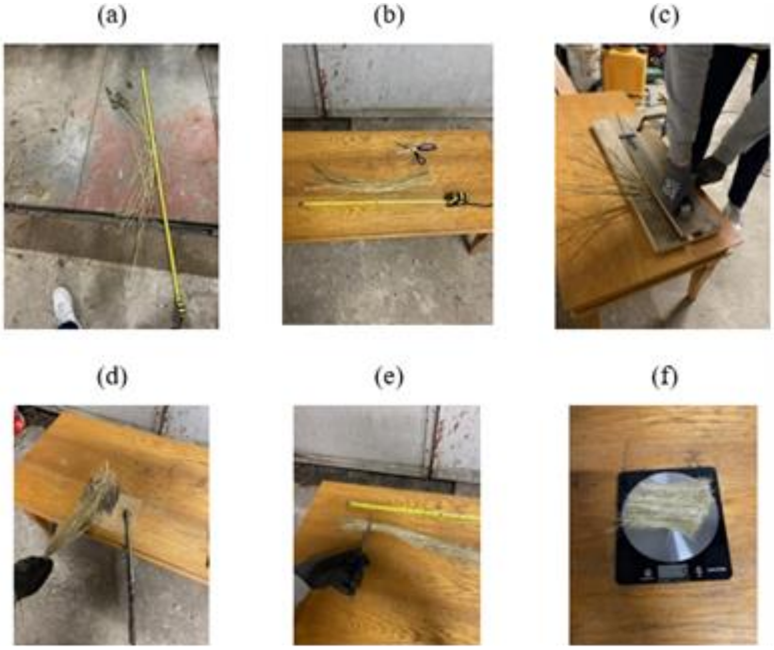

Figure 4. Processing of hemp fibre

3.2 METHODOLOGY

3.2.1 Hot box test

To determine the thermal resistance rating of the hemp fibre insulation specimens a calibrated hot box test procedure was used as per ISO 8990:1997 (1997). Results were recorded and compared, and a conclusion was deduced. The hot box used for testing was built by a previous student, Mark O'Brien, in the 2019/2020 academic year who used it for his thesis at the School of Architecture, Building and Environment (SABE), TU Dublin. Specifications of the hot box were acquired from a previous student, Paul Mc Gettrick, who also used the hot box for his thesis in the 2020/2021 academic year. The Hot Box was composed of Polyisocyanurate (PIR) insulation board (0.021 W/mK), Oriented Strand Board (OSB) (0.13W/mK) and Extruded Polystyrene (EPS) insulation Board (0.033W/mK). Specifications of the box are shown in TABLE 1.

TABLE 1. Hot Box Specification

Hot Box Element	U-Value (W/m²K)
Walls and Roof	0.154
Floor	0.097

The condition of the hot box and specimen holder when received is shown in Figure 5a and Figure 5b, respectively. A new specimen holder was made from 80mm PIR insulation from Xtratherm with a TC of 0.022W/mK shown in Figure 5c and Figure 5d. The hot box was upgraded using airtightness tape as well as Tec7 sealant to create airtightness at all necessary junctions shown in Figure 5e and Figure 5f. A new light bulb was purchased as a heat source shown in Figure 5g for the hot box.

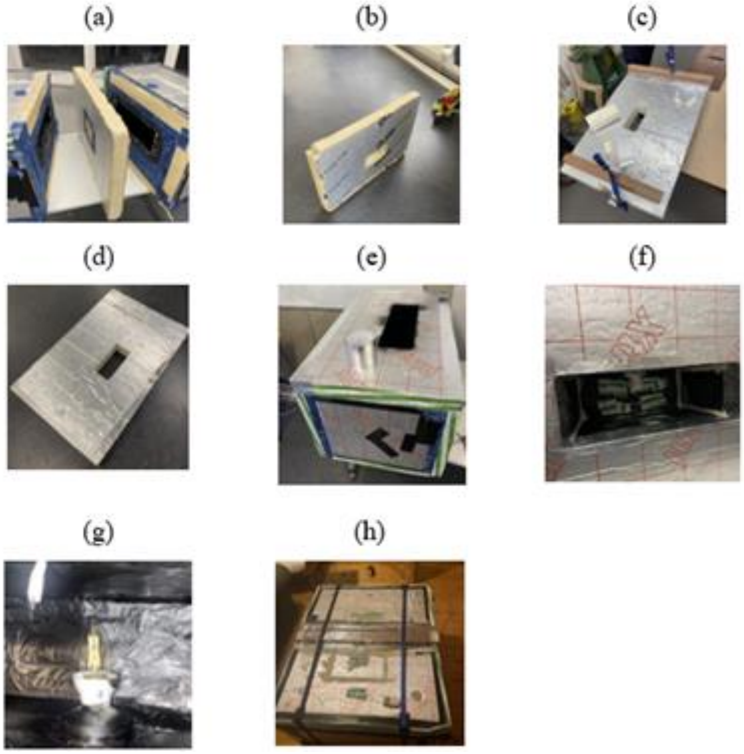

Figure 5. Retrofitting of Hot Box

3.2.2 Apparatus to log temperature data

Loggers from Elitech were used to record temperatures. The temperature for all tests was logged in 15-minute increments. Once a temperature logger had recorded data, it was downloaded onto the laptop and the data was analysed.

For calibration, the hot box test procedure was conducted with a 25mm piece of PIR insulation with a known TC of 0.022W/mK. All samples within this study had their TC calculated from the calibration process.

The hot box used for the test had an external dimmer switch connected to the heat source (incandescent light bulb). This dimmer switch was used to control the heat input to the hot box. The dimmer switch had 3 heat settings. Once the sample/specimen was placed within the specimen holder and the boxes were sealed together, the test procedure could begin.

To begin the test procedure, the power was set to the first of three heat settings. The boxes were left until the temperature of both the hot and cold boxes reached a steady state. For this test, steady state meant the same temperature range for a minimum of 2 hours within a ± .2ºC range. Once a steady state was reached, the temperature in each box was recorded. This process was repeated for second and third heat setting, and results were compared.

3.2.3 Samples for hot box testing

The samples for testing were first identified to establish a logical order for testing. These test samples are displayed in TABLE 2.

TABLE 2. Sample Size chart

Sample no.	Density	Orientation	Fibre length
1	30kg/m³	Mixed Orientation to Heat Flow (HF)	33mm
2	75kg/m³	Mixed Orientation to Heat Flow	33mm
3	80kg/m³	Mixed Orientation to Heat Flow	33mm
4	85kg/m³	Mixed Orientation to Heat Flow	33mm
5	90kg/m³	Mixed Orientation to Heat Flow	33mm
6	85kg/m³	Mixed Orientation to Heat Flow	65mm
7	85kg/m³	Parallel to Heat Flow	65mm
8	85kg/m³	Perpendicular to Heat Flow	65mm

3.2.4 Laid orientation samples

Examples of how the fibre orientation looked within the sample container are shown in Figure 6 below.

Figure 6. Fibres laid within sample container

3.2.5 Sample container

The sample size was limited to a brick size (215x102.5x65mm) for this study due to the lack of hemp fibres.

A sample container was made from a 3mm medium-density fibre (MDF) board and glue, with a removable lid to hold the hemp. The TC of this container was identified through the hot box testing procedure. This value was subtracted from the TC obtained from each sample to get an accurate value for each sample. This step was carried out at each of the three power settings to ensure that the sample container did not affect the results of any of the samples at each of the three power settings.

3.2.6 Consistency across samples

The hemp fibre samples were each laid within the sample container by hand. Consistency in the way the fibres rest in the sample container cannot stay perfect in each case as it is being hand-laid. In an attempt to limit variation, the author used the same laying technique for each sample, to try and maintain consistency throughout all samples.

4. Results and discussion

4.1 HOT BOX TESTING

The TC of all samples tested are shown in TABLE 3.

TABLE 3. Thermal conductivity results

Sample no.	TC (W/mK) – Heat setting 1	TC (W/mK) – Heat setting 2	TC (W/mK) – Heat setting 3	Average TC (Across 3 Heat settings)
1 – (30kg/m³, 33mm, Mixed HF) *	0.141	0.014	0.085	0.080
2 – (75kg/m³, 33mm, Mixed HF) *	0.061	0.077	0.058	0.065
3 – (80kg/m³, 33mm, Mixed HF) *	0.072	0.027	0.083	0.061
4 – (85kg/m³, 33mm, Mixed HF) *	0.006	0.077	0.086	0.056
5 – (90kg/m³, 33mm, Mixed HF) *	0.039	0.076	0.055	0.057
6 – (85kg/m³, 65mm, Mixed HF) *	0.057	0.057	0.052	0.056
7 – (85kg/m³, 65mm, ‖ HF) *	0.160	0.099	0.076	0.112
8 – (85kg/m³, 65mm, ⊥ HF) *	0.034	0.042	0.056	0.044
Key: (75kg/m³, 65mm, Mixed HF) * - the sample had a density of 75kg/m³, the fibre length used in the sample was 65mm, and the fibres were placed perpendicular to the heat flow direction, (‖ - Parallel, ⊥ - Perpendicular)				

4.1.1 Optimum density of fibres for thermal performance

The thermal conductivities of five samples with different densities were compared. Each sample was tested over three different heat settings. The results show that the density of the hemp fibres influences the TC of the hemp fibres. On average, the density of fibres with the lowest thermal conductivities was 85kg/m³ shown in Figure 7.

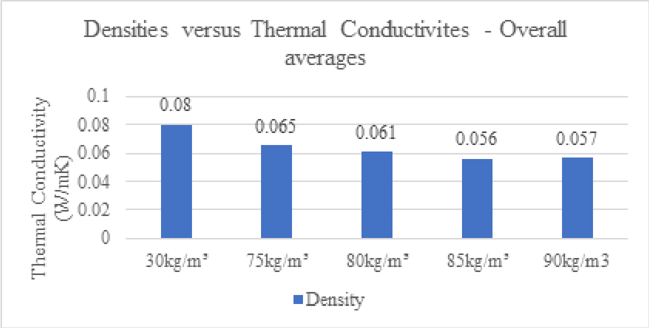

Figure 7. Density vs TC results from Hot Box Test

4.1.2 Fibre orientations influence on thermal performance

The thermal conductivities of three samples with the same density, but with different orientations (Parallel to HF, Perpendicular to HF, and Mixed to HF) were tested. Each sample was tested over three different heat settings. The results show that, on average, the lowest TC of 0.044 W/mK was achieved when the fibres were laid perpendicular to HF shown in Figure 8. Mixed Orientation achieved a TC of 0.056 W/mK which was the second lowest TC followed by Parallel to heat flow which performed the worst thermally achieving an overall TC of 0.112 W/mK shown in Figure 8.

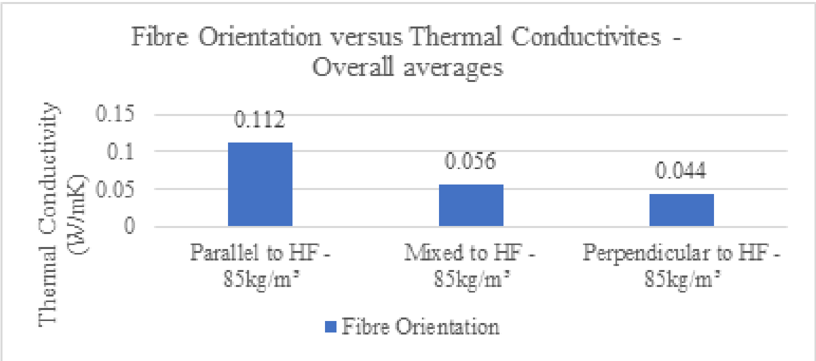

Figure 8. Fibre orientation vs TC results from Hot Box Test

4.1.3 Fibre Lengths influence on thermal performance

The TCs of two samples with the same density, but with different fibre lengths (33mm and 65mm fibre length) were tested. Each sample was tested over three different heat settings shown in Figure 9. The results show that, on average, both samples achieved a TC of 0.056 W/mK shown in Figure 9. Fibre length did not have a difference in the overall average TC of the hemp fibre as a material.

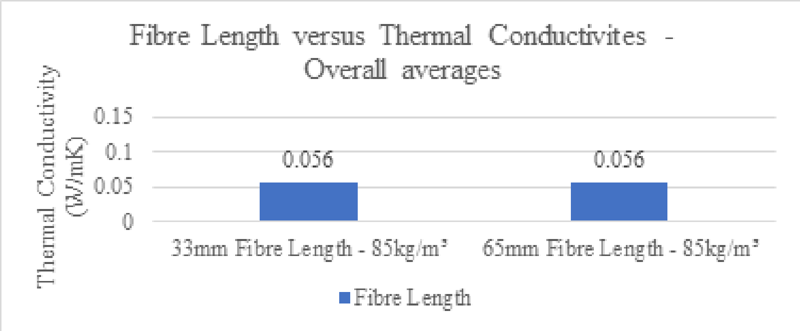

Figure 9. Fibre length vs TC Results from Hot Box Test

4.2 WATER ABSORPTION TESTING

The moisture content of hemp fibres was recorded shown in TABLE 4.

TABLE 4. Moisture content at regular conditions

Sample no.	Mass at standard conditions	Mass after being oven dried	Moisture content
Sample 1	7.782g	7.066g	0.7016g (9.02%)

The moisture content of hemp fibres resting at 20ºC is 0.7016g/7.782g or 9.02%.

4. Conclusion

Based on this investigation's results it can be concluded that the optimum density of hemp fibre for TC is 85kg/m³. The lowest TC of 0.056 W/mK was achieved with a density of 85kg/m³. This shows that a density of 85kg/m³ is required for the lowest TC.

This study showed that fibre orientation to heat flow has an influence on thermal performance (TC). In this study, the parallel to HF orientation performed the worst thermally achieving a TC of 0.112 W/mK at a density of 85kg/m³. This shows that this orientation should be avoided for thermal performance. Mixed orientation achieved a TC of 0.056 W/mK at a density 0f 85kg/m³. This shows that if the hemp fibres were to be blown into a wall system where orientation cannot be controlled, it suggests a TC of 0.056 W/mK could be achieved at a density of 85kg/m³. This TC is comparable to popular synthetic insulations such as Mineral Wool insulation (0.032-0.035W/mK) and has potential. Finally, the perpendicular to HF orientation performed the best thermally achieving a TC of 0.044 W/mK at a density of 85kg/m³, which is a 21% decrease from Mixed orientation to HF. This was the optimum fibre orientation to HF.

This study concluded that fibre length did not influence the thermal performance of hemp fibres as an insulation material. Both the 33mm and 65mm fibre length samples achieved a TC of 0.056 W/mK. This is significant for future research in blown-in insulation-type systems.

5. Future research and recommendations

If further hot box testing is to be conducted, it is recommended to use a larger specimen size as per ISO 8990:1997 to minimise error.

In this study, it was concluded that when the fibre orientation was perpendicular to HF it performed the best thermally with the lowest TC. Further research should be conducted to find a way in which this orientation can be used in future insulation systems to optimise thermal performance. This would reduce the amount of hemp fibres required, potentially resulting in less manufacturing and embodied carbon.

A Life Cycle Assessment on a particular hemp fibre batt with a polyester binder should be conducted to assess the Embodied Carbon and Global Warming Potential (GWP) the polyester binder has on the composite batt. This should then be compared to a loose-fill hemp fibre insulation that achieves the same U-Value to compare embodied carbon values.

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AN EXPLORATION OF LIMESTONE CALCINED CLAY CEMENT (LC3) AS A LOW-CARBON ALTERNATIVE TO ORDINARY PORTLAND CEMENT IN AN IRISH CONTEXT

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Abstract. Portland cement manufacture produces significant amounts of CO_2; for every tonne of cement manufactured, approximately one tonne of CO_2 is emitted. Additionally, cement production is projected to increase globally due to rapid urbanisation in developing countries, adding to growing concerns regarding the ongoing climate crisis. Limestone calcined clay cement (LC^3) is a low-carbon cement which is becoming more prevalent in the cement industry. A combination of limestone and calcined clay can significantly reduce the clinker content in cement. Additionally, the manufacture of LC^3 promotes optimised resource efficiency, lower energy consumption, and reduced carbon emissions. Concrete made with LC^3 can achieve mechanical performance and qualities similar to and/or greater than OPC, despite possessing a significantly lower clinker content. This research investigated LC^3 under a variety of headings: its compressive strength in hardened concrete; the availability of LC^3 in Ireland; and its embodied carbon in an Irish context.

Keywords: cement, calcined clay, clinker, low carbon, embodied carbon

1. Introduction

Concrete is the second most used material in the world after water (Wangler et al. 2016). Durability, cost-effectiveness, and flexibility are just a few of its countless attributes. It has been an essential component of infrastructures for generations, from buildings to bridges. Unfortunately, the production of cement, the primary constituent of concrete, is damaging our environment. Cement is a global commodity that accounts for 8% of annual global emissions (Vásquez-Torres et al. 2022) and is projected to reach as high as 15% by 2030 (Díaz et al. 2017). Energy consumption associated with cement production is also at an excessive high; 60-130kg of fuel oil and 110kWh of electrical energy is required to produce one tonne of cement (Cembureau, 2020). Exploring a low-carbon alternative to ordinary Portland cement (OPC) is the main objective of this research.

Limestone calcined clay cement (LC^3) is a rapidly developing low-carbon cement, made from a blend of clinker, calcined clay, limestone, and gypsum which can reduce CO_2 emissions by up to 40% (Sharma et al. 2021). The substantial emission reductions are attributed to a high level of clinker substitution along with reduced energy consumption during the manufacture of LC^3. In addition, LC^3 uses industrial waste materials such as low-grade kaolinitic clays, which optimises resource efficiency and reduces the use of scarce raw materials for OPC production (Scrivener et al. 2018). Although LC^3 is relatively new to the industry, the analysis of its material technology has displayed optimistic signs of its future potential as an environmentally friendly cementitious material (Sánchez-Berriel et al. 2016).

Figure1. Limestone calcined clay cement (LC3, 2023)

1.2 AIMS

Research states that manufacture of LC^3 can significantly reduce the expanding carbon footprint of the cement industry. The aim of this research is to determine whether LC^3 can act as a viable alternative to OPC with lower environmental impact in an Irish context.

1.3 OBJECTVES

The objectives of this research include:

- A detailed investigation into the material composition of LC^3 and the methods used to manufacture this material.
- An examination of the compressive strength of a selection of concrete cube prototypes that possess dissimilar ratios of calcined clay and limestone.
- An analysis of the microchemistry of LC^3 and how various proportions of calcined clay and limestone determine the compressive strength properties of hardened concrete.
- An investigation into the availability of LC^3 in Ireland.
- An assessment of the embodied carbon of LC^3 in an Irish context.

2. Literature Review

Studies that examined the various aspects of LC^3 reviewed for this research. Due to limited availability of research into LC^3 in an Irish context, the majority of research papers that were reviewed were published by educational institutes in Switzerland, India, and Cuba, who have collaborated with each other on this material since 2014.

2.1 LIMESTONE AND CALCINED CLAY

Clays, along with limestone, are some of the most prevalent materials in the earth's crust (Cardinaud et al. 2021). Clays that contain kaolinite, a clay mineral, have shown to be highly pozzolanic when calcined at 700-850°C (Fernandez et al. 2011), meaning they can form cementitious compounds upon chemical reaction with cement and water (cement hydration).

Kaolinitic clays are among the most abundant source of highly reactive pozzolans, making them a valuable resource for the development of blended cements (Díaz et al. 2020). Limestone is also a widely available material used for countless construction applications, including cement (Cassar et al. 2010). A blend of clinker, calcined clay, granulated limestone, and gypsum produces limestone calcined clay cement (LC^3).

LC^3 was first proposed by the École Polytechnique Fédérale de Lausanne (EPFL) of Switzerland in 2014, where they received financial investment from the Swiss Agency for Development and Cooperation to support their endeavour. The EPFL also collaborated with partners in Cuba and India on this project to optimise resource efficiency while decreasing carbon emissions in the manufacture of cement.

2.2 MATERIAL COMPOSITION AND MICROCHEMISTRY

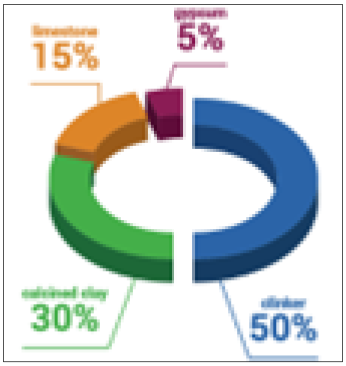

Figure 2. Material composition of LC^3 (LC3, 2023)

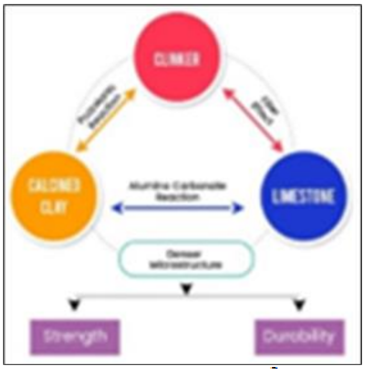

Figure 3. Microchemistry of LC^3 (LC3, 2023)

LC^3 is a Portland cement-composite comprising of clinker, calcined kaolinitic clay, limestone, and gypsum. A conventional LC^3-50 blend of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum can achieve mechanical qualities equivalent to a CEM I composite (OPC) over a seven-day period (Vizcaíno-Andrés et al. 2015).

As shown in Figure 3, a pozzolanic reaction occurs between clinker and calcined clay. During LC^3 hydration, the calcium hydroxide from clinker particles combines with the calcined clay to produce calcium aluminosilicate hydrate, the primary binder in blended cement (Zhao et al. 2023). Limestone powder, when mixed with cement and water, accelerates the hydration of clinker by providing crystallisation sites for the precipitation of calcium-silicate hydrates, coatings of interlocking crystals that form upon cement particles during cement hydration (Cardinaud et al. 2021). Additionally, an aluminum carbonate reaction between the limestone and calcined clay also occurs; the calcium carbonate particles in limestone react with the aluminium silicate particles in calcined clay to harden the fresh concrete mix and release heat.

2.3 KAOLINITE AND METAKAOLIN

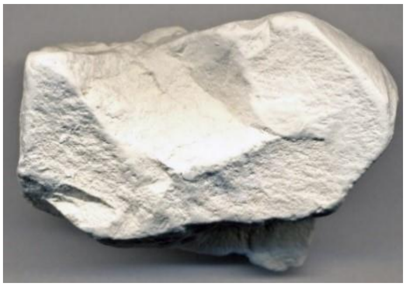

Figure 4. Kaolinite (Minerals Education Coalition, 2023)

Kaolinite is a common clay mineral formed from the weathering of primary and other secondary minerals in rocks (Schulze, 2005). For example, feldspar, the primary mineral of the igneous rock, granite, weathers to kaolinite in clays and soils. Kaolinite can also be formed from the weathering of basalt, an igneous rock (Oyebanjo et el. 2021) in clays and sedimentary rocks such as sandstones and shales (Milliken, 2014).

When kaolinite undergoes thermal treatment, a very fine powder known as metakaolin (MK) is produced (Fabbri et al. 2013), which can be used as a supplementary cementitious material (SCM) to enhance the mechanical properties of concrete and reduce the environmental impact of the cement industry.

Figure 5. Engineer Souza Dam , Brazil (CTG, 2023)

The utilisation of MK to replace cement was adopted as early as the mid-1900's (Tang et al. 2021). Reports state that the Bhakra Dam in India was constructed with calcined clays in 1948. In 1960, the Engineer Souza Dias Dam in Brazil, formerly known as the Jupiá Dam, was also constructed with the addition of MK as a SCM, which replaced 30% of the total cement content.

2.4 LOW-GRADE CLAYS

Utilising low-grade clays for LC^3 manufacture optimises resource savings (Krishnan et al. 2020). There is currently a large demand for high purity kaolinitic clays for the ceramic, painting, and paper industries (Malacarne et al. 2021). In addition, the cost of pure MK is approximately 3 times the cost of OPC (Scrivener et al. 2018). Therefore, the use of conventional metakaolin for LC^3 is not economically feasible.

However, there are copious amounts of low purity kaolinitic clays that contain secondary minerals such as iron, quartz, and feldspar, that are unsuitable for use in these industries, according to Scrivener (2018). For example, the presence of iron will cause clays to colour, rendering it unsuitable for use in the paper and cosmetic industry. According to research at EPFL, a kaolinite content of 40% in an LC^3-50 blend (50% clinker, 30% calcined clay, 15% limestone, 5% gypsum) can achieve similar performance to OPC (Scrivener et al. 2018).

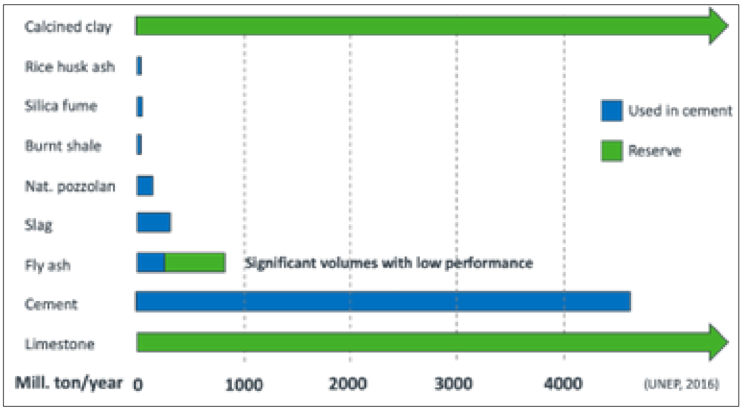

Figure 6. Availability of common SCMs (LC3, 2023)

Additionally, the presence of secondary minerals in kaolinitic clays, such as quartz and iron, do not appear to affect its application for LC^3 manufacture. Scrivener (2018) also states that clays with a minimum kaolinite content of 40% are widely accessible, and since clay is often a primary raw material used to make cement, they may even be found in existing cement plant quarries. The utilisation of low-grade clays for LC^3 manufacture promotes a more sustainable cement manufacture, environmentally and economically, while avoiding demand from other industries.

2.5 COMPRESSIVE STRENGTH

Compressive strength testing of 100mm concrete cubes comprising OPC, LC^3, and FA30 binders was carried out in India (Dhandapani et al. 2018). In addition, a chemical additive known as a superplasticiser (SP), which improves workability, reduces water demand, and increases concrete strength, was embedded into each mix to achieve target slumps of 80-120mm prior to compacting the mix into cube moulds. Results exhibited that the cubes made with LC^3 achieved greater strength development than OPC and FA30 at all ages (2, 7, 28, 90, and 365 days), despite possessing a significantly lower clinker content. The results also demonstrate the effect of improved hydration in LC^3 regarding the mechanical properties of concrete. In comparison to OPC, LC^3 also achieved greater increases in strength development between 28 and 365 days, exhibiting the binder's long-term strength development properties.

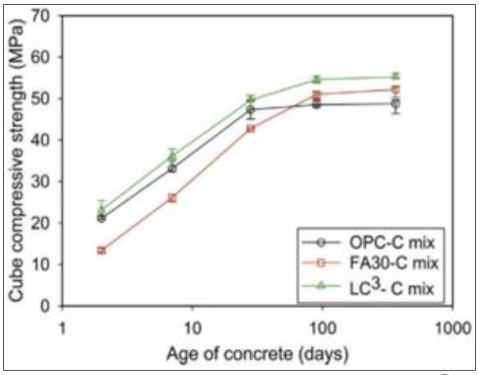

Figure 7. Evolution of compressive strength in OPC, LC^3, and FA30 mixes (Dhandapani et al. 2018)

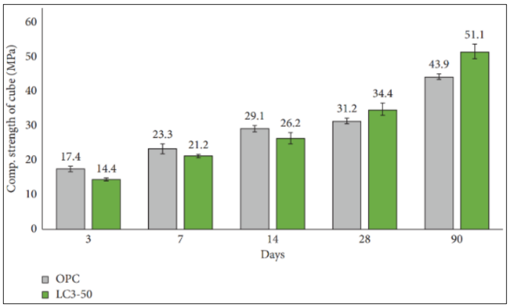

Figure 8. Compressive strength in OPC and LC^3 mixes (Sheikh et al. 2023)

However, Sheikh et al. (2023) reported that the strength development of LC^3 concrete without an SP additive was inferior to OPC during the first 28 days of hydration, but greater after that period.

2.6 ENVIRONMENTAL IMPACT

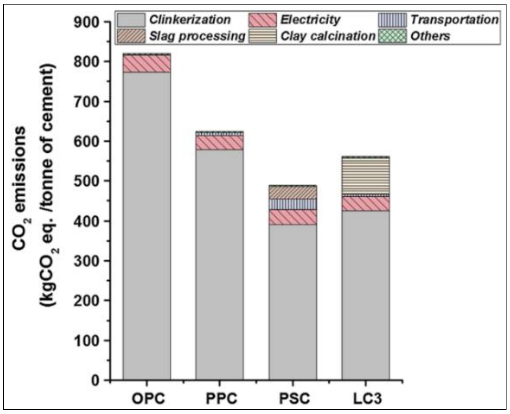

Figure 9. Global warming potential impact of various cement productions in Cuba (Gettu et al. 2019)

Significant emission savings in LC^3 manufacture are attributed to the significant partial substitution of clinker along with reduced electrical energy and fuel consumption. To investigate the embodied carbon of LC^3, detailed life-cycle assessment (LCA) studies were carried out in Cuba (Sánchez Berriel et al. 2016) and India (Gettu et al. 2019), assessing the environmental impact of the material from the extraction of its raw materials to its disposal. LCA results concluded that LC^3 can reduce carbon emissions by up to 30% in both Cuban and Indian contexts compared to OPC. A significant decrease in GHG emissions makes LC^3 very attractive from an environmental standpoint.

3. Methodology

This research will examine LC^3 under multiple headings - its compressive strength in hardened concrete; the embodied carbon of the material in an Irish context; and its level of availability in Ireland. The methodology will follow an objectivist approach by reporting only what the data of these procedures reveal (Hiller, 2016). In conjunction, a positivist viewpoint is adopted, where only the findings of the methodology are accepted. A collection of both quantitative and qualitative data will be gathered in the form of analysing numerical data from physical testing and conducting semi-structured interviews with cement industry experts. Interviews will add depth to this research beyond the quantitative data, by providing both context and a means of validating the findings.

3.3 COMPRESSIVE STRENGTH TESTING

Figure 10. Compressive strength testing of concrete cube (Authors, 2023)

A selection of concrete testing cubes of 150mm size will be made with LC^3 and OPC binders, placed within a hydraulic press, and tested in accordance with BS EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens. 5 mix types will be tested: 2 cubes per type. Concrete mixes will be compacted into cube moulds to set for 24 hours. After setting, cubes will be submerged in a temperature-regulated water tank at 22°C for 7, 28, and 56 days. Testing will be conducted in the TU Dublin structural and civil engineering laboratory.

3.3.1 Purpose of Testing

Compressive strength testing of concrete cubes made with LC^3 by Dhandapani et al. (2018) used an LC^3-50 blend of 50% clinker, 30% calcined clay (MK), 15%

limestone, and 5% gypsum. For this reason, the experimentation of this research aims to analyse how various proportions of MK and limestone determine the compressive strength of hardened LC^3 concrete, and how their developments compare to OPC.

As exhibited in Dhandapani et al. (2018), concrete made with a conventional LC^3-50 blend (along with a SP additive) exhibited superior early and long-term strength development to OPC. Sheikh et al. (2023) reported inferior strength development at early stages but greater development at later stages. Strength development of these cubes will be assessed over 7-, 28-, and 56-day periods.

Testing LC^3 mix 1 after 7 and 56 days will reveal the early and long-term strength development of hardened concrete made with a lower content of calcined clay (25%) and a greater content of limestone (20%) than that of the conventional LC^3-50 blend. If LC^3 mix 1 can achieve similar to and/or greater compressive strength development than OPC at early and/or long-term stages, carbon emissions could be reduced as a result of the lower content of MK.

The compressive strength of LC^3 mix 1 after 56 days will be compared to the compressive strength of an OPC cube after 56 days from another study, as an OPC cube for 56-day testing was not cast at the time the other cubes were.

3.3.2 Concrete mix design

Composing fresh concrete mixes involves a process of selecting the appropriate materials and their relative proportions under several variables, which include.

- margin for mix design
- water/cement ratio
- total cement content
- total aggregate content
- total wet density of concrete.

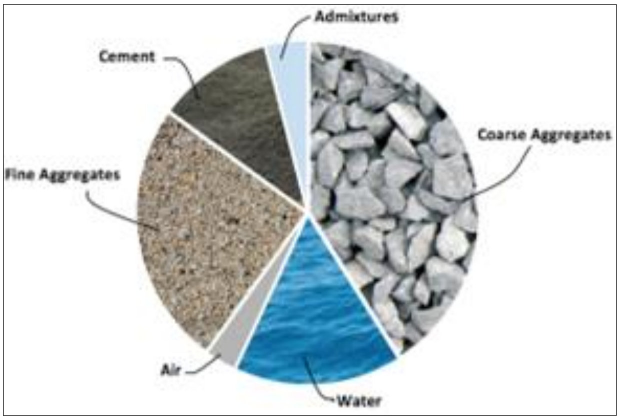

Figure 11. Material composition of concrete mix (Giatec, 2023)

The purpose of following a mix design process is to produce workable, durable, and high-quality concrete to achieve the desired strength. Mix design calculations will be made using the Design of Normal Concrete Mixes (*2nd edition*) by BRE. Specific variables and values for each test mix are shown in Table 1.

TABLE 1. Specified variables and relative values for concrete mix (Authors, 2023)

Variable	Value
Specified characteristic strength	35N/mm^2
Standard deviation	8N/mm^2
Defective level	1.64
Water/cement ratio	0.52
Total cement content	435kg/m^3
Total free-water content	225kg/m^3
Total wet density of concrete	2375kg/m^3
Total aggregate content	1715kg/m^3

3.3.3 Materials

Materials that comprise LC^3 (clinker, MK, limestone, gypsum) will be sourced locally and mixed to produce a bespoke LC^3 mix. Irish Cement CEM I 42.5 Rapid Hardening Portland Cement, which contains a clinker content of 95%, will be used as a substitute for pure clinker as is not a readily available material. MK used for testing is Metakaolin MKZL, a fine powder with a distinct cream colour, composed of fully amorphized kaolinite (90-93%) with a pozzolanic reactivity equal to 1400mgCa $(OH)_2$ per gram of MK. White Rhino Hydrated Lime and Gyproc 'Skimcoat' are used as forms of limestone and gypsum.

TABLE 2. Composition of test mixes (Authors, 2023)

Mix	Cement	Aggregates	Water/cement ratio
LC^3 mix 1	50% OPC, 25% MK, 20% limestone, 5% gypsum	Sand (fine aggregate – 40% of total aggregate content), 20mm crushed stone (coarse aggregate – 60% of total aggregate content)	0.52
LC^3 mix 2	50% OPC, 30% MK, 15% limestone, 5% gypsum	Sand (fine aggregate – 40% of total aggregate content), 20mm crushed stone (coarse aggregate – 60% of total aggregate content)	0.52
LC^3 mix 3	50% OPC, 35% MK, 10% limestone, 5% gypsum	Sand (fine aggregate – 40% of total aggregate content), 20mm crushed stone (coarse aggregate – 60% of total aggregate content)	0.52
LC^3 mix 4	50% OPC, 40% MK, 5% limestone, 5% gypsum	Sand (fine aggregate – 40% of total aggregate content), 20mm crushed stone (coarse aggregate – 60% of total aggregate content)	0.52
OPC mix	100% OPC	Sand (fine aggregate – 40% of total aggregate content), 20mm crushed stone (coarse aggregate – 60% of total aggregate content)	0.52

3.4 SEMI-STRUCTURED INTERVIEWS

Semi-structured interviews are an effective method of gathering qualitative, open-ended data and exploring the thoughts, feelings, and beliefs of participants regarding a particular topic (DeJonckheere et al. 2019). As LC^3 is currently not a readily available building material in Ireland, semi-structured interviews with cement industry experts will be conducted to discuss LC^3 under various headings of an Irish context, which include: the development of calcined clay manufacture to date; sources of kaolinitic clays, which could potentially be extracted for calcination; and the current level of availability of LC^3.

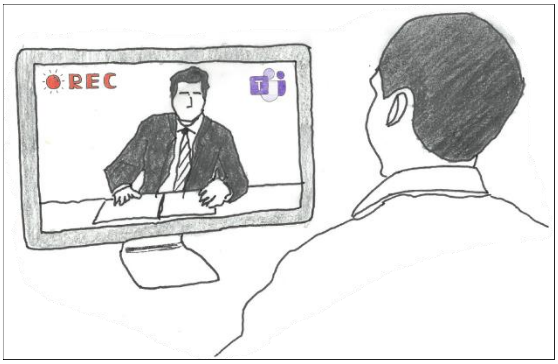

Figure 12. Semi-structured interview (Authors, 2023)

3.4.1 Data Collection

All interviews will be conducted online using Microsoft (MS) Teams. Participants will be contacted via email to enquire if they would participate in the research. If accepted, they will be sent an invite to MS Teams, an information sheet, and a hyperlink to a standard consent form. The standard consent will be created in MS Forms and filled out online. Interviews will last approximately 60 minutes and will be recorded for analysis thereafter.

3.4.2 Interview participants

A total of three interviews were conducted with three participants, each with extensive experience in the cement industry and great knowledge of LC^3 and calcined clays. Participants include.

- Participant A - Quality and Laboratory manager of a cement manufacturer
- Participant B - Committee member of the Institute of Concrete Technology and university faculty member
- Participant C - Research and Development manager of a mineral and quarry processor, former Director of Research and Development of a geopolymer and blended cement manufacturer, and committee member of the British Standards Institution.

Participants will remain anonymous as this allows them to speak more openly during their interviews.

3.5 EMBODIED CARBON

According to research by Sánchez Berriel et al. (2016), Gettu et al. (2019), and FLSmidth (2020) have shown that production of LC^3 can reduce emissions by 30-40%

in comparison to OPC. Therefore, LCA's will be conducted to estimate the embodied carbon of LC^3 and OPC manufactured in Ireland. The approach of this methodology is to calculate the total equivalent CO_2 emissions associated with each material using inventory numerical data.

3.5.1 Scope of analysis

The scenario for this LCA is as follows; fuel and raw materials are extracted and transported to a cement plant based in Coleraine, Derry, where they will be processed and combusted through grinding, calcination, and cooling units to produce LC^3 and OPC. The (estimated) embodied carbon for each cement will account for 1 tonne of material. Overall system boundaries include extraction and transportation of fuel and raw materials, as well as manufacturing processes (A1-A3; cradle-to-gate). Sources of fuel and raw materials will be no farther than 120km. The scope of analysis will conclude once the cement is ready for distribution.

3.5.2 Raw materials

Approximately 1,650kg of limestone, 400kg of clay and 200kg of coal, is required to manufacture 1 tonne of OPC (British Geological Survey, 2005) (Cementis, 2020); a fraction of 0.5 will be applied to these figures (limestone; 825kg, clay; 200kg, coal; 100kg) for LC^3-clinker manufacture. An additional 150kg of raw limestone is required for grinding in LC^3 production (Scrivener et al. 2018). Cement plant figures reveal an estimated 1,150kg of raw kaolinitic clay is required for calcination.

3.5.3 Inventory analysis

The embodied carbon of specific processes for various materials will be calculated using CO_2 emission factors and derived from cement plant data, energy authority statistics, environmental design guides, and research papers. Due to confidentiality issues, the cement manufacturer that provided data for this assessment cannot be directly disclosed. Tables 3 & 4 represent the electrical energy consumption of various processes associated with OPC and MK production.

TABLE 3. Electrical energy consumption processes of OPC manufacture (Potgieter, 2012)

Process	Electrical energy demand (kWh/tonne of OPC)
Extraction & blending	5.5
Raw material grinding	26.4
Raw meal homogenisation	6.6
Clinker production	24.2
Cement grinding	41.8
Conveying, packing & etc.	5.5
TOTAL	**110**

Again, a fraction of 0.5 is applied to each figure in Table 3 for LC^3 clinker manufacture. Figures from Table 3 will be used to estimate the electrical energy consumption for the intergrinding of limestone (150kg) and calcined clay (300kg);

these materials will subsequently be interground with clinker (500kg) and gypsum (50kg) in the final stages of manufacture to produce a fully homogenised material.

TABLE 4. Electrical energy consumption processes of MK manufacture (Cement plant data)

Process	**Electrical energy demand (kWh/tonne of MK)**
Drying & milling	7
Flash calcination	600
TOTAL	**670**

TABLE 5. Emission factors for extraction and manufacturing processes of LC[3] manufacture (Author, 2023)

Material	**Raw materials/processes**	**CO_2 emission factors (kgCO2eq./kg)**
Clinker	Limestone (Ext., Cal., Mill.)	0.00219 (Ext. of limestone) *, 0.00294 (Ext. of shale) *, 0.5323 (Cal. of clinker – includes combustion of coal) *
	Shale (Ext., Cal., Mill.)	
	Coal (Ext. + Comb.)	0.665 *
	Electricity production	0.33[a] **
	Truck transportation (limestone; 77km, clay; 56km, coal; 68)	0.121[b] ***
Limestone	Limestone (Ext. + Mill.)	0.00219 *
	Truck transportation	0.121[b] ***
	Electricity production	0.33[a] **
Kaolinitic clay	Clay (Ext., Cal., Mill.)	0.004 (ext.) *, 0.112 (Cal. – includes electricity and fuel consumption) *
	Truck transportation	0.121[b] ***
	Electricity production	0.33[a] **
Gypsum	Gypsum	0 *
	Truck transportation	0.121[b] ***
	Electricity production	0.33[a] **

Abbreviations: Cal. – Calcination, Ext. – Extraction, Comb. – Combustion, Mill. – Milling
Exceptions are indicated: a - kgCO_2 eq./kWh, b - kgCO_2 eq./tonne-km. *Cement plant data (Pillai et al. 2019) **Environmental Protection Agency of Ireland (2021) ***The Environmental Design Pocketbook (Pelsmakers, 2015)

4. Findings and Discussion

This section presents the results and findings of this research, first assessing the workability and compressive strength of LC[3] in fresh and hardened forms of concrete, followed by an analysis of the current availability and embodied carbon of the material in Irish contexts.

4.2 COMPRESSIVE STRENGTH TESTS

The outcomes of the strength testing were promising as concrete cubes made with LC^3 demonstrated similar and greater strength development than OPC at early and later stages of hydration.

4.2.1 Strength development after 7 days

Strength development of the LC^3 mixes after 7 days were promising. As shown in Figure 13, the conventional LC^3 mix comprising 30% MK and 15% limestone achieved an effectively identical result to the OPC mix. In addition, the LC^3 mix consisting of 35% calcined clay and 10% limestone produced a relatively similar outcome. A variation of no more than 1% occurred amongst LC^3 mix 2, LC^3 mix 3, and the OPC mix. In contrast, LC^3 mixes 1 and 4 obtained strength development inferior to the OPC mix; strength development in both mixes lagged by approximately 12% in comparison to OPC.

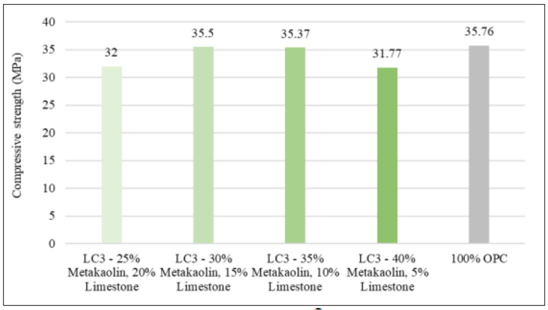

Figure 13. Compressive strength of LC^3 and OPC mixes after 7 days (Authors, 2023)

4.2.2 Strength development after 28 days

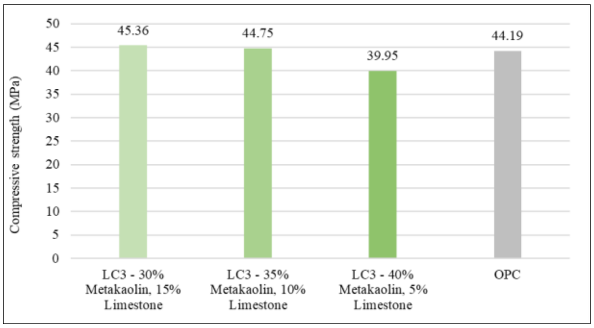

Figure 14. Compressive strength of LC^3 and OPC mixes after 28 days (Authors, 2023)

The conventional LC^3 mix continued to produce favourable results. At 28 days, the mix attained greater strength development than OPC by 3%. Considering the conventional LC^3 mix in Dhandapani et al. (2018) exhibited an approximate increase of 6% (with a SP additive), the result are quite impressive. Additionally, the mix consisting of 35% MK-10% limestone achieved greater strength development than OPC by 1%. As expected, the mix containing 40% metakaolin and 5% limestone fell short again by approximately 11%.

4.2.3 Strength development after 56 days

Strength development of LC^3 mix 1 after 56 days of hydration was admirable as the mix acquired a considerably greater compressive strength (51.71MPa) than the OPC mix in Kagadgar et al. (2017); 43MPa.

TABLE 6. Comparison between concrete mix designs (Authors, 2023)

Material	**OPC mix**		**OPC mix (Kagadgar et al. 2017)**	
	1m³	**0.004m³ (150mm cube)**	**1m³**	**0.004m³ (150mm cube)**
Cement (kg)	435	1.7	455	1.82
Water (kg)	225	0.9 (0.52 w/c ratio)	186	0.744 (0.45 w/c ratio)
Fine aggregate (kg)	685 (sand)	2.74	693 (sand)	2.772
Coarse aggregate (kg)	1030 (20mm crushed stone)	4.12	1179 (20mm crushed stone)	4.716

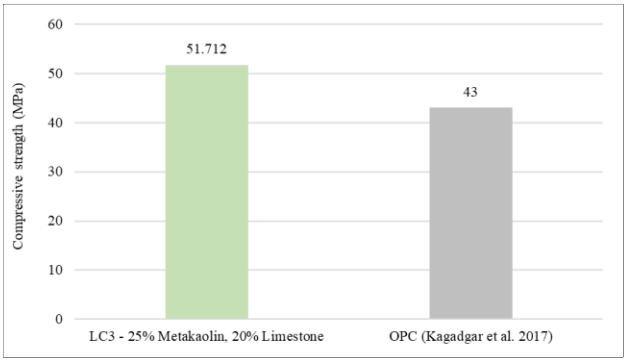

Figure 15. Compressive strength of LC^3 and OPC mixes after 56 days (Authors, 2023)

The OPC mix used in Kagadgar et al. (2017) possessed a concrete mix design relatively similar to the design used in this research, as shown in Table 6. Although LC^3 mix 1 possessed a greater w/c ratio, a greater strength increase of 17% was still achieved.

4.2.4 Discussion

Mechanical characteristics of LC^3, without the aid of a SP, remain impressive as the binder demonstrated similar and greater mechanical performance than concrete made with OPC at early and later stages. LC^3 binders comprising 30% MK-15% limestone and 35% MK-10% limestone are optimal to achieve strength development similar to OPC after 7 and 28 days, while binders containing 25% MK-20% limestone

40% MK-5% are suboptimal. Although, the long-term strength development of a 25% MK-20% LC^3 mix is noteworthy and should be examined further.

However, it is presumed that optimal strength gain in the LC^3 mixes was not achieved. Due to additional gypsum from the OPC, gypsum content in all 4 mixes (≈10%) was greater than required (5%). As gypsum is known as the retarding agent of cement, it is presumed that the increased gypsum content prevented maximum strength development. One could assume that the highly pure MK (90-93% amorphized kaolinite) compensated for the gypsum's prevention of peak strength gain, by attaining (marginally) greater strength gain than OPC. The homogenisation of materials in the LC^3 mixes, in which the consistency was not to an industrial-level standard, is another plausible explanation.

It is suggested that LC^3 possesses a greater heat of hydration than OPC as a large volume of pores developed across the surfaces of the LC^3 cubes, which could have potentially affected their performance during testing. Contrastingly, cubes made with OPC exhibited none. SP's can also reduce porosity in concrete mixes which could increase LC^3 concrete strength to a degree as the decrease in concrete volume through pores, from heat of hydration, are minimised.

4.3 AVAILABILITY OF LC^3 IN IRELAND

The information gathered from the semi-structured interviews provided greater insights into LC^3 and its current position as a readily available material in Ireland. From the interviews, multiple themes arose which include the manufacture of MK in Ireland to date; depositories of kaolinitic clays in Ireland; and the estimated time of production of LC^3 in Ireland.

4.3.1 Banah UK

Participants B and C provided detailed and extensive information regarding Banah UK and their operations. Established in 2008, Banah set out with an objective to develop and manufacture geopolymer cement, a low-carbon and environmentally friendly alternative to OPC which substitutes clinker completely. Their cement comprised of calcined kaolinitic clay and an alkali-silicate liquid activator. Banah extracted readily available precursor (kaolinitic clays naturally derived from volcanic episodes) from Co. Antrim, Northern Ireland.

> "Banah extracted clays that were formed from the weathering of basalt rocks and were of low-purity kaolinite, which they used to develop their geopolymer cement. The clays possessed a kaolinite content of approximately 50% and were calcined at 750°C. Banah produced 12 tonnes of calcined clay an hour" – Participant C.

According to Participant C, the geopolymer cement exhibited impressive acid and fire resistance properties, which performed ideally for underground structures, such as sewers. Banah began to manufacture a blended cement comprised of clinker, calcined clay, and GGBS, after determining that their geopolymer cement could not be marketed as a cost-effective building material like OPC.

4.3.2 Sources of kaolinitic clays in Ireland

No participants had any knowledge of any depositories, let alone sources, of kaolinitic clays in Ireland (outside of the Antrim region). However, Participants A and B revealed that cement manufacturers in Ireland are currently surveying potential depositories of kaolinitic clays for quarrying but did not disclose which manufacturers due to confidentiality reasons.

Participants stated that kaolinitic clays which are appropriate for calcination are dependent on their geology; whether there is sufficient kaolinite in the clays; and their elemental composition.

> "It cannot be assumed that all traces of kaolinite are suitable for metakaolin production." – Participant A.

> "Contents of silicon dioxide (SiO_2), aluminium dioxide (Al_2O_3), and iron oxide (Fe_2O_3) vary among different sources of kaolin, which effectively determine their suitability for calcination. A combination of the elements that is greater or equal to 70% of the clays elemental composition are required to achieve sufficient pozzolanic reactivity in metakaolin, with SiO_2 and Al_2O_3 each constituting substantial proportions. Secondary minerals in clays could have detrimental effects, such as smectite, a swelling mineral within clay that can cause concrete to swell at incorrect calcination temperatures." – Participant C

All participants indicated that x-ray fluorescence, x-ray diffraction and thermogravimetric analysis are viable methods to examine the elemental composition, crystallographic structure, and thermal stability of clays prior to quarrying. Participant C added that simultaneous thermal analysis could be used, which combines thermogravimetry with differential thermal analysis or differential scanning calorimetry, to measure the thermal stability of materials and providing information regarding their reactivity or composition concurrently.

4.3.3 Manufacture of LC^3 in Ireland

Participants A and B estimate that LC^3 manufacture could be implemented into Irish cement production as early as 2025. Participant C, however, was unable to gauge an approximate time span before manufacture begins in Ireland.

> "I'm unsure as to how long until LC^3 manufacture is integrated into our cement plants. There are a lot of factors to consider, such as standards and increasing carbon taxes for cements, the efficiency of existing machinery to manufacture this material, and kaolin depositories being identified." – Participant C.

The lack of knowledge regarding kaolinitic clay depositories across the country suggests to Participant C that the production of calcined clay, and subsequently LC^3, will not occur in Ireland for the foreseeable future. Furthermore, it is still unclear as to which approach cement plants will follow to facilitate the production of LC^3, whether it is refurbishing existing kilns and modifying pre-heater units or completely transforming the plant's production infrastructure.

According to Participant C, capital investment will undoubtedly play a significant role in the industry's transition to LC^3 manufacture and will vary by plant. As a committee member of the British Standards Institution (BSI), Participant C revealed that standards for Portland cement composites utilising pozzolans would soon be revised to facilitate the use of MK in all design chemical classes for blended cements. BS 8615-2:2019, the current standard for composite blends of Portland cement and highly reactive calcined pozzolanas, permits a clinker replacement of up to 25%.

4.3.4 Discussion

As there was no available information regarding LC^3 in an Irish context prior to the commencement of this research, the semi-structured interviews conducted were insightful as they allowed for the collection of in-depth data on the subject. Reduced emissions in the Irish cement industry could be attained in the near future, based on the anticipations of Participants A and B that LC^3 production in Ireland will commence in 2025.

Presumably, these anticipations are somewhat optimistic and based on a 'best-case' scenario compared to the judgement of Participant C, who could not offer an approximate duration until LC^3 is implemented into Irish cement manufacture based on several limitations surrounding production.

In hindsight, the fact that capital investment or standards were not referenced in Participant's A and B's estimations is questionable to an extent. The overlap of comments made by all three participants suggests that LC^3 production will begin in the latter years of this decade.

4.4 EMBODIED CARBON

The findings of the cradle-to-gate LCA for Derry-based LC^3 were formidable as a significantly lower embodied carbon than that of OPC was achieved.

4.4.1 Life-cycle assessment

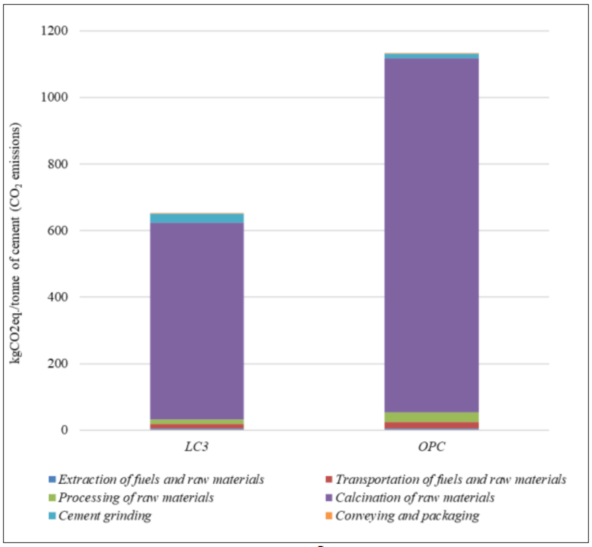

Figure 16. Estimated embodied carbon of LC^3 and OPC manufacture (Authors, 2023)

LCA's of LC^3 and OPC revealed a substantial variance between production emissions. Per tonne of material, LC^3 produced 651.63kgCO_2eq. while OPC produced 1134kgCO_2eq., indicating an emission saving of 482.36kgCO_2eq. (≈43%). As illustrated in Figure 16 above, significant emission savings in LC^3 manufacture were attributed to lower energy consumption during the calcination of raw materials

(591.3kgCO_2eq.), concurring with the literature review. The LCA of LC^3 manufacture also revealed notable decreases in raw material transportation and processing emissions, by -31% and -53%, respectively. However, cement grinding for LC^3 required greater electrical energy demand than OPC (+194%) due to the separate grinding of clinker-gypsum and MK-limestone, followed by intergrinding of both composite mixes to produce the final product. Along with energy consumption, the extraction of fewer virgin raw materials contributes to the resource efficiency of LC^3. The results of both LCA's indicate that LC^3 manufacture is a more environmental alternative to the production of OPC, as previously highlighted in the literature review.

4.4.2 Discussion

Reductions in clinker content and energy consumption in LC^3 manufacture were discussed earlier in this paper - it is not surprising that the LCA conducted in this research exhibited a gulf in production emissions between LC^3 and OPC. Perhaps more importantly, the variation in production emissions (43%) is higher than the value suggested in the literature review (30–40%), indicating an even greater reduction in environmental impact.

5. Conclusion

5.1 OVERVIEW OF RESEARCH

The research aimed to investigate LC^3 in relation to; its workability in the form of fresh concrete, its compressive strength in hardened concrete, its availability in Ireland, and its embodied carbon in an Irish context. Based on a disaggregation of quantitative and qualitative data, it can be concluded that:

- LC^3-50 blends comprising 30% MK-15% limestone and 35% MK-10% limestone are viable for attaining similar to/and greater strength development than OPC after 7 and 28 days of hydration. However, this research established that an LC^3-50 blend of 25% MK-20% limestone possesses superior long-term strength development to OPC.
- Manufacture of LC3 in Ireland is expected to commence in the latter years of this decade.
- Manufacture of Ireland-based LC3 produces approximately 43% less CO2 emissions than that of OPC.

The purpose of this study was to ascertain whether LC^3 could act as a low-carbon substitute to OPC in an Irish context. The findings of this research illustrate the evident potential of LC^3 to be a viable alternative to OPC in the forthcoming years which will certainly reduce the carbon footprint of the Irish cement industry significantly.

5.2 RECOMMENDED FURTHER RESEARCH

- A mineralogical and geochemical analysis of kaolinitic clays in Ireland using XRF, XRD, and TGA should be carried out to establish whether such clays are suitable for MK production.

- Scrivener et al. (2018) states that LC3 is a cost-effective building material, with a price range similar to OPC. A cost analysis of both Ireland-based LC3 and MK should be conducted to assess how economically viable these materials are in the cement market.
- This research highlighted the compressive strength properties of LC3 concrete. Tensile strength testing of reinforced LC3 concrete should be carried out to determine the characteristics of the binder's tensile strength.
- Furthermore, an assessment of the bond behaviour and corrosion status of reinforced steel bars in LC3 concrete should be carried out, to evaluate the binder's chemical behaviour and mechanical performance in the presence of steel.

Acknowledgements

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EXPLORING THE IMPACT OF DESIGN PROFESSIONALS ON THE ENERGY RETROFIT OF DWELLINGS IN IRELAND: A QUALITATIVE METHODOLOGY

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Abstract. Research in the areas of building science tends to be quantitative in nature however qualitative research brings a depth of information that is more human centred. Here a qualitative research approach was taken to investigate the role of design professionals in the energy retrofit of external wall insulation to dwellings in Ireland. The research method combines document analysis with semi structured interviews. Document analysis, in this case, is used to both help inform the questions for the interviews and as a means for validation. The SEAI One Stop Shop grant scheme and PAS 2035framework were selected for detailed document analysis to gain a better understanding of the context in which design professionals are working in Ireland and compare it to the energy retrofit framework in the United Kingdom. This was investigated by mapping the data using the online visual whiteboarding cloud-based platform MIRO and from that the findings are presented and the questions for the interviews were extrapolated. The semi-structured interviews were used to further understand the experience of design professionals in Ireland and their roles in energy retrofit. From the interviews a thematic analysis was carried out; the interview findings were presented; and the conclusions drawn and verified. One of the key research findings was that when it comes to energy retrofit the role of the design professional is not clearly defined in Ireland and that if anything they are omitted from the energy efficiency grant application process. An energy retrofit framework like PAS 2035 would be worth exploring further in the Irish context as it provides clear roles and responsibilities and associated minimum qualifications.

Keywords: qualitative research methodology, document analysis, semi-structured interviews, energy retrofit, external wall insulation.

1. Introduction

Ireland has committed to retrofitting 500,000 homes to a building energy rating of B2 (or cost optimal or carbon equivalent) by 2030 to facilitate its plan of achieving 50% reduction in greenhouse gas emissions by 2030 and net- zero by 2050 (Government of Ireland, 2020). These targets are driving increased activity in residential energy retrofit, helped along by higher energy costs and increased grant aid.

While external wall insulation is only one aspect of energy retrofit the researcher focused on this area due to the complexity and potential for large-scale failures as seen in the UK (King, 2019; BRE Wales, 2016; Bonfield, 2016). In Fishwick Estate in Preston there was external wall insulation failure on 350 properties with moisture issues, water ingress, inadequate detailing, cold bridging, and lack of adequate ventilation cited as the cause.

Design professionals including architects, architectural technologists, and engineers are well positioned to play a valuable role in the design of external wall insulation, however how they fit into the energy retrofit process is not well understood in Ireland. This paper aims to address the lack of clarity surrounding the role of the design professional in energy retrofit by conducting qualitative research using a combination of document analysis and semi-structured interviews. The paper explores the benefits and barriers to having a design professional involved as well as comparing the Irish and UK energy retrofit frameworks.

This paper contributes to the literature on energy retrofit by providing a methodological framework that can be adapted for similar research.

2.1. AIMS AND OBJECTIVES

The aim of this research is to investigate the role of the design professionals in energy retrofit of dwellings in Ireland with a focus on grant aided external wall insulation.

The research objectives are as follows; identify and summarise the relevant retrofit frameworks in Ireland and the UK; investigate and discuss the role of design professionals in energy retrofit of dwellings; design and conduct semi-structured interviews with design professionals and industry experts and report findings of thematic analysis.

2.2. THE ROLE OF THE DESIGN PROFESSIONAL

2.2.1. Ireland

In Ireland, the Code of Practice for Inspecting and Certifying Buildings and Works, Building Control Regulations 1997-2015 deals with the key roles involved under the current building control act (Government of Ireland, 2019). An assigned certifier is defined as a chartered engineer, registered architect, or chartered building surveyor (providing they are competent in relation to the particular works involved). These are referred to as BC(A)R professionals after Building Control (Amendment) Regulations.

The role of the assigned certifier is to inspect and coordinate the activities during construction and to certify the building or works on completion. They include a definition of what a competent person is; “a person is deemed to be a competent person where, having regard to the task he or she is required to perform and taking account of the size and/or complexity of the building or works, the person possesses sufficient training, experience and knowledge appropriate to the nature of the work to be undertaken” (Government of Ireland, 2019). As well as the assigned certifier there is a design certifier who must also be a BC(A)R registered professional. They are responsible for the preparation of relevant documentation related to the design of the building and the collation of ancillary certificates from members of the design team.

2.2.2 United Kingdom

While Ireland is in the European Union (EU), the United Kingdom (UK) is the closest geographically in terms of climate. Following retrofit failures, in the UK, the British Research Establishment (BRE) carried out a report looking at potential issues and unintended consequences associated with retrofit of cavity wall and external wall insulation. They identified several roles for energy retrofit; retrofit assessor; retrofit designer; retrofit coordinator and retrofit installer/ site staff (King et al, 2019).

A further development of retrofit roles is established in the whole house retrofit framework PAS 2035. PAS 2035 was introduced, in the UK, by the British Standards Institute (BSI) and is a framework and specification for 'whole-house' or 'whole-building' retrofit. It outlines roles and levels of competency required for different levels of risk and sets out a required standard (BSI, 2019).

Under PAS 2035 the roles in a whole-house energy retrofit are identified as the retrofit advisor; retrofit coordinator; retrofit assessor; retrofit designer; retrofit installer and retrofit evaluator. There are more retrofit roles identified compared to what was included in the King (2019) report. The list of professions suited for retrofit designers were architects (professional members of RIBA, RIAS, AABC and CARE), building surveyors (professional members of RICS and CIOB) and architectural technologists (professional members of CIAT).

2.2.3 The Role of the Energy Retrofit Designer

In Ireland the BC(A)R professionals are key design professionals as they are responsible for certification of building projects, but this role is not tailored to energy retrofit. In contrast under the PAS 2035 framework in the UK there are clearly defined roles and responsibilities including an energy retrofit designer role.

Energy retrofit of external wall insulation is complex. To avoid failure, it is important that it is correctly applied, and that detail design and moisture management is understood. Looking at the energy retrofit failures in the UK the issues of poor survey, poor design, and poor installation all have an impact on the success or failure of energy retrofit (King, 2019). For the design professional it is important to recognise that poor design is part of the problem whether that be poor design by design professionals or a lack of any design input from design professionals.

2. Methodology

2.1. RESEARCH APPROACH

The methodology used in this research is phenomenology. Phenomenology holds that any attempt to understand social reality must be grounded in people’s experiences of that social reality (Given, 2008). It is more focused on the human experience of the real world and so it was felt that semi-structured interviews would provide valuable insight into the experience of the design professional. Kelly and Bowe (2011) argue, in reference to engineering students, that in some cases a qualitative approach is required and that these studies provide open, explanatory and a richness in data.

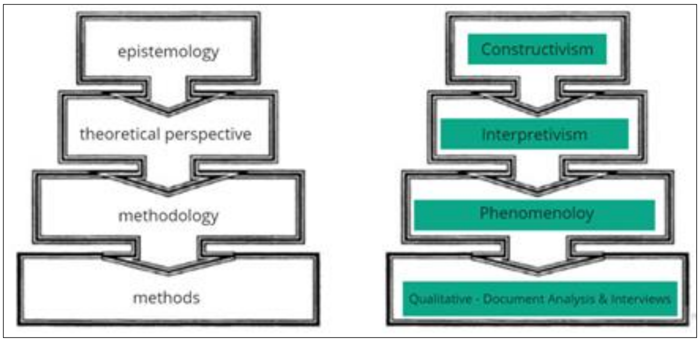

Figure 1: Left is an extract from The Foundations of Social Research showing a proposed framework. To the right is the researcher's interpretation of the diagram for the purposes of this research. (Crotty, 1998, p 4)

The research method combines semi structured interviews with document analysis. A benefit of combining these qualitative methods is it provides a way of triangulating the information (Bowan, 2009; Natow, 2019). The process used is data collection, data reduction, data display and conclusion drawing/ verifying (Groat and Wang, 2013). This process was used for both the document analysis and the semi-structured interviews as shown in figure 2.

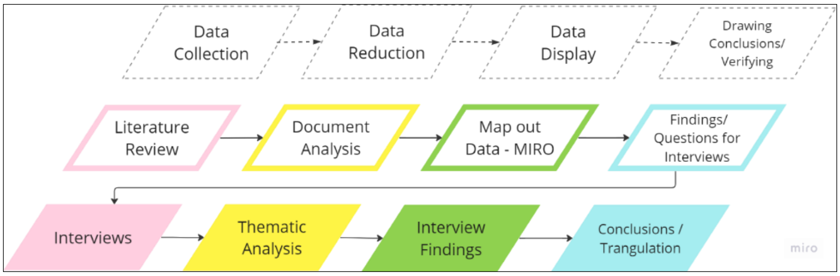

Figure 2: Diagram illustrating the research methodology and process steps. Created using the online whiteboarding platform, MIRO.

2.2. DOCUMENT ANALYSIS

2.2.1. Data Collection: Literature Review

Document analysis was used to both inform the questions for the interviews and as a means of validation. The literature review focuses on the role of design professionals in energy retrofit of dwellings in Ireland and the UK.

2.2.2. Data Reduction: Document Analysis

Following the literature review, key documents were selected for a deeper review. This was used to provide a better understanding of the role of design professionals in energy retrofit. The documents selected were the Sustainable Energy Authority of Ireland (SEAI) One Stop Shop model and PAS 2035 (SEAI, 2020 & BSI, 2019).

2.2.3. Data Display: Use of MIRO to map out relevant data

MIRO, an online, visual whiteboarding, cloud-based platform, was used as a research tool to map relevant information and as a way of visually organsing the research. An analysis of the One Stop Shop providers based on their websites was carried out to map out the different processes and roles associated. Similarly, MIRO was used to map out the PAS 2035 framework and compare it with the SEAI One Stop Shop model.

2.2.4. Drawing Conclusions/ Verifying: Questions for Interviews/ Triangulation

Based on the findings from the document analysis, the researcher prepared a standard set of questions for the interviews. The questions were open ended questions allowing room for the participants to elaborate as they wished.

2.3. SEMI STRUCTURED INTERVIEWS

2.3.1. Data Collection: Semi-Structured Interviews

There were 9 interview participants in total. Of the 9 people 6 were architects, 1 was an architectural technologist and 2 were engineers. The participants have been divided into two categories: Category A (Architecture) all are working in practice and/ or have recent experience of energy retrofit. Category E (Experts) were industry experts who are involved in energy retrofit but are not practicing design professionals. The interviews were undertaken by one researcher which provides a consistency in the way questions are asked and prompts provided (Green & Bowden, 2009, p 58 in Beagon, 2021).

2.3.2. Data Reduction: Inductive/ Thematic Analysis

The method of analysis was an inductive thematic analysis. The flow of the analysis was in line with Groat and Wang (2013) which is as follows; become familiar with the data; assign codes to the data; search for patterns or themes within the data set; review, define and name the themes and complete analysis. Inductive analysis is about discovery (Gray, 2014). Colour coding was used to identify themes and highlight key information in the interview transcriptions.

2.3.3. Data Display: Interview Findings

MIRO was used to map out and display the interview findings and to group themes and sub themes.

2.3.4. Drawing Conclusions/ Verifying – Conclusions/ Triangulation

Once themes emerged the findings were grouped together under the individual themes. The interview findings were triangulated with the literature review and the data findings of the document analysis to substantiate and verify the overall findings.

Bowen (2009) describes document analysis as a system for reviewing and evaluating documents and it is often used in combination with other qualitative methods to triangulate finding. Document analysis in this case was used to both help inform questions for the semi-structured interviews and as a means of validation or triangulation.

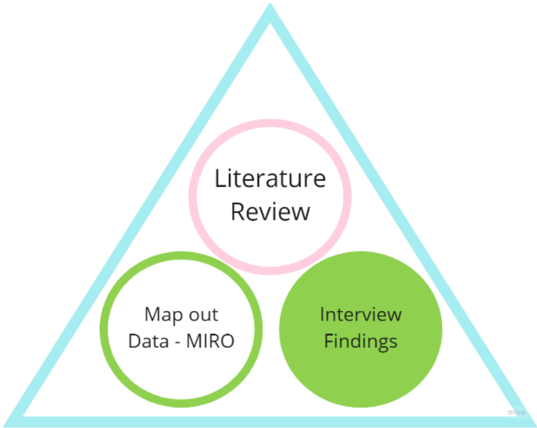

Figure 3: Diagram illustrating the triangulation of data as the literature review, the document analysis findings and the interview findings. Created in MIRO.

3. Findings and Discussion

3.1. DOCUMENT ANALYSIS

2.3.1. SEAI Grants and One Stop Shop Model

To help accelerate the energy retrofit of the Irish housing stock, the National Retrofit Plan approved a package of grant supports which are administered by SEAI, in 2020 (Government of Ireland, 2019). There are three options available to homeowners: One Stop Shop service, individual energy upgrade grants, and fully funded energy upgrade. In the case of the One Stop Shop model, which was launched in spring 2022, the process is managed by the relevant One Stop Shop provider and is focused on providing whole-house energy retrofit measures. One of the key roles envisaged for the One Stop Shop energy retrofit delivery model is that it will be responsible for end-to-end delivery of retrofit, including quality assurance of work done by service providers (Government of Ireland, 2020).

While each One Stop Shop varies, a typical service involves; initial consultation with an advisor to determine the homeowners needs; followed by a detailed home energy assessment and bespoke plan. The One Stop Shop determines the level of grant aid available and in some cases may have additional finance options. The One Stop Shop typically manages the energy retrofit of projects including selecting suitable contractors and carrying out site inspections. As part of the grant application a pre and post works building energy rating assessment is required. The stages, roles and qualifications have been mapped out in the diagram in figure 4.

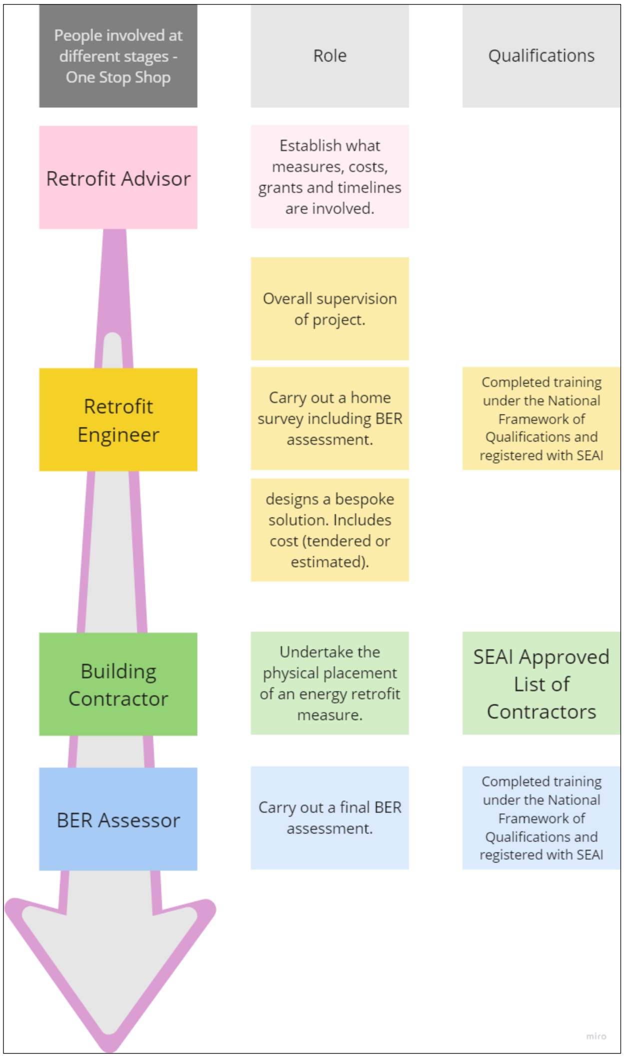

Figure 4: Diagram illustrating the roles and corresponding qualification requirements for SEAI One Stop Shop based on a review of existing One Stop Shop providers. Created in MIRO

2.3.2. PAS 2035 Framework

PAS 2035 was introduced, in the UK, by the British Standards Institute (BSI) and is a framework and specification for 'whole-house' or 'whole-building' retrofit. The purpose of PAS 2035 is to raise standards by introducing whole-house retrofit in place of shallow, measures-based installs (Retrofit Academy, 2022). Under PAS 2035 the roles, responsibilities and qualifications are clearly defined with corresponding qualification requirements. These roles are mapped out below in figure 5.

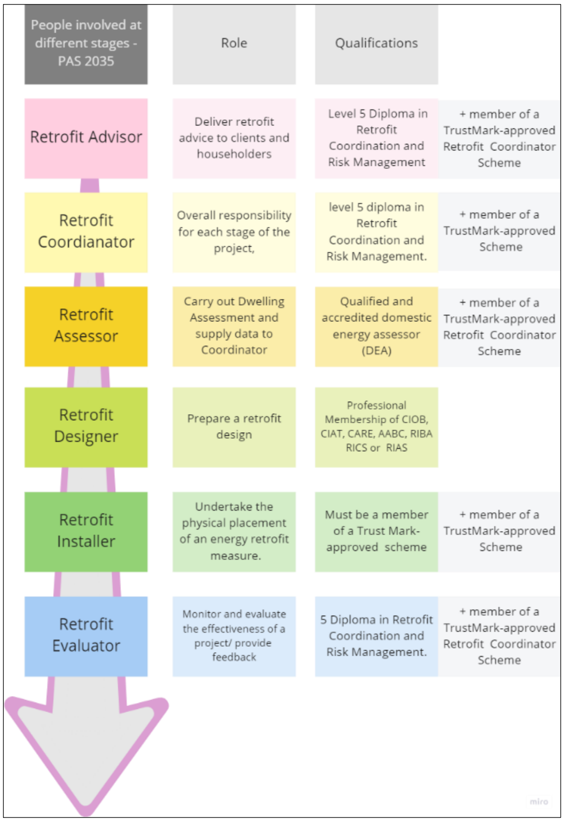

Figure 5: Diagram illustrating the roles and corresponding qualification requirements for PAS 2035 created in MIRO

2.3.3. Comparative Analysis of SEAI One Stop Shop and PAS 2035

A comparative analysis of the roles in the One Stop Shop were mapped against the roles defined in PAS 2035 (figure 6). These two frameworks are not directly comparable however the exercise is about trying to identify potential gaps that require further definition. In this case the researcher is highlighting a potential gap where a retrofit designer or design professional may be a valuable addition to the One Stop Shop model. The diagram raises the questions about how the design professional interacts with One Stop Shop grants and what their role is.

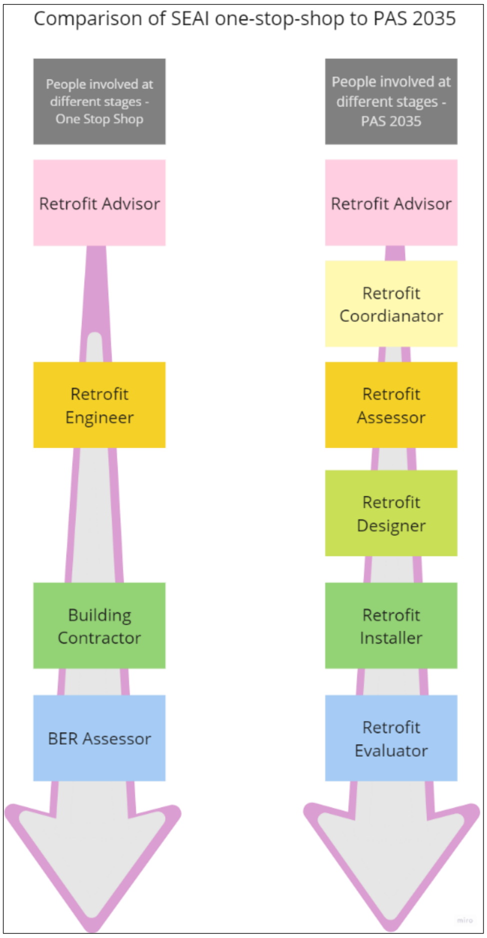

Figure 6: Diagram comparing SEAI One Stop Shop and PAS 2035. Created in MIRO.

3.2. INTERVIEW FINDINGS AND DISCUSSION

From the interviews several themes and sub themes emerged under the role of design professionals in energy retrofit including key people involved in energy retrofit; role of design professionals; benefits and barriers of design professionals; SEAI grant; UK energy retrofit framework (figure 7).

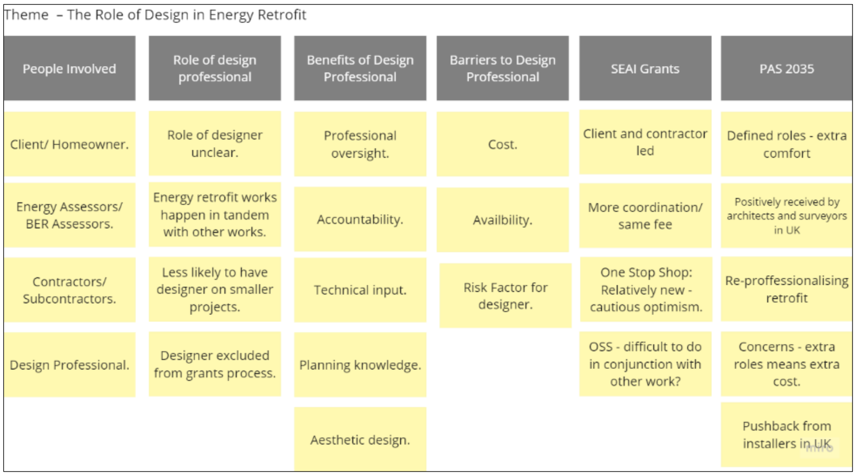

Figure 7: A diagram mapping the sub themes that emerged under the theme 'The Role of Design in Energy Retrofit' in the interviews, created in MIRO.

3.2.1. Role of Design Professionals

Participants were asked about their own experience in domestic scale projects. They identified key people involved in energy retrofit of dwellings as clients or homeowners; energy assessors and/or building energy rating assessors; contractors and subcontractors; sometimes an engineer or quantity surveyor and sometimes an architect. It was noted that when it comes the energy retrofit measures often a design professional may not be involved, and the works are carried out directly with a contractor or with a One Stop Shop provider. This is substantiated by Zuhaib et al (2017) where they comment that professional advice is not necessarily being sought for retrofit projects. Where the design professional is more likely to be involved is when the energy retrofit works are being carried out in tandem to other renovation works.

As the researcher is focused on the role of design professionals in energy retrofit the interviews explored the benefits and barriers to having a design professional involved. The benefits highlighted included having professional oversight; having the formal engagement of stages and roles; proper contracts; independent advice; accountability; technical input and awareness of other elements like building character; planning permission implications and aesthetic design. The professional oversight and certification process was generally considered important as a way of ensuring works are meeting a required standard.

The barriers to having a design professional involved, particularly when it comes to single measures, was the cost and the lack of availability. Another issue highlighted by participant A1, on smaller jobs, was the tight fees and subsequent risk factor. They noted that on a smaller design team the one person needs to have more skills to manage that process.

3.2.2. SEAI Grant Frameworks and One Stop Shop model

Of the participants, most had some experience with the SEAI individual energy upgrade grants and two participants spoke of the experience with SEAI fully funded energy upgrade grants. As the One Stop Shop is relatively new only one participant had direct experience, but others were familiar or had investigated it as an option for their clients. The grant applications are typically made by the homeowners. This influences how willing the participants were to engage with the grants process.

Participant A2 notes that in their experience the architect has more of a co-ordination role for the homeowner, giving advice and helping with the interface between the homeowner, assessor and the subcontractor. In his experience it was the homeowner and the contractor who are interacting with SEAI and the input of the architect is limited to stating on the contract that they must use “SEAI registered people”.

It was noted by a few of the participants that when there are grants involved there is additional work required, which they may not have accounted for in their professional fees. Participant A4 explains that they find, as the architect, that there is an additional role, which is to coordinate the client and subcontractors to do it the right way, follow the SEAI instructions, gather information, organise the building energy rating certificate, all within certain time frame, which adds work but is not properly accounted for in fees.

Under the One Stop Shop grants the process is managed by the One Stop Shop provider. The idea is that it is a single point of contact focused on the energy retrofit measures only. This raised an issue around coordinating with other remodelling works or extensions and was seen as a barrier. Participant A2 looked at the One Stop Shop option and found it difficult to coordinate it with other renovation works. Participant A4 noted that he would be advising his clients away from the One Stop Shop if they are doing other works.

With the absence of a clear framework of how other renovation works can be combined it is likely putting off design professionals and instead they are two separate streams of work for homeowners. Participant A2 comments that where there are works happening in tandem it requires a lot of coordination and a very clear definition of division of responsibilities between the One Stop Shop and the main contract and he felt that it is an aspect that is actually not well understood at the moment.

3.2.3. UK Energy Retrofit Framework - PAS 2035

More than half the participants had knowledge of the PAS 2035 framework and were positive towards it. They felt that a similar framework could work in Ireland. Participant A3 commented that “the area of energy retrofit is quite complex and because it's more complex we need a framework for it to work”. A concern raised about introducing a similar framework was the potential cost of having more defined roles and more people involved.

Participant E1 had a unique insight into the PAS frameworks as both a UK architect but also having been involved in PAS. PAS 2035 was introduced into the UK in 2019. When asked how well it was received by industry in the UK participant E1 said that it was embraced by sections of the industry who were already learning and engaged with retrofit so people like architects and surveyors. It was seen as a way of re-professionalising energy retrofit through the introduction of the retrofit assessor, coordinator and designer. However, there was push back from some installers who were concerned it was too challenging.

Since the original PAS 2035 this participants view has changed on certain aspects including the role of the retrofit designer. He notes that increasingly most measures in energy retrofit are designed by specialists and therefore “I have begun to see the retrofit designer less as someone who is producing a big package of design drawings and specifications, and more like a lead designer would be in the commercial sector. Someone who is coordinating the work of all the specialists and bringing them together and making sure that everything joins together properly, and nothing falls through the cracks”.

When asked about the suitability of a framework like this in Ireland participant E1 felt that a retrofit standards framework is a really good idea and PAS is a way of bringing standards together. He noted the importance of having an equivalent to Trustmark to impose it. In the UK, government will not fund programs unless it meets the standards set out by Trustmark.

3.2.4. Discussion on Role of Design Professionals in Energy Retrofit

Zuhaib and al. (2017) identified that the construction sector in Ireland is fragmented and lacks coherent strategies in the energy retrofit process. The interviews in this research support this finding and suggests that five years later the energy retrofit industry is still fragmented with roles poorly defined. While there are design professionals involved in the energy retrofit of dwellings their role has not been formalised and becomes blurred when energy grants are involved.

In the case of individual grant measures, the homeowner manages the process; in the case of the One Stop Shop the One Stop Shop provider manages the process and in the case of fully funded energy upgrades the process is managed by SEAI. However, in the projects that the interview participants worked on, they were the main person specifying and driving design of energy efficiency measures despite not having a formal role in the managing of grants. While this does not take the design and specification of the materials outside of the design professionals scope it can exclude them from at least part of the process. -

The researcher proposes that a clear framework, like PAS 2035, with roles and responsibilities would be useful to formalise the design element. The concern is that the homeowners do not understand the complexity of energy retrofit and so it becomes a contractor led process, leading to unintended consequences as was seen in the UK in relation to external wall insulation.

This sentiment is captured by interview participant A4 when commenting on the risks associated with energy retrofit: “it's a lot of complexity and I'd say if people really understood that clients and contractors would say, how could you do these projects without a designer?!”.

4. Conclusion

This paper investigates the role of the design professional in the energy retrofit of external wall insulation of dwellings in Ireland and compares the Irish and UK frameworks related to energy retrofit. The paper uses a qualitative methodology and combines document analysis and semi-structured interviews.

The paper finds that when it comes to energy retrofit the role of the design professional is not clearly defined and that if anything they are omitted from the energy efficiency grant application process. The BC(A)R professionals are well placed to design and certify external wall insulation solutions however they need to be able to demonstrate a competency in the complex area of energy retrofit. There needs to be a clear understanding of what works are energy retrofit and what are renovation and who is responsible for the design of specific packages.

An energy retrofit framework like PAS 2035 would be worth exploring further in the Irish context as it provides clear roles and responsibilities and associated minimum qualifications specific to energy retrofit. This could be a way of formalising design in of energy retrofit measures and professionalising the energy retrofit industry in Ireland.

4.1. RECOMMENDATIONS FOR FURTHER STUDY

This paper is based on part of the research carried out by the author in completing the Master of Science (MSc.) in Building Performance (Energy Efficiency in Design) in the thesis ‘An Investigation into the Role of Design Professionals in the Energy Retrofit of External Wall Insulation to Dwellings in Ireland and the Associated Knowledge and Skills’

The researcher, based on her own background as an architectural technologist, is interested in what the future role of the architectural technologist is in energy retrofit and how the knowledge and skills of architectural technologists fit into the overall picture.

Acknowledgements

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AN INVESTIGATION INTO OPTIMISING THE VISUAL APPEARANCE AND THERMAL PERFORMANCE OF WINDOWS IN A PROTECTED STRUCTURE WITH THE AID OF MODELLING AND ANALYSIS SOFTWARE

A comparison of replacement windows for a protected structure using modelling and analysis software

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Abstract. This study investigates the benefits of using modelling and analysis software when considering repairing or replacing windows in a protected structure. Building Information Modelling has become a key tool in the construction industry and is advancing year on year. Technology can optimise the outcome of restoring components of existing buildings. However, it is essential to look at best practice when restoring windows in protected structures as the character of existing buildings must be respected. Primary research consisted of a survey and a case study. The survey gathered information on whether to repair or replicate windows in a protected structure from experienced working professionals. Survey participants included architects, architectural conservationists, architectural technologists and window manufacturers. The information gathered from the survey was used to create 3 window replacement options for the case study. The case study was an 1860's deconsecrated congregational church located in Galway City. The building was a protected structure under the NIAH (National Inventory of Architectural Heritage). The original windows no longer remain. As part of the case study, 3D software was used to model the 3 window replacement options. Renders were generated to provide optimal aesthetics. Flixo was used to provide optimal performance and ensure a continuous thermal envelope. The results of the research were very interesting. Both modelling and analysis software aided in developing the most suitable window for the case study.

Keywords: Building Information Modelling, Building Conservation, Protected Structure, Thermal Bridging, Respect to Buildings, Aesthetics, Conservation Charters, Vernacular and Retrofit, Respect the Special Interest Quality of Protected Structures.

1. Introduction

Technology is an ever-growing phenomenon that continues to contribute to the construction sector in many different shapes and forms. The Columban Hall is located on Sea Road, Co. Galway. It is of special interest under architectural, artistic, and social categories. The registration number on the NIAH is 30318045 (NIAH, 2008).

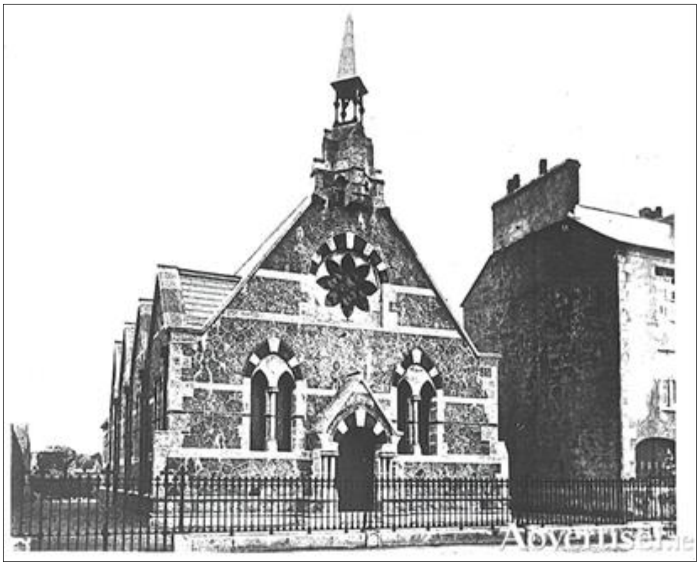


Figure 1. Photo of the Columban Hall taken in the 1920s showing the windows, steeple, and gables over each window on the left of the picture (Advertiser, 2018).

The Columban Hall is a High-Victorian, free-standing gable fronted, former congregational church, built in the 1860's (Figure 1). The building had a short life as a congregational church, due to dwindling numbers within the community. This led to its closure, and it being deconsecrated in 1919. The Jesuit community bought the building soon after and was used as a soup kitchen feeding many needy children at the time (Advertiser, 2018).

The building compromises of a 4-bay single storey nave with a single-storey chancel to the north-west of the building. There is a pitched slate roof with moulded limestone copings at the gables. The building compromises of many elaborate tooled limestone details. This continues to the windows where there is cut limestone sills with a sandstone band halfway up the windows. The window head is made up of polychrome sandstone and limestone voussoirs with polychrome brick courses above. Each window has cut limestone pilasters directly to the left and to the right on the south-west and north-east facades. None of the original windows remain. Timber casement windows are now present. The building remains an attractive component of Sea Road and even in its disrepair, greatly contributes to the streetscape. It is a landmark in the area (NIAH, 2008).

2. Aim

The aim of this paper is to assess the benefits that modelling, and analysis software have on optimising visual appearance and thermal performance of windows in a protected structure.

2.1. OBJECTIVES

1. To review relevant conservation measures required for replacing missing elements in a protected structure using the Venice Charter.
2. To compare window components and construction methods to enhance thermal performance using analysis software.
3. To compare window designs to enhance visual appearance using modelling and rendering software.
4. To investigate the benefits that modelling, and analysis software offer when replacing a window in a protected structure.

3. Secondary Research

Secondary research for this paper was gathered regarding the history of windows, conservation and U-value requirements in Ireland, window components and modelling & analysis software.

Secondary research was obtained from as credible sources as possible, primarily from Ireland and Europe. It was important to find Irish sources of literature for topics which refer to thermal performance and material components of windows. This is due to the high levels of moisture present in the Irish climate. Sources included research articles, books, government documents and peer reviewed studies.

3.1. HISTORY OF WINDOWS

The earliest form of windows were unglazed openings which were covered in various ways. The openings were often covered with oiled cloth, shutters or even sheets of horn.

In 16th century Britain (Ireland included during this period), glazed windows were reserved for buildings of the highest stature and were generally small panes of glass set in lead strip latticework. During this period, glass was handmade in small factories or workshops around the country, and due to its rarity, glass was a sign of wealth.

Due to a greater degree of prosperity, windows became larger and more prosperous households used window size and extravagance as a means of displaying their wealth. Glazed windows were still rare in smaller homes, but their use was on the rise. (Sharman, 2017) The first extensive use of windows in Ireland can be seen at Ormond Castle in Carrick-on-Suir Co. Tipperary, dating back to the 16th century.

In the 17th century, the Renaissance had a strong influence on window shape. This trend made its way to Britain resulting in windows becoming taller that they were wide and often divided into four by a mullion and transom. Timber frames then came into fashion, resulting in narrower mullions and transoms, and the glass was placed almost flush with the exterior façade, allowing for larger glazed areas and less visible frames (Sharman, 2017).

With the introduction of crown glass came the sash window. Crown glass was expensive in the 17th century which prohibited its popularity, allowing for casement with lead glazing to be the most popular type. This changed in the 18th century as sash window design evolved, glazing bars became thinner and window size became more standardized (Sharman, 2017).

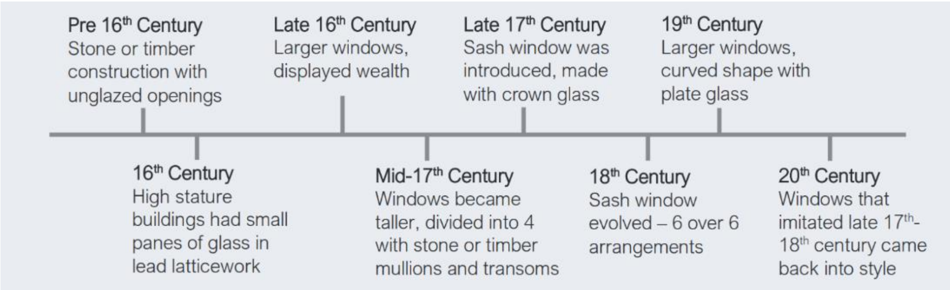


Figure 2: History of Windows Timeline in Britain & Ireland (Source: Author).

3.2. GLASS MANUFACTURING IN IRELAND IN THE 19TH CENTURY

In the 19th century, Ireland was part of Britain. Window tax was abolished in the mid-19th century in Britain allowing people to have larger windows in their homes. In 1834, a cylinder sheet process for glass making was imported from Germany allowing for larger sheets of glass to be made (Sharman, 2017). This process of glass making could have been used in the windows for the Columban Hall.

Crown glass was also popular in 19th century Britain. The process of making crown glass involved blowing the glass into a bubble, piercing it, and spun to form a disc. The glass was then cooled and cut into panes (Sharman, 2017). It is likely that crown glass was used in the Columban Hall as it was still common in Ireland in the 1860s.

It is important to note that the Great Hunger of the 1840s led to the emigration of many skilled glass makers. Irelands glass industry fell for some time and would take many years to fully revive (Haggerty, 2022). The Columban Hall was built approximately 15 years after the Irish Famine.

3.3. CONSERVATION IN IRELAND

In Ireland, the NIAH is the national authority that identifies and records the post-1700 architectural heritage of Ireland.

The NIAH surveys provide the basis for the recommendations of the Minister for Housing, Local Government and Heritage to the planning authorities for the inclusion of particular structures in their Record of Protected Structures (NIAH, 2021).

The Columban Hall is protected under Architectural, Artistic and Social categories of special interest (NIAH, 2021). This implies that conservation charters must be adhered to when adding an extension or undertaking restoration works to the building or site.

The Venice Charter is an international charter for the conservation and restoration of monuments and sites. The Venice Charter contains 16 articles each referencing different aspects of conservation and restoration of monuments and sites. Below are the most relevant articles:

Article 5 of the Venice Charter outlines that *'The conservation of monuments is always facilitated by making use of them for some socially useful purpose.'* This is the basis of why the Columban Hall is being restored. It is of little use in its current state and would be a useful facility if restored. Article 5 further states that if such use if therefore desirable '*it must not change the layout or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.'* Since the original windows in the Columban Hall no longer remain, the windows are then considered as the replacement of missing parts to the building (ICOMOS, 1964).

Article 12 states that *'Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.'* (ICOMOS, 1964). This article applies directly to the windows.

3.4 U-VALUE REQUIREMENTS

TGD Part L (2022) is the Technical Guidance Document for the Conservation of Fuel and Energy in Ireland.

Section 0.6 (Application to Buildings of Architectural or Historical Interest) outlines the procedures when dealing with protected structures. Part L does not apply to works of a protected structure. However, it is still advised that best practice is achieved. The aim should be to improve the energy efficiency as far as reasonably practicable (Department of Housing, 2022). The maximum U-value for windows is 1.6W/m^{2}K *(Figure 3).*

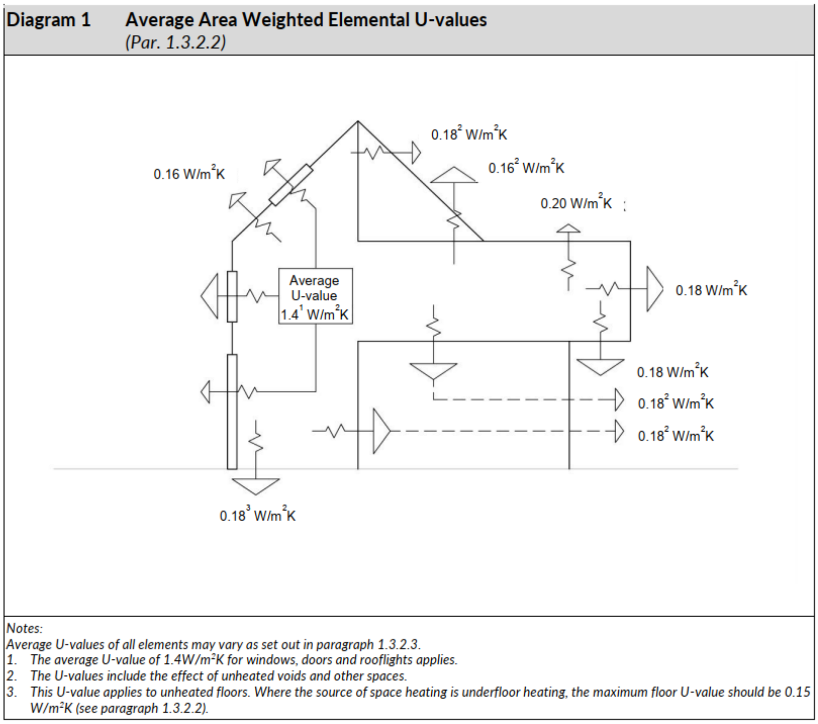


Figure 3: Average Area Weighted Elemental U-values (Department of Housing, 2022).

3.5 WINDOW FRAME MATERIALS

There are many materials that could be used for the window frame. The chosen material would have to be thermally efficient, aesthetically pleasing and must respect the building fabric.

Wood is a sustainable material that could be used as a window frame material. Accoya wood is often used for windows and doors. It is made from radiata pine trees, and then undergoes a modification process called acetylation. This process turns the wood into a much more stable product than it was (Accoya, 2022).

Steel window's greatest quality are their narrow sightlines. Their slender lines have been incorporated into the design of many buildings with an elegance which is rarely matched by bulky profiles of aluminium, wood, or PVC-U (SWA, 2014).

Concerns are often expressed at the risk of condensation through thermal bridging. The temperature difference between inside and out causes condensation if there is no proper ventilation. Proper ventilation must be sourced as a means of control (SWA, 2014).

3.6 GLAZING UNITS

The Glass & Glazing Federation of Ireland have stated that there are modern variations for Insulated Glass Units (IGU's) for conservation and heritage buildings being designed and developed. There are two types being developed are:

1. Narrow Cavity Units
2. Shallow sight lines

Both have become common due to a desire to keep narrow rebate platform widths, especially in the 'heritage/ conservation' area (GGF, 2017).

Low-e coatings are highly insulating. They reflect heat back into the building. However, when light shines through the coating, a green tint can often show in the room. This is more noticeable when windows are facing south as the tint is strongest when facing south (DunRite, 2021). Due to this low-e coatings would not be aesthetically pleasing in the Columban Hall.

Krypton and argon gas are often used in window cavities, as they are both highly insulating inert gases. Argon is cheaper but krypton is a better insulator (Argon: 0.016W/m2K, Krypton: 0.0088W/m2K). Manufacturers often mix air, argon, and krypton together to balance cost and performance (Knowledge, 2020).

3.7 SOFTWARE

Windows are considered the weakest link of the energy behaviour of buildings. 2D tools such as Flixo or Therm can be used to assess heat loss at window junctions.
For modelling the window, Autodesk Revit is often used. Revit is a BIM package for architects and engineers which enables the modelling of 3D data (Kirby, 2018).

Lumion is a rendering engine often used by architects and designers. It is the fastest 3D rendering software. Twinmotion is also used by architects and designers for visualization execution. Both have a plug-in to Revit, where the model can be exported to the rendering engines, allowing for the creation of realistic views (Denerel, 2021).

4. Primary research

4.1 CASE STUDY

Documentation has been sourced identifying the original windows in the Columban Hall and can be seen below *(Figure 4).*

Figure 4: A photo of the Columban Hall from 1938 showing the original windows (Source: The Jesuit Archive).

They are of lead strip latticework frames with diamond shaped pieces of glass held in place. An appropriate option for the design of the new windows would be to incorporate some features of the originals, or, to replicate them with slight changes to satisfy the Venice Charter.

The front windows are paired lancet-headed lights to sides of nave having tooled limestone block-and-start surrounds, polychrome sandstone, and limestone voussoirs with polychrome brick courses above, and limestone mullions. Figure 5 shows a section of the existing window.

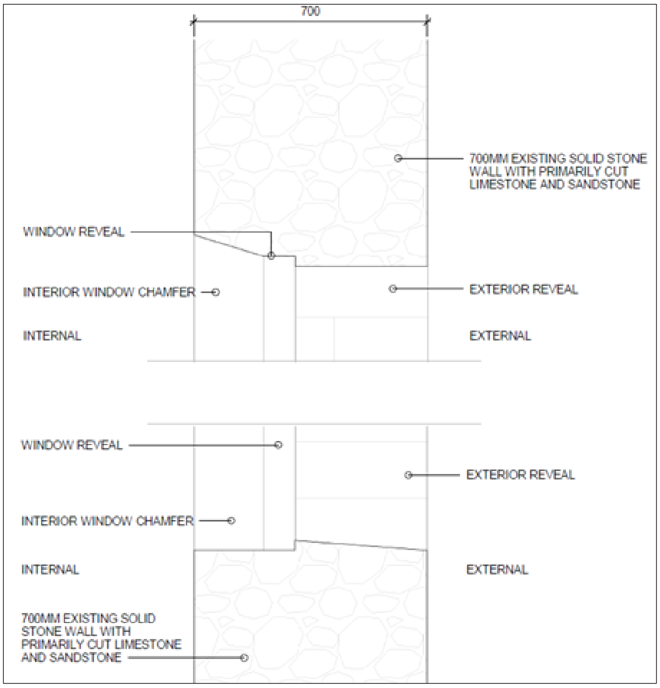


Figure 5. Existing Section of a Window of the Columban Hall (Source: Author).

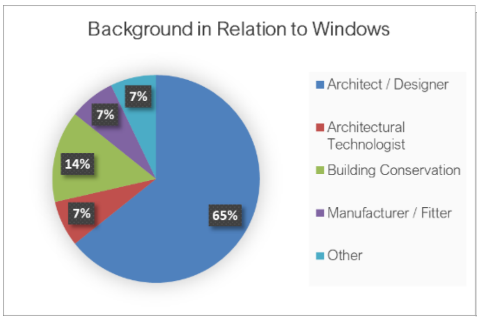
4.2 SURVEY

A survey was conducted to gather information from the industry to aid in developing the most suitable replacement window for a protected structure. Each participant of the survey was given the Columban Hall as a case study. Each participant had the option of completing the survey in either Microsoft Forms or Microsoft Word.

As the Columban Hall is a protected structure, it was chosen to use the RIAI Practice Directory as a source of finding Conservational Architects and Architectural Technologists. The internet was used to find manufacturer's email addresses. The survey was first sent out on the 8th of March 2022. 12 respondents out of a sample of 35 participated in the survey.

Question 1:

What background do you have in relation to windows?



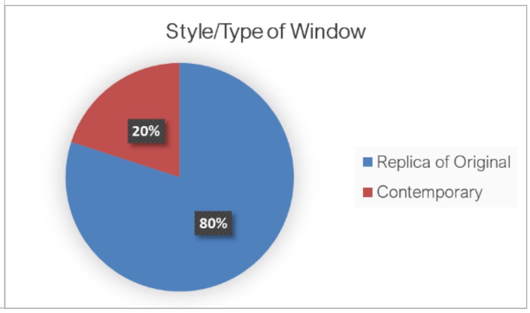
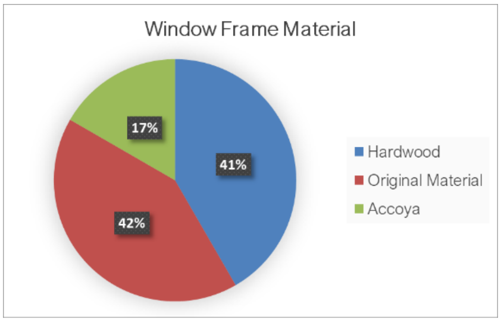


Figure 6. Pie Chart showing the survey participant's background (Source: Author).

Figure 7. Pie Chart showing the style of window recommended in the survey (Source: Author).

Question 2: (Open ended Question)
For a protected structure, what style/type of window would you recommend when replacing windows that are either missing or beyond repair? Eg. Replica of Original, Contemporary etc.
Summary of Responses:
For this question, there was a strong lenience towards a **replica of the original.** 80% of respondents advised on replicating the original windows due to valuable documentation being present on what the originals were like. Respondent 12 stated that adequate documentation to determine the original style and age should be looked at, along with other congregational churches designed by Raffles Brown.

Question 3: (Open ended Question)
For a protected structure, what window frame material would you recommend and please state why.
Summary of Responses:
For the window frame, timber was advised, along with the original material that would have been used in the building. Some respondents stated that windows of that period were usually of timber construction with either cast iron or lead camed glazing bars. Respondent 8 suggested that Accoya wood could be used as it is a low carbon approach. Respondent 12 recommended using matching materials, which would be in keeping with best conservation practice as well as Irish legislative requirements for the protection of character.



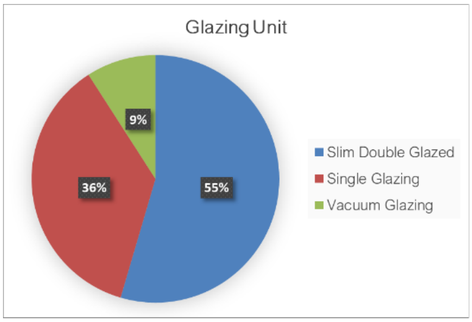


Figure 8. Pie Chart showing the window frame recommended in the survey (Source: Author).
Figure 9. Pie chart showing the glazing unit recommended in the survey (Source: Author).

Question 4: (Open ended Question)
For a Protected Structure, what glazing unit would you recommend?
Summary of Responses:
The general takings from this question were to put visual appearance over thermal performance, but to also try to improve thermal performance as much as possible, without effecting the look of the windows. It was strongly advised to use no more than a double-glazed unit. Secondary glazing was recommended along with a replica of the original glazing on the exterior. Respondent 5 stated that Lambstongue & Pilkington manufacture slim double-glazed units for conservation buildings.

Question 5: *(Open ended Question)*

If relevant, what software would you recommend for analysing the thermal performance of windows? Please state why.

Summary of Responses:

Relevant responses were limited for this question, as many respondents stated that a minimum U-value requirement is not required for protected structures in TGD Part L. This is true but achieving a low U-value is still advised. Therm and Flixo were both mentioned as they are user-friendly, and widely used for assessing thermal bridges at windows (Respondents 6 & 11). Thermal imaging cameras were recommended for indicative heat loss (Respondent 12).

Question 6: (Open ended Question)

If relevant, what software would you recommend for optimising the visual appearance of windows? Please state why.

Summary of Responses:

Like the previous question, useful responses were limited due to this question not being relevant to some participants of the survey. However, some responses were very useful and specific. Revit is often used as it easily generates plans, sections and elevations of the window and surround (Respondent 1).

Question 7: (Open ended Question)

In a protected structure without any insulation yet present, please explain how you would achieve continuity of insulation at the window surround? (reveal, head, sill)

Summary of Responses:

Since insulating the external walls of the Columban Hall is not possible due to the opus insertum stonework, insulation was recommended on the interior side of the walls. Low carbon approaches were recommended such as Calsitherm boards or Diasen Diathonite Evolution which is a cork-based plaster, (Respondent 1, 6, 8, 12). 15mm of Diathonite was recommended with 3-5mm of Argecem HP plaster, which is a low carbon material. The use of these materials would regulate localised humidity and ensure full breathability of the wall. This will resist mould formation thanks to a high PH level of 12. Many restoration/renovation projects in the past would have used concrete plaster internally which didn't allow the wall to breathe, causing mould growth and condensation.

Question 8: (Open ended Question)

Do you have any further comments on replacing windows in a protected structure that has not been mentioned above?

In general, the main comments from this question were to repair rather than replace. Retaining the existing and seeing if it can be repaired was also recommended in relation to the windows. Secondary glazing was highly recommended, which would benefit the building thermally while also allowing the visual element of stained glass/decorative mullions to be enjoyed. Other important points were mentioned below:

- It was stated by respondent 3 that traditional architecture placed beauty over function, which is an important aspect to keep in mind when trying to change existing elements.

- It was stated by an Irish conservation company that it would be essential to ask the local authority for a pre-planning meeting to discuss material changes to windows and internal plasterwork prior to lodging a planning application for conservation works. Ideally this would be carried out as early as possible to know what the local authority will allow or not (Respondent 12).

- Working shutters can improve the thermal efficiency of the building. This would be a smart addition to windows in the Columban Hall due to its new use being a theatre, which will require the windows to be easily blacked out when events are taking place (Respondent 10).

4.3 MODELLING WINDOWS FOR THE COLUMBAN HALL

The three windows were modelled in Revit and are as follows:

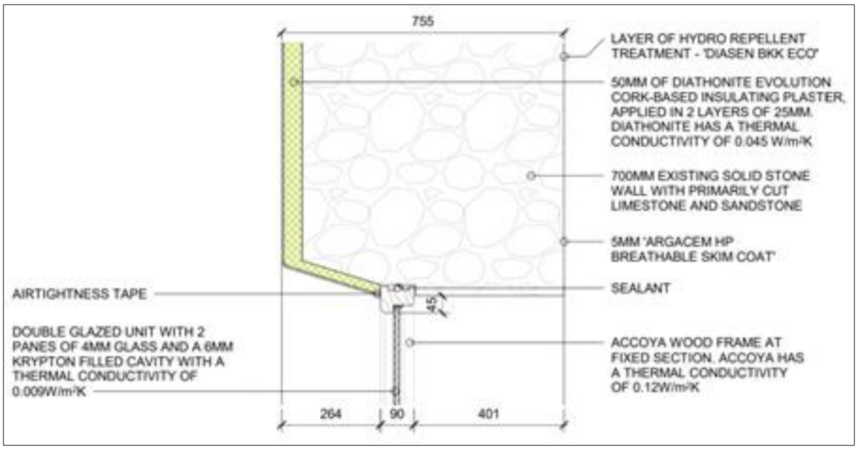
1. Accoya framed window with double slim glazing. Accoya was recommended in the survey due to it being a low carbon material. Accoya wood can accommodate a slim profile due to its robustness and durability. This will suit the Columban Hall, as a slim profile is required.

2. Replica of original with clear glass. The replica approach was strongly advised in the survey, primarily due to the visual appearance of the building.

3. Replica of original with stained glass. The photo from 1938 shows the original windows of the Columban Hall. On further inspection of the windows, the pieces of glass are shaded different colours, hinting that stained glass was present.

Accoya Window:

The Accoya framed window is fitted with a slim double-glazed unit, allowing for an improved thermal efficiency. the window is split into 3 parts, with the bottom section functioning as an inward opening section. Diathonite insulating plaster wraps around the reveal to touch the inside of the frame. The window must be fitted first, and then the application of the insulating plaster can be carried out.



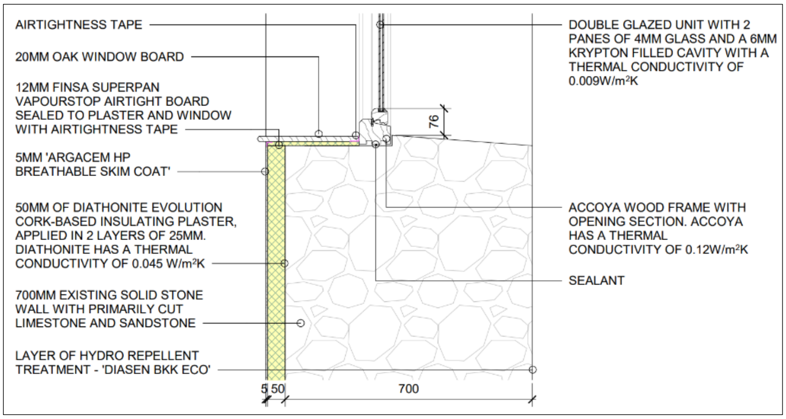


Figure 10: Accoya Windowsill & Head Detail (Source: Author).

Figure 11. Render of the Accoya Window in Lumion (Source: Author).

Figure 12. Render of the Accoya Window from inside the Columban Hall (Source: Author).

Replica Window with Clear Glass:

The replica window consists of a timber outer frame, which holds the steel frame with leaded lights. This is likely to be the original window design. It is likely that crown or cylinder sheet glass was used. Crown and cylinder sheet glass would have a slight distortion, adding to the character of the windows. This would be used in the replica window. The glass would be held by strips of lead known as ‘lead camed’.

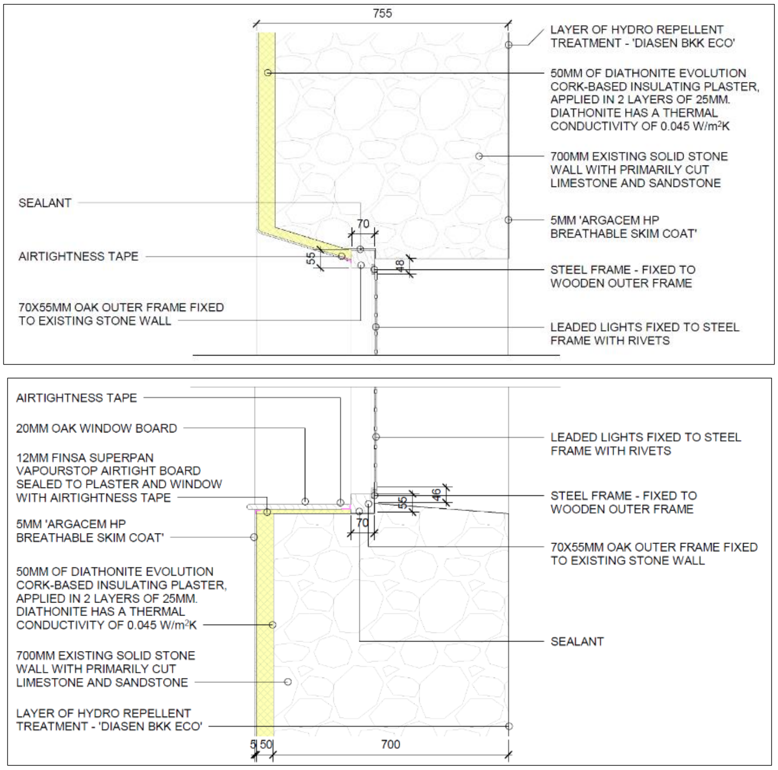


Figure 13 Replica Windowsill & Head Detail (Source: Author).

Figure 14. Render of the Replica Clear Glass Window (Source: Author).

Figure 15. Render of the Replica Clear Glass Window from inside the Columban Hall (Source: Author).

Replica Window with Stained Glass:

Stained glass is most found in churches. It is likely that stained glass was used in the windows of the Columban Hall due to many churches of the same period and function (congregational church) having stained glass. The window structure is the same as the replica window with clear glass. This stained-glass window was modelled primarily for aesthetic reasons, and to visualise how light would enter the building through the glass.

Figure 16. Render of the Replica Window with Stained Glass (Source: Author).

Figure 17. Render of the Replica Window with Stained Glass inside the Columban Hall (Source: Author).

Figure 18. Render of the Replica Stained Glass Window with Secondary Glazing (Source: Author).

Summary of Renders:

The realistic views generated by Lumion allow for a thorough analysis to be made on the visual aspects of all 3 window types. The external renders show how the windows fit into the building, while the internal renders show how light travels through the glass and into the building.

4.4 ANALYSIS SOFTWARE

Flixo was chosen to assess the windows thermal performance. Since the two replica windows are the same other than the colour of glass, only 1 will be modelled as single glazed. The three options to be assessed were chosen from the advice from the survey.

Each window will be shown as a jamb detail, cutting through an opening section of the window.

The three windows are:

1. Accoya slim glazed window.

2. Single glazed replica window.

3. Replica window with secondary glazing.

Accoya slim glazed window:

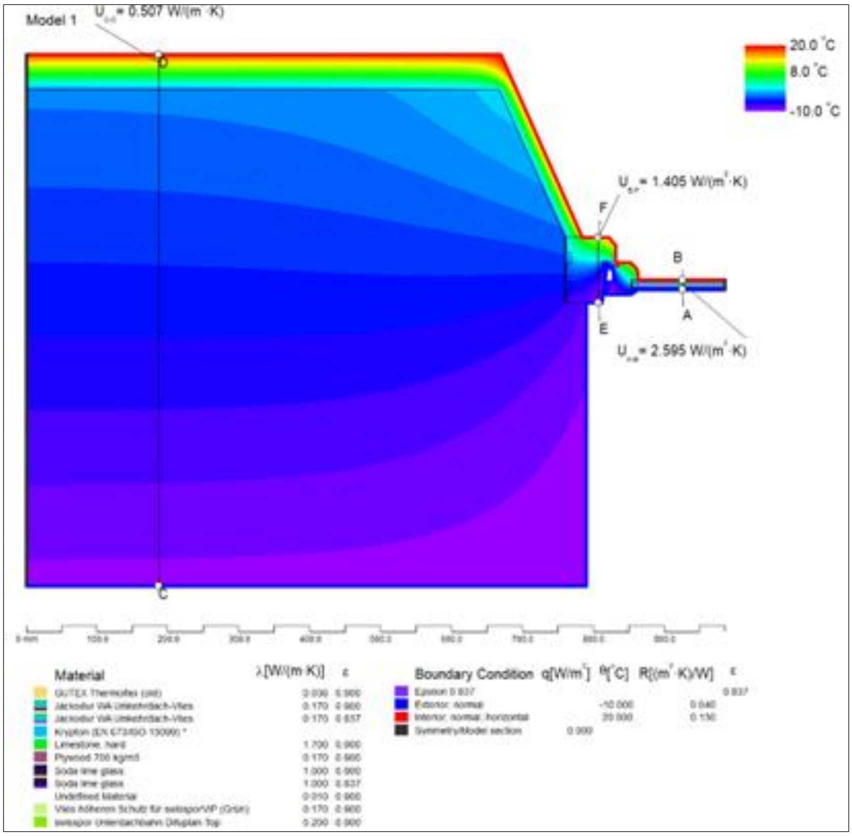


Figure 19. Temperature Field of an Accoya Slim glazed window at the window jamb (Source: Author).

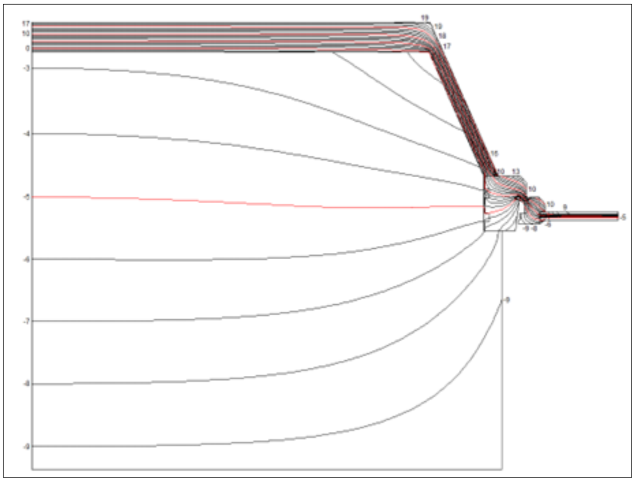


Figure 20. Temperatures at the critical points of the window and reveal (Source: Author).

Summary:
The Accoya window performs well when looking at U-value figures at both the window frame and at the glazing unit. The insulated space bar keeps the continuity of insulation at the window, otherwise there would be a thermal break at that point. The Accoya wood performs well, as it has a low thermal conductivity.

Single Glazed Replica Window:

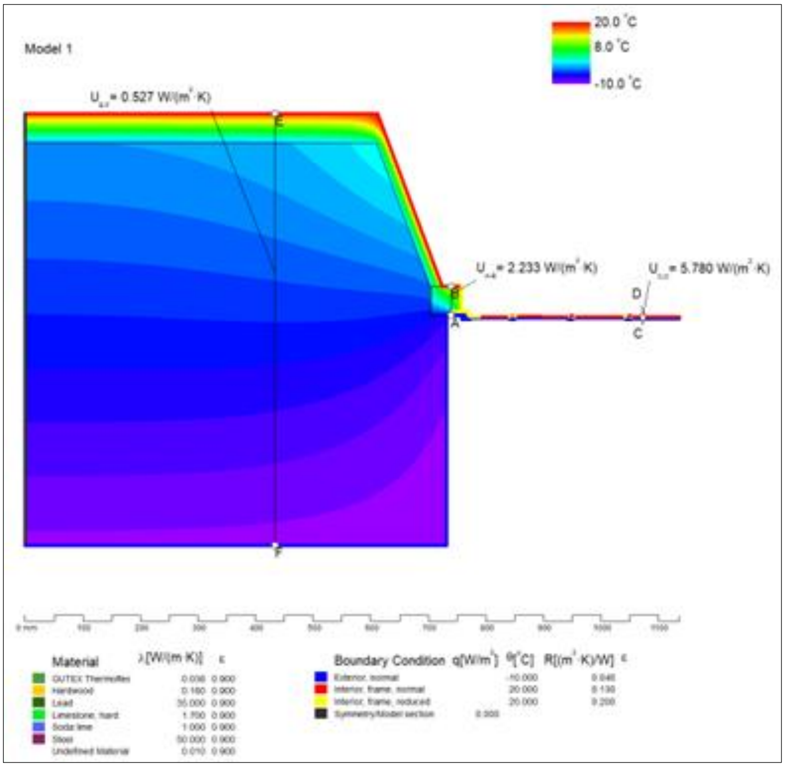


Figure 21. Temperature Field Diagram of a Single Glazed Replica Window

at the jamb (Source: Author).

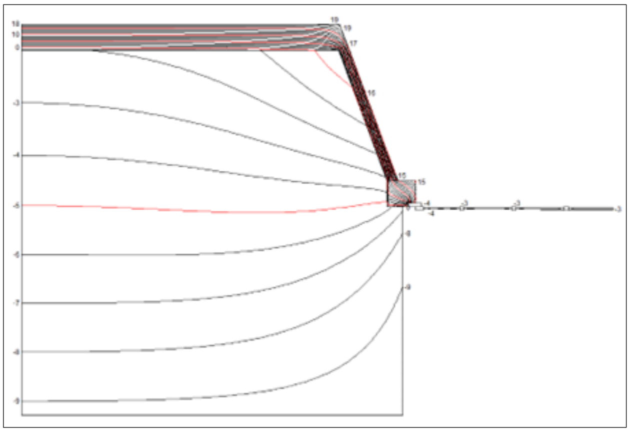


Figure 22. Temperatures at the critical points of the window and reveal (Source: Author).

Summary:

Thermally, this window performs poorly, as it is made from primarily steel, lead, and glass, which are all good conductors of heat. The U-values are very high in comparison to the existing wall, which could possibly be a point in the building where condensation / mould growth could occur.

Replica Window with Secondary Glazing:

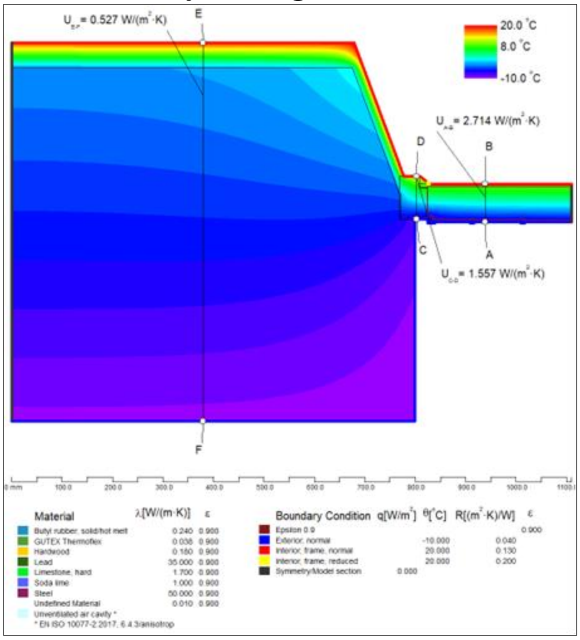


Figure 23. Temperature Field Diagram of a Replica Window with secondary glazing at the jamb (Source: Author).

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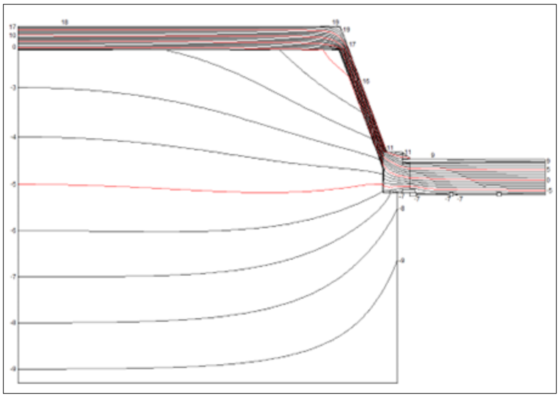

Figure 24. Temperatures at the critical points of the window and reveal (Source: Author).

Summary:

The temperature field diagrams show how much heat is kept within the building by using secondary glazing. There are no thermal breaks along the interior of the building, which lowers the chance of condensation / mould growth occurring.

5. Results

TABLE 1. Window Aesthetics Matrix (Source: Author).

Matrix for Aesthetics of the windows:							
Attribute:	**External Aesthetics**	**Internal Aesthetics**	**Respect to the Building**	**Narrow Sightlines**	**Integration with Building**	**Quality of light into Building**	**Total:**
Weighting	20	20	15	15	15	15	**100**
Accoya Slim Glazed	15	15	13	14	11	14	**82**
Replica with Clear Glass	17	17	14	14	14	12	**88**
Replica with Stained Glass	18	19	14	14	14	14	**93**

This matrix was designed to create scores for each window in relation to aesthetics. The renders were used as a base to work off. Both external & internal aesthetics have the highest weighting, while respect to the building, sightlines, integration, and quality of light all weigh 15%. The replica with stained glass scored highest in this matrix due to its attractive aesthetics and respect to the building fabric.

By analysing the external renders, the replica windows integrate into building better than the Accoya contemporary window. The internal renders show that more light is allowed in by the contemporary window, but aesthetically, the replica windows prevail.

TABLE 2: U-value Figures at Critical Points (Source: Author).

U-value Figures at Critical Points (Flixo Calculations)			
Window:	U-value of the Glazing:	U-value of the Frame:	U-value at the Wall:
Accoya Slim Glazed Window	2.595	1.405	0.507
Single Glazed Replica Window	5.780	2.233	0.507
Replica Window with Secondary Glazing	1.557	2.714	0.507

6. Conclusions & Recommendations

6.1 CONCLUSIONS

Replacing windows in a protected structure can be very difficult to execute correctly. It is essential to review all aspects of replacement windows and how they will fit in a particular building. Through using modelling and analysis software to compare materials and designs, it is much easier to visualise and analyse how the window looks and how it performs.

Objective 1 – *To review relevant conservation measures required for replacing missing elements in a protected structure using the Venice Charter.*
The Venice Charter outlines how missing elements can be replaced. As missing elements must be distinguishable from the original, the replica windows would not be allowed under the Granada Convention. However, after further review, the windows only need a slight change to them to make them distinguishable, eg. Change of handle.

Objective 2 – *To compare window components and construction methods to enhance thermal performance using analysis software.*
Window components make a huge difference in ensuring continuity of insulation. The interface between the wall and window frame is extremely important. Flixo demonstrated that the loss of heat through the space bar can be huge if an insulating material is not used. Without using Flixo, this would be difficult to pick up on.

Objective 3 – *To compare window designs to enhance visual appearance using modelling and rendering software.*
Window designs can be easily analysed within its opening by modelling both the window and the wall. For protected structures, this is very beneficial, as intricate details and stonework can be easily modelled in Revit and rendered to a high resolution in Lumion.

Objective 4 – *To investigate the benefits that modelling, and analysis software offer when replacing a window in a protected structure.*
By using modelling and analysis software, it is easy to compare window components both aesthetically and thermally. Thermal performance can be analysed in Flixo, which gives figures in relation to U-values. Modelling software shows how windows can look prior to any site work taking place, this reduces the risk of errors occurring on site.

6.2 RECOMMENDATIONS

This report has shown that using modelling and analysis software is extremely beneficial when choosing windows to be fitted as replacements in a protected structure. From conducting this research, recommendations would be made to encourage the use of new technology such as the laser scan data and rendering images.

From a thermal perspective, the Accoya slim glazed window would be the best option after reviewing the U-value at both the frame and glazing unit. The same window also allows a lot of light into the building in comparison to the replica windows.

From an optical perspective, the replica window with stained glass is the best option for the Columban Hall. The arrangements and colours of the glass contrast very well with the opus stonework. Internally, sunlight filters through the stained glass and into the building, creating a warm and comfortable atmosphere in the building, which the clear glass replica cannot replicate.

However, a balance must be struck between a thermally efficient window and an aesthetically pleasing window. Because of this, I would recommend the stained-glass window with internal secondary glazing. This would ensure a lower U-value while also providing an aesthetically pleasing window. A possible area of future research would be to incorporate insulated shutters which would further lower the U-value.

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AN INVESTIGATION INTO THE POTENTIAL OF REDUCING THE IMPACT OF PLUVIAL FLOODING IN DUBLIN, USING BLUE-GREEN ROOFS WITH SMART CONTROL DEVICES

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Abstract. This paper investigates the potential of blue-green roofs with smart control devices to reduce pluvial flooding in Dublin. Blue-green roofs combine green and blue roofing technologies and have the potential to retain and release large volumes of run-off water at a controlled rate. Smart flow control valves are specialised roof outlets that are connected to building management systems and can automatically respond to weather changes. These roof systems are a contemporary sustainable drainage approach, primarily focused on reducing runoff into drainage systems. Simultaneously, they serve the purposes of irrigating the vegetation layer, rainwater harvesting, and offering amenity. Smart control devices can improve the functionality of these roofs by maximising the buffer capacity and reduce the impact of extreme weather events. Urban flooding due to extreme precipitation has had a devastating impact in recent times in Dublin, with an increase in the frequency of these events expected due to climate change. This research shows that the integration of blue-green roofs with smart control devices into new and existing building stock can reduce the impact of weather extremes in Dublin. Traditionally, green roofs have been used for the management of storm water on rooftops, but their effectiveness at managing storm water during high rainfall events has been criticised because of limitations in its water buffer capacity. It was found that blue-green roofs with smart control devices reduced both the volume of run-off and the peak run-off rate on an existing site in Dublin, showing their potential to be used to mitigate against flooding. This paper uses a combination of digital simulations using hydraulic modelling software, and physical simulations using a blue-green roof prototype. The results demonstrate how blue-green roofs with smart control devices can be integrated into drainage systems to reduce the impact of weather extremes. The results highlight the need for specification of these systems within urban environments such as Dublin, where space for other Sustainable Urban Drainage System (SUDs) components are an issue due to rapid urbanization. More leadership is needed regarding these new stormwater management systems, along with more guidance to promote confidence within the construction industry.

Keywords: blue-green roof, blue-roof, smart flow control valve, precipitation, urban run-off, sustainable urban drainage system, SUDs, pluvial flooding, combined sewer overflow.

1. Introduction

The frequency of extreme weather events has risen worldwide due to climate change. This is evident in Ireland, with increases in both average annual rainfall and storm intensity in recent years. Met Eireann has predicted that the frequency of heavy precipitation events will increase by 20% in the autumn and winter months (The Office of Public Works, 2019). Pluvial flooding occurs when heavy rainfall cannot be absorbed by the ground or drainage system (Morris et al., 2009). Due to rapid urbanisation in Dublin along with climate change, there has been an increase of pluvial flooding events due to urban run-off and a lack of permeable surfaces. As a result of excess run-off, combined sewer overflows have caused billions of litres of untreated wastewater to be discharged into the Liffey Estuary since 2015. Consequently, public beaches have been forced to close at times (The Journal, 2019).

Green roofs, which transform roof surfaces from impermeable to permeable, reduce stormwater runoff (Shafique et al., 2016). However, they have limitations related to water buffer capacity during heavy rainfall and vulnerability to droughts without irrigation (Busker et al., 2022). An innovative approach is the "blue-green" roof, designed to store larger water volumes. These roofs incorporate a reservoir that serves as a water source for the green layer through capillary risers. A “smart control valve” is a specialised roof outlet that responds to weather changes. The valve opens and closes automatically at certain times to optimise the water buffer capacity to improve the overall performance of these roof systems (Busker et al., 2022).

This paper explores how blue-green roofs with smart control devices can help reduce the risk of pluvial flooding. The paper uses a combination of physical and digital simulations to compare blue green roofs with smart controls to other flat roof solutions with a focus on stormwater management. The paper uses a case study building with a history of flooding in Ringsend, Dublin.

1.1 AIMS AND OBJECTIVES

The aim of this research is to investigate whether these roof systems could be used in Dublin to manage stormwater. The research objectives are to conduct a literature review into preceding studies on these roof systems and how effective they are at managing stormwater; to compare the effectiveness of blue-green roofs systems with smart control devices to other flat roofing solutions regarding stormwater management; and to determine the impact these systems have at reducing run-off from an existing site in Dublin.

1.2 RATIONALE

Urban flooding has profound economic repercussions. More than half a billion euros have been expended on property and infrastructure damages since 2008, with extreme cases leading to loss of life (Insurance Ireland, 2014). Notably, a 2011 flood in Dublin, resulting from combined pluvial and fluvial flooding, caused two fatalities and approximately €130 million in insured damages (The Office of Public Works, 2019).

Dublin City Council have introduced guidance on blue-green roofs within their Dublin City Development Plan (2022-2028), however, the requirements that are outlined only relate to the percentage of blue-green roof coverage, with no requirements specifically for water storage (Dublin City Council, 2021). Whilst green roofs can provide reasonable stormwater management, there must be more consideration for how large amounts precipitation can be stored on rooftops and released slowly over a period.

2. Literature Review

The literature reviewed for this paper focused on the stormwater management capabilities of blue-green roofs with smart control devices and considers how they are tested in other countries. Sustainable drainage at a macro level is also examined along with the role of blue-green infrastructure on a wider scale.

2.1 BLUE-GREEN ROOFS AND SMART CONTROL DEVICES

Around the world, the stormwater management capabilities of blue-green roof systems have been tested and analysed. Shafique et al. (2016) investigated a blue-green roofs' performance at reducing stormwater run-off and peak run off delay. The research demonstrated that the stormwater management potential of a blue-green roof could be measured completing a field study by comparing the peak run-off rate and run-off reduction of a blue-green roof prototype and a typical flat roof prototype. It was found that the blue-green roof reduced the amount of stormwater discharged and was lower than the control roof, and that the peak run-off rate was also reduced.

The Netherlands are the frontrunners regarding smart technology for blue-green roof systems. Busker et al. (2022) designed a hydrological blue-green roof model that uses precipitation forecasts in the Netherlands to control an automated valve that regulates the water level of the system to optimise its functionality. They compared the performance of a control roof, a green roof, a blue-green roof, and a blue-green roof with forecast-based drainage and measured how effective they are at stormwater management and reducing urban heat. *RESILIO: Final Report (2021),* referenced by Busker et al. (2022) is a report describing a large-scale project in Amsterdam, where 10,000m^2 of blue-green roofs were installed on existing social housing and privately owned real estate. These roofs have smart control valves which anticipate heavy rain or drought, releasing or retaining water accordingly.

Szmudrowska et al., (2018) conducted a literature review on smart blue-roof systems for *Sustainable Technologies* in Canada, for phase one of their smart roof project. The survey provides information on active and passive blue-roof systems, along with other areas such as safety features, maintenance, IoT systems (smart devices), and examples of blue roof systems around the world. The method used includes a survey to provide "background information necessary to conduct a thorough technical and financial feasibility analysis". The results from their literature review revealed that there is little information about blue roofs, however, several businesses are beginning to implement them within the private sector in Canada.

2.2 BLUE-GREEN INFRASTRUCTURE

Countries have implemented government funded programmes to incentivise blue-green infrastructure. Li et al. (2017) analysed the sponge city construction programme that was launched in 2015 to tackle water pollution and environmental issues in China. The study surveyed 30 pilot sponge cities and identified a broad array of challenges, including technical, physical, financial, and institutional challenges with many uncertainties and risks highlighted. Some major technical challenges included ambitious goals without extensive research, local conditions not being considered and vague guidelines. Based on the results, some proposals were made which included a requirement that local governments adopt sponge city regulations, along with permits to alleviate water quantity and pluvial flooding issues.

In Dublin, only the effect of green roofs has been analysed on a larger scale. Nesbitt (2012) conducted a study on the Docklands region in Dublin, assessing the impact that intensive (trafficable) and extensive (lightweight) green roofs would have on pluvial flooding. The study involved the recording and mapping out of potential green roofs in Dublin's Docklands, and how retrofitting flat roofs in the area could slow down the run-off discharging into the existing drainage system. He concluded that grouping clusters of roofs would provide the best outcomes in flood hotspots. He notes that further research is needed on the structural capacity of existing flat roofs.

3. Research Methods

Physical simulation and digital simulation methods were used to represent the characteristics of extreme storm events, using a physical prototype and urban drainage analysis software respectively (Groat and Wang, 2001). The data arising from these simulations were then collected and analysed.

3.1. PHYSICAL SIMULATION

The stormwater management capabilities of a blue-green roof can be measured by analysing the peak run-off rate, and reduction in run-off during a rain event with high intensity (mm/hr). Physical simulation tests were carried out to compare the effectiveness of blue-green roofs with smart control devices with other flat roofing systems at managing stormwater. The test results were compared to that of a green roof and a non-vegetated flat roof, using the Rational Method (Equation 1).

$$Q = C\,i\,A \qquad (1)$$

A blue-green roof prototype was constructed, with household items being used to mimic the storm conditions (hose), and the smart control valve (bucket). Historical storm conditions applicable to Dublin were simulated in the absence of a high specification smart control valve capable of predicting extreme events. As a result, results were based on its effectiveness during a previous storm rather than a future storm event, as a true smart control valve would.

Figure 1. Blue-Green Roof Prototype.

3.2. DIGITAL SIMULATION

A wider range of storm simulations were completed using InfoDrainage, a stormwater design and analysis software. ESB SPORTSCO in Ringsend was the chosen case study building due to a history of pluvial flooding.

As described in Figure 1, the existing site was modelled to fully understand the site characteristics, such as the percentage of impervious areas, roof outlet locations and manhole locations. Important details such as invert levels and cover levels were recorded during the site audit. Three different site conditions were modelled into InfoDrainage with three different roof types as described in Figure 1. As there is no blue-green roof catchment option within InfoDrainage, the available tools were developed to simulate how a blue-green roof would perform. For the blue layer, the storage layer was modelled as a detention tank, as it can be described as a layer that temporarily stores stormwater (Shafique et al., 2016).

Different rainfall methodologies are available in InfoDrainage, however, the only one applicable to Ireland is the Flood Studies Report rainfall model. The chosen rainfall return period was 1-in-100 years, in line with Dublin City Councils recommendations for new developments (Dublin City Council, 2022). To account for climate change, a 20% increase in the amount of rainfall was used. Winter storms were chosen for these simulations, as they produce a higher amount of precipitation compared to summer storms. The design storm durations that were chosen included 15-, 30-, 60- and 120-minute durations. To further measure the roof systems stormwater management potential in Dublin, a historical storm was also designed within InfoDrainage. The chosen storm occurred on the 24th of October 2011.

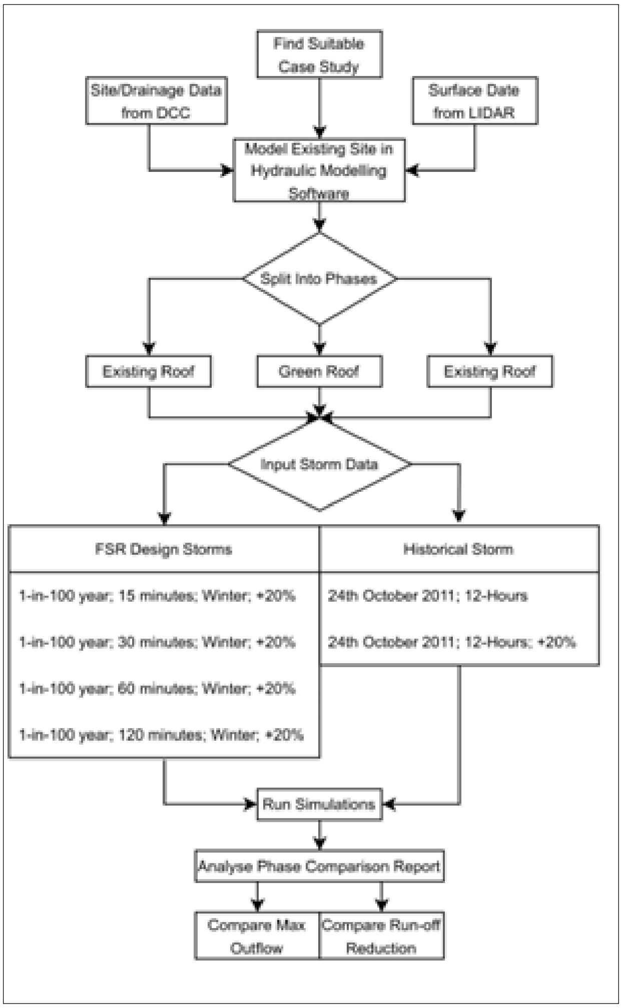

Figure 2. Digital Simulation Workflow.

3.3 LIMITATIONS OF RESEARCH

Certain limitations were encountered throughout this research. For the physical simulations, household items were used in place of a sophisticated smart control valve and a historical storm was simulated to demonstrate how the valve operates, whereas a true smart control valve would use weather forecasts to predict future extreme events.

Due to timeframe, only four short storms and one longer storm was simulated. While the results were positive, a wider range of storms should be completed to fully determine how effective the roof system is at mitigating pluvial flooding.

4. Results and Discussion

4.1 PHYSICAL SIMULATION

The simulation tests carried out on the roof prototype during the 6-hour storm conditions were compared to the peak run-off estimation of a green roof and typical flat roof prototype. Two iterations of the test were completed: one with and one without the smart control valve releasing the water applied to the roof on the previous day.

4.1.1 With Smart Control Valve

The first iteration of the test began at 12:00 and finished at 18:00, with dry weather conditions for the duration of the simulation. Figure 2 illustrates the flow rate over the six hours, with a peak flow rate of 0.16 L/min recorded at 16:15 and 16:45. This is lower than the estimated peak run-off rate of a typical flat roof (0.29 L/min) and a green roof (0.21 L/min). A run-off reduction of 36% was recorded after the roof was fully drained.

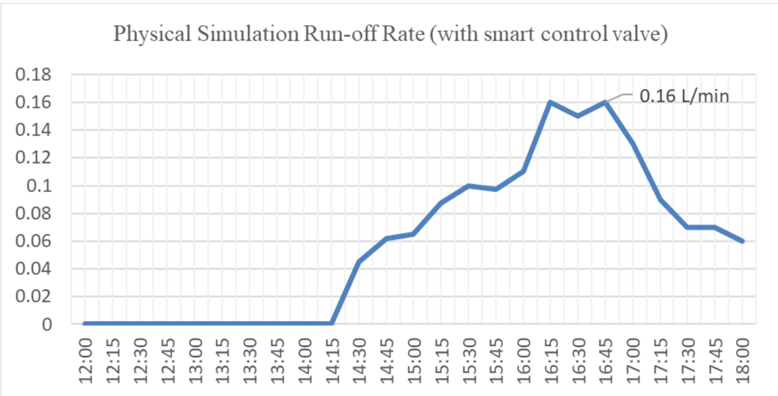

Figure 3. Physical simulation flow rate (Iteration 1).

4.1.2 Without Smart Control Valve

The second iteration of the test began at 11:00 and finished at 17:00, with dry weather present for the duration of the simulation. The flow rate is illustrated in Figure 3, with a peak run-off rate of 0.16 L/min recorded at 15:45. The reduction in run-off was reduced to 28%, which is lower than the 36% reduction recorded in the first iteration. A full summary of the two iterations is shown in Table 1.

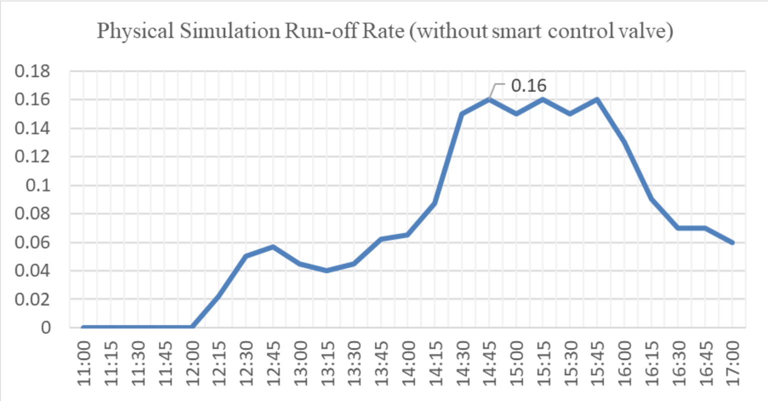

Figure 4. Physical simulation flow rate (Iteration 3).

TABLE 1. Physical Simulation Results Summary.

Prototype	Rainfall Volume (L)	Discharge Volume (L)	Max Run-off Rate (L/min)	Run-off Reduction Rate (%)
Flat Roof	60	Not measured	0.29	Not measured
Green Roof	60	Not measured	0.21	Not measured
Blue-green Roof (with smart valve)	60	37.5	0.16	36
Blue-Green Roof (without smart valve)	60	43.6	0.16	28

4.2 DIGITAL SIMULATION

The two results provided by the digital simulation analysis that are linked to stormwater management include: max outflow (run-off rate) and run-off reduction rate. Max outflow is an important factor regarding flooding on site, as when the run-off rate exceeds the site limit, pluvial flooding can occur. The run-off reduction rate is important on a larger scale as it indicates the percentage of run-off that exits the site after the storm, which in combination with large amounts of run-off from other sites can cause widespread flooding in urban areas. The outflow and run-off reduction calculations were measured from the final manhole which is connected to the combined sewer.

4.2.1 FSR Design Storm

For all four of the storm lengths included in this analysis, the blue-green roof reduced the max outflow significantly compared to the existing roof, which would mitigate any chance of flooding during these storm lengths. The blue-green roof caused the max outflow to be reduced to 1.55 L/s on average between the four storms, which is in line with DCC requirements of a max outflow of 2L/s/ha (Dublin City Council, 2021). The green roof still reduced the max outflow for the four storms; however, the blue-green roof is most effective at reducing peak run-off rate to reduce the chance of pluvial flooding on site. The run-off rate over time for the 15-minute storm is shown in Figure 4, with the peak runoff rate highlighted. Both the blue-green roof and the green roof delayed the discharge of run-off by 11 minutes, with the flow restriction of the smart control valve allowing the drainage layer to fill and discharge at a steady rate.

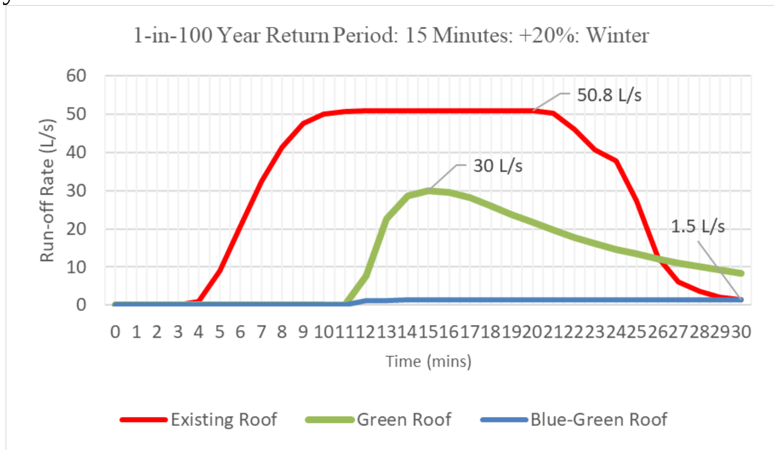

Figure 5. 15-Minute storm outflow comparison.

The run-off reduction rate was also significantly improved for all four storm lengths with the addition of a blue-green roof. For the 15-minute storm, the blue-green roof reduced the run-off volume by 97%, although this was reduced as the storm length increased, with an 85% reduction for the 120-minute storm. The green roof still reduced run-off rate: however, the blue-green roof reduces the percentage of run-off by an extra 30%, so there will be even less discharge entering the combined sewer. A summary of the 15-minute storm is shown in Table 2.

TABLE 2. 15-minute FSR Design Storm Summary.

Phase	Rainfall Volume (m3)	Discharge Volume (m3)	Max Outflow (L/s)	Run-off Reduction Rate (%)
Existing Roof	66.789	56.033	50.8	16
Green Roof	66.789	20.736	30	69
Blue-green Roof	66.789	1.765	1.5	97

4.2.1 Historical Storm

For the chosen storm event (October 24th, 2011) the blue-green roof reduced the max outflow significantly compared to the existing roof and the green roof. The recorded max outflow was 1.8 L/s which is also in line with DCC requirements of 2L/s/ha (Dublin City Council, 2021). The max outflow for the green roof was not reduced, as after four hours the green layer became saturated and matched the flow rate of the existing roof. This further highlights the effectiveness of the blue-green roof, especially for a longer storm. The run-off rate over the 12 hours is illustrated in Figure 5, where the blue-green roof and green roof delayed the discharge by four hours, with the outlet flow restriction allowing the blue-green roof to discharge at a steady rate whilst the green roof matched the outflow of the existing roof.

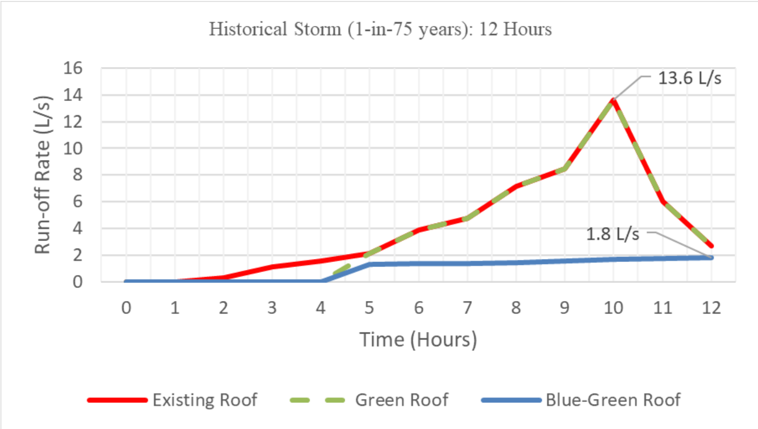

Figure 6. 12-Hour Historical storm outflow comparison.

The blue-green roof also significantly improved the run-off reduction rate compared to the existing and green roof conditions, with a 70% reduction in run-off after 12-hours compared to the green roof and existing roof. A summary of the historical storm results is shown in Table 3, and a summary showing the results with a 20% increase in rainfall depths to account for climate change are shown in Table 4.

TABLE 3. 12-Hour Historical Storm Results Summary.

Phase	Rainfall Volume (m³)	Discharge Volume (m³)	Max Outflow (L/s)	Run-off Reduction Rate (%)
Existing Roof	207.506	184.226	13.6	11
Green Roof	207.506	169.611	13.6	18
Blue-green Roof	207.506	61.958	1.8	70

TABLE 4. 12-Hour Historical Storm Results Summary (+20% for Climate Change).

Phase	Rainfall Volume (m^3)	Discharge Volume (m^3)	Max Outflow (L/s)	Run-off Reduction Rate (%)
Existing Roof	249.007	221.162	16.3	11
Green Roof	249.007	206.550	16.3	17
Blue-green Roof	249.007	63.545	1.9	74

4.3 Discussion of Findings

The results that were recorded from the simulation tests show a reduction in peak run-off rate run-off volume observed across the physical and digital simulation tests.

The first iteration of the storm simulation, which involved lifting the bucket to release the standing water from the previous day, reduced the peak run-off to 0.16 L/min with a 36% reduction in run-off. The run-off was delayed by 3.5 hours, which highlights the effectiveness of the green layer. The second iteration, which involved keeping the bucket on the outlet to prevent the release of the standing water also reduced the peak run-off rate to 0.16 L/min. However, the reduction in run-off was reduced to 28% which highlights the effectiveness of the smart control valve. These findings align with results reported by Shafique et al. (2016), who concluded that a blue-green roof prototype reduced peak run-off rate and run-off volume. It must be noted that Shafique et al. (2016) carried out the testing under real storm conditions, over a 10-day period. This study used physical simulation rather than a real storm however the results are still valid revealed that further restricting the flow of water using a smart control valve is an effective way to reduce peak run-off rate and limit the overload on the drainage system.

The digital simulation results were also positive. For the short, winter design storms the blue-green roof provided between 85% and 97% of a reduction in run-off, which was substantially more than the green roof and existing roof. The max outflow/run-off rate was also significantly reduced, which means any pluvial flooding due to the overload of discharge on site would be eliminated. The effect of the blue-green roof was further highlighted after completing the longer historical storm simulation, where 70% of the run-off was reduced, compared to only 17% for the green roof due to the saturation of the green layer. The blue-green roof was also the only system that reduced the max outflow, which highlights the green roofs ineffectiveness for the longer storms. For all the storm simulations, the max outflow from the site was reduced to meet the DCC requirement of 2 L/s/ha for new developments. Busker et al. (2022) also concluded that blue-green roofs with smart control devices performed well during extreme weather events in Amsterdam, with an

83% decrease in run-off. The digital simulation in this paper focused solely on a chosen site, whereas Busker et al. (2022) completed simulations using 27 roofs. Overall, the digital simulations confirm that blue-green roofs with smart control devices can decrease the rate of run-off and the amount of run-off entering the drainage system.

4. Conclusion

The aim of this research was to investigate if blue-green roofs with smart control devices can reduce the impact of pluvial flooding in Dublin.

Through the literature review, it was found that other countries such as the Netherlands and Canada have already commenced research and testing into these roof systems, and how they could be utilised in a practical manner to reduce pluvial flooding in urban areas. Regulations and guidance were also evident in other countries, with China implementing Sponge City regulations to provide a clear direction regarding blue-green infrastructure. This paper has shown that Ireland is significantly behind other European countries on the integration of sustainable drainage systems and modern technologies that aid in the prevention of flooding. A lack of leadership regarding Sustainable Urban Drainage systems (SUDs) is evident in Ireland, with no policy to promote SUDs retrofit to existing building stock (Council Journal, 2019). Consequently, there are many unused rooftops in Dublin with the potential to manage stormwater at the source, using blue-green roofs.

Physical simulation testing of a blue-green roof prototype was completed to compare the stormwater management capabilities of the system to a green roof, and a typical flat roof under storm conditions applicable to Dublin. An iteration with and without the smart control valve action was conducted to demonstrate how the valve can maximise the systems effectiveness.

Digital simulations using urban drainage analysis software were completed to determine if a blue-green roof can reduce the impact of pluvial flooding on a chosen case study site in Dublin. Three versions of the site were modelled: one with the existing roof, one with a green roof, and one with a blue-green roof. Storm simulations using rainfall data from the Flood Studies Report and Met Eireann were completed, with the max outflow and run-off reduction for each storm recorded. The positive results highlight how these roof systems can be used as a form of Sustainable Urban Drainage, on sites with a lack of available space for other SUDs features.

5.1 FURTHER RESEARCH

Further research using a blue-green roof prototype and an authentic smart control valve over an extended period would allow a full exploration of its effectiveness. Once prototype testing is completed, large scale monitoring on a full-scale roof system could be carried out once there is a concrete incentive to do so.

The digital simulations were conducted using a methodology unique to this paper, which involved using the tools available in InfoDrainage to recreate how a blue-green roof captures rainwater and release it to the drainage system. If more tools were available, an advanced hydrological modelling system like the one used by Busker et al. (2022) would have been used.

The range of potential benefits arising from the specification of blue-green roofs such as rainwater harvesting, cooling buildings to reduce cost and improving air quality in urban areas may also warrant investigation.

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THERMAL COMFORT IN BUILDINGS FOR OLDER PEOPLE: CASE STUDY OF A NURSING HOME IN BSHS CLIMATE

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Abstract. The recent pandemic has emphasised the importance of guaranteeing comfort standards in nursing homes for older people. Most buildings show a lack of air ventilation, a key aspect in terms of respiratory diseases and disease transmission. The object of this research was to test if nursing home buildings are adapted to the specific thermal comfort sensation that older people have in a Dry Mediterranean Climate such as in Alicante (Spain). A case study building was evaluated through analytical models, simulations and air flux diagrams based on BIM models and digital twins. A comparison was made to observe how the building architecture and passive strategies determine thermal comfort for nursing home residents. Ventilation and solar gains were also evaluated as factors that influence thermal comfort. Results show that older peoples' response to cold temperatures is worse than their response to warm temperatures, which they may be better at adapting to. Hybrid ventilation during winter reduces heat loss and cross natural ventilation during summer, with solar control, dissipates overheating and may improve comfort levels.

Keywords: Thermal Comfort, Rehabilitation, Ventilation, BIM, Older people, Nursing home.

1. Background

The health of the older population is especially vulnerable to environmental conditions. Many specialist buildings, such as nursing homes, have modernized and updated their conditions according to regulations, but without focusing on thermal comfort. This sector of the population tends to have a lower capacity for thermoregulation compared to most of the population (apart from very young children and babies). This means that older people are more sensitive to temperature fluctuations and may have difficulty adapting to severe temperature conditions (Hoof & Hensen, 2006).

An environment with extreme temperatures can have a negative impact on the health of the older people. Excessive heat can increase the risk of dehydration, heat exhaustion, and even heat stroke, as the ability to regulate body temperature is compromised with age. Additionally, high temperatures can worsen pre-existing medical conditions, such as heart or respiratory diseases, and may cause an increase in the frequency of fainting or dizziness (Carreiro-Martins et al., 2016; Teresa et al., 2021.)

Controlling an adequate thermal comfort can help to mitigate and prevent these health problems in the older population. Maintaining a moderate room temperature, controlling relative humidity, and ensuring adequate air circulation can contribute to overall wellbeing (Yang et al., 2016).

In this sense the Fanger Method can be used to accurately measure the degree of thermal comfort (Castejón Vilella, 1983). Thermal comfort is defined as a subjective sensation of satisfaction with the thermal environment (ASHRAE STANDARD 55 - 2020,2020). To measure thermal comfort, Fanger elaborated a procedure that involved different variables that influence the perception of thermal comfort (Fanger, 1973). Fanger´s model of comfort defines comfort through the Predicted Mean Vote (PMV) in a scale between -3 and 3, being -3 extremely cold and 3 extremely warm. Between -0,5 and 0,5 thermal comfort is considered maximum. At the same time, it is also defined the Predicted Percentage of Dissatisfied (PPD) as a percentage that must be below 10% to stay in thermal comfort. Although Fanger model hasn´t been updated, there are several new studies regarding different population strata supporting its validity (Wang et al., 2017).

However, older people have particular characteristics that should be considered. Metabolic rate is one of the factors considered by Fanger and it is heavily related to thermal comfort (Charles, 2003). As humans age their activity rate tends to decline (Henry, 2005; Pannemans & Westerterp, 1995) and this affects individuals' thermal comfort sensation. Therefore, buildings such as nursing homes should be designed to be focused on their specific thermal comfort sensation.

The aim of this research is to determine, through Fanger´s PMV and PPD, how elderly people may perceive thermal comfort in a case study building in Alicante. At the same time, it is the aim to define the difference between thermal comfort perception in adults and in the older population. Moreover, it is also intended to determine what type of ventilation fits better for nursing home residents and the influence of solar gains as key factors for achieving thermal comfort.

2. Methodology

The starting point of this research is a nursing home for older people located in Alicante, Spain. Alicante is in the south-east part of Spain in the BShs climate zone, within a Warm Semi-Arid Climate according to Köppen climate classification. It is considered as a moderated climate with mild winters and warm summer temperatures.

Extreme climate situations in Alicante are often related to high relative humidity (Chazarra Bernabé et al., 2022).

The building under research was built in the 1970s according to the building construction standards of the time. It has a gross floor area of 1600m2, with appreciable compartmentalization and few openings in the façade, as can be seen in Fig. 1. Enclosures are made of aerated ceramic brick with mortar coating. There is no thermal insulation in façades and roofs.

Figure 1. Floor plans of the elderly people housing

To evaluate thermal comfort in the case study building a digital twin based on a BIM model was created. Over this digital model, an iterative process has been developed with simulation performed with the software DesignBuilder. It is one of the most renown tools for performing building simulations based on EnergyPlus calculation engine. Calculations were made under the same ambient circumstances to compare the response of adults and elderly considering a metabolic rate of 43,5 W/m2 in adults and 37,5 W/m2 in elderly (Teresa et al., 2021.). To show graphically this variation in PMV, Computational Fluid Diagram (CFD) was made in a 3,5x3,5x3m room of the case study building with one person standing. Simulations were performed in the coldest (January) and warmest (August) days of the year.

Regarding ventilation, two different studies were conducted. The first one compares the relation between ventilation and its effect on thermal comfort over adults and older people. These simulations are based on the cooling effect caused by air flow and its effect quantified on the digital twin. The second part of the analysis evaluates what type of ventilation fits better for providing thermal comfort for older residents. In a similar way, the influence of solar gains on the feeling of thermal comfort that the residents may experience was evaluated. The other line of research relates ventilation and stale air. Using CO2 parts-per-million as a measure of how contaminated the air is, different types of ventilation and its impact were evaluated.

All the calculations were made without any air conditioning or heating system. Air renovation is set at 8,5 ren/h when produced mechanically. When produced naturally, this depends on external air velocity. Clo factor (clothes factor) was set at 1 for simulations made in January and 0,5 when simulations were made in August.

3. Results

3.1 EVALUATION OF THERMAL COMFORT ACCORDING TO THE BUILDING ARCHITECTURE

The evaluation of the building performance shows comfort situations outside the limits of 10% of Predicted Percentage Dissatisfied (PPD) established by the ASHRAE 55 (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard both for adults and for older residents, as can be seen in figure 2. It deeply depends in winter on the solar gains within the building, and in summer it stays very far of the limits.

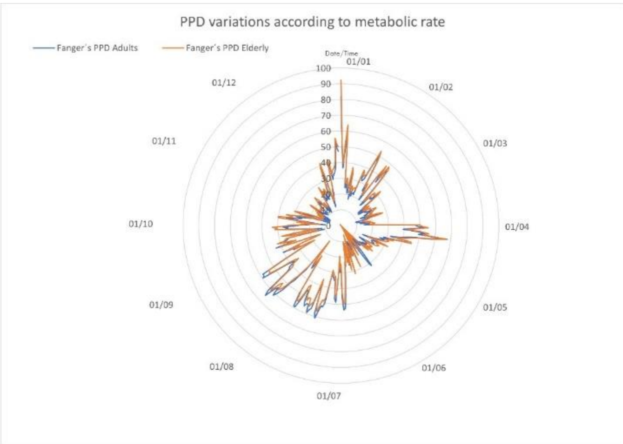

Figure 2. PPD in the case study building

The analysis of the Fanger’s PMV for winter and for summer and both for adults and for older people is shown at the Figure 3. On top (Augst 15TH), adult PMV range variates between 1,92 and 1,77. Meanwhile, for older people PMV fluctuates between 1,48 and 1,34. On the bottom (January 15TH) results are less evident due to the general low temperature, but adult PMV range variates between -1,54 and -1,36. Meanwhile, the PMV for older residents fluctuates between -1,91 and -1,73.

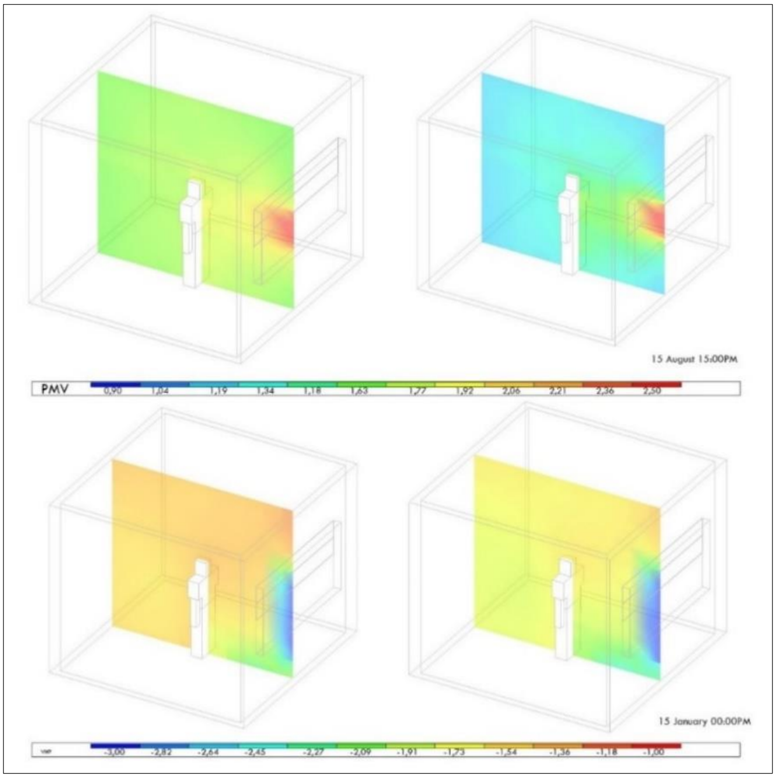

Figure 3. Predicted Mean Vote (left adults, right elderly)

3.2 VENTILATION AND ITS EFFECTS

For measuring ventilation impact CFDs were made comparing PMV and air velocity. For the investigation, air velocity has not been limited according to Spanish regulations. Figure 4 shows a CFD carried out on the night of July 15, where a decrease in PMV is expected due to the effect of natural ventilation.

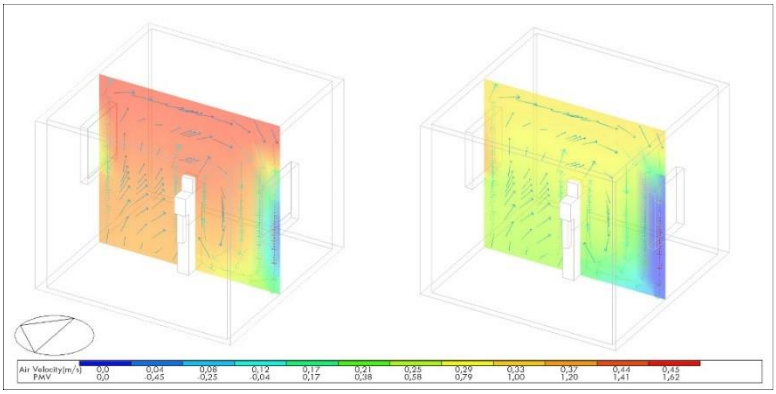

Figure 4. Comparison of air velocity effects on PMV (August 15 22:00PM) (left adults, right elderly)

As can be seen, ventilation produces a much more pronounced decrease in PMV in the sense of comfort of the older residents. The same air speed reduces PMV in the older population by up to 0.41 more than compared to adults. Therefore, the effects produced by air currents are much more pronounced in the older population. These results have been obtained by comparing cross ventilation, given that it is the system that produces the highest air velocity. To know which ventilation system is the most effective in local climate for increasing the thermal comfort of the residents, four different situations have been proposed that renew the air: simple ventilation, cross ventilation, mechanical ventilation, and hybrid ventilation (mechanical ventilation + 5% opening in window).

All four situations have been calculated with a 1,5x1m opening (cross ventilation with two equal windows with half surface). Mechanical ventilation and hybrid ventilation has been calculated with 8,5 renovations per hour, according to the Spanish regulations for older people housing.

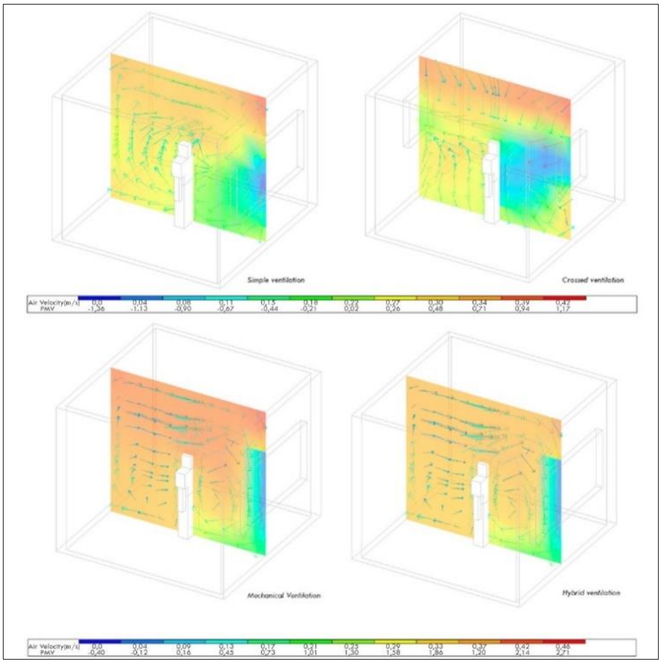

Figure 5. 15 August CFDs of PMV and air velocity 22:00 PM

As it can be seen in the figure 5, where it is compared PMV and air velocity in summer, On top left (simple ventilation), PMV surrounding the occupant range variates between 0,26 and 0,48. On top right (cross ventilation) PMV fluctuates between -0,67 and 0,25. On the bottom left (Mechanical ventilation) results show PMV between 1,58 and 2,14. On the bottom right (Hybrid ventilation) PMV variates between 1,58 and 1,86.

3.3 SOLAR GAINS AND ITS EFFECTS

Solar gains in the building has been analysed based on its present shape. In figure 6 the internal gains are the second most important heat gain in the building (as previously stated, heating devices were not considered).

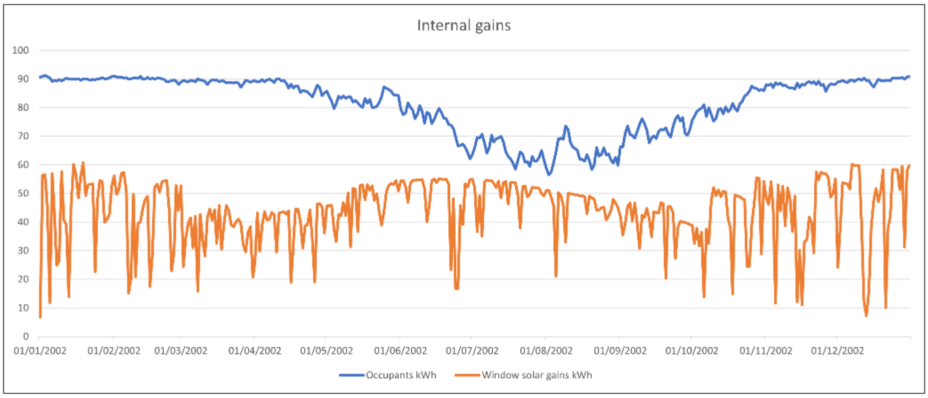

Figure 6. Internal gains in the case study building

Meanwhile occupant gains vary with number of hours of ventilation, solar gains variate with the number of hours of sun. Solar gains are reduced during spring and fall because of the greater number of cloudy days, while in summer and winter sunny days are more common. Figure 7 shows the difference between south-east and north-west solar gains. As could be expected, the south-east gains are from two to eight times larger. Solar gains in summer being lower than winter occasionally relates to the existence of overhangs and external objects than project shadow to the building.

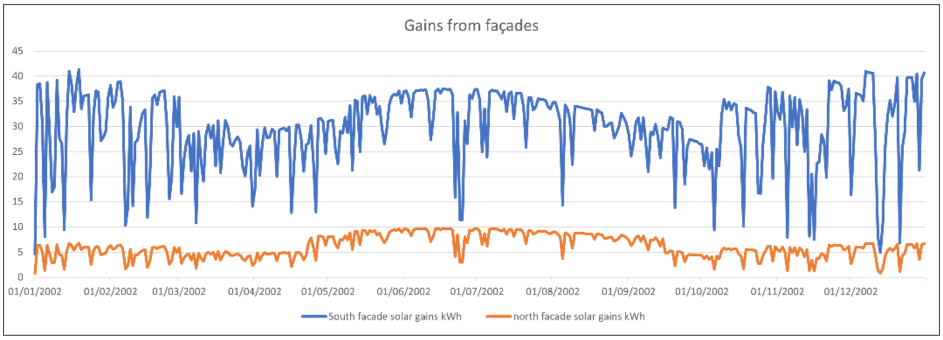

Figure 7. Comparison of solar gains according to the facade

To understand how solar gains affect thermal comfort depending on age, a comparison was made between the PPD of adults (Figure 8). For this, 4 days in winter have been chosen, 2 with high solar gains and 2 with low gains, and the PPDs of the older residents and adults have been compared. In Table 1 it can be seen that high solar gains in winter reduce the difference in discomfort between 0.3 and 0.5%. When low gains occur the sensation of discomfort is a 3% difference.

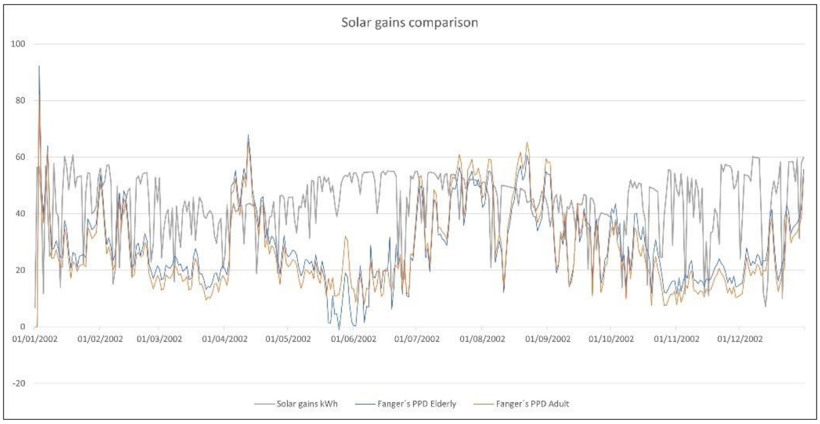

Figure 8. Solar gains and PPDs of elderly and adults

TABLE 1. Solar gains and thermal comfort in winter

	Date	Solar gains	PPD adults	PPD elderly
Low solar gains	05/01/2002	11,8341486	61,79752	64,02090132
	07/02/2002	15,161094	36,39674	39,35036908
High solar gains	19/01/2002	60,7602546	19,57626	21,01346154
	18/02/2002	52,3241856	24,83527	25,12128011

Four days have also been chosen in summer, 2 with high solar gains and 2 with low gains, and the PPDs of the older residents and adults have been compared. In Table 2 can be seen that high solar gains in summer produce a difference in comfort between 0.3 and 0.4%, while when low gains occur the sensation of discomfort is between 0.2 and 1% difference.

TABLE 2. Solar gains and thermal comfort in summer

	Date	Solar gains	PPD adults	PPD elderly
Low solar gains	25/06/2002	16,8213649	10,7697309	10,57331633
	05/08/2002	21,0278965	23,99233	22,77103195
High solar gains	18/07/2002	53,779941	52,2866499	51,94921209
	10/08/2002	50,0215956	22,9305493	23,33246577

3.4 AIR QUALITY

Regarding air quality three situations has been produced: simple ventilation, cross ventilation, and hybrid ventilation. All of them in the same room.

In Figure 9 it is possible to see that cross ventilation eliminates more efficiently air contamination as it is the scenario that refreshes the air in larger quantities. Simple ventilation turned out to be the least efficient. Adapting this data to the nursing home can provide a better picture of the efficiency of each system in the actual building.

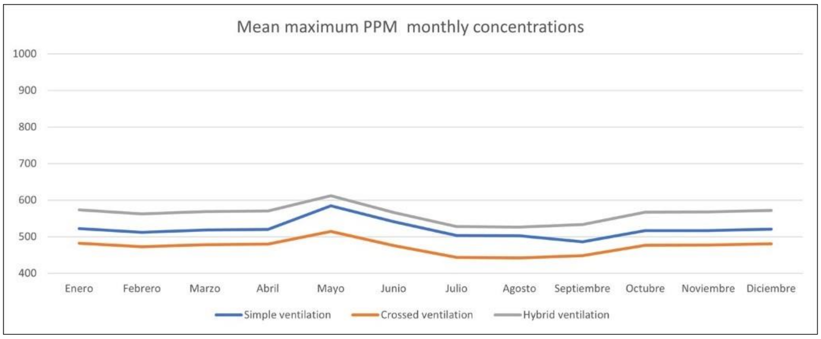

Figure 9. Mean maximum ppm of CO2 monthly concentrations in one room.

Actual nursing home air renovation depends on natural simple ventilation, which is the least effective air change system according to figure 10, this simulation is made in the whole building. A hypothetical situation has been tested doubling the percentage of window openings in the façades, proving to be the best system during 4 months of the year.

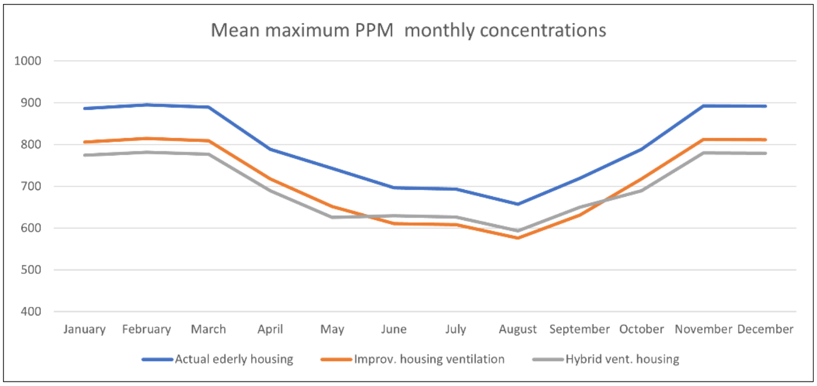

Figure 10. Mean maximum ppm of CO2 monthly concentrations in all the building.

Overall, hybrid ventilation is the most efficient way to renovating air when analysed from the air contamination point of view during the whole year.

4. Discussion of results

Results of the research confirms that in winter the response of the older residents to the analysed situations is worse than in the case of adults for thermal comfort. Older people PMV´s situates between 0.1, and 0.15 under adults PMV during winter (figure 11). In addition, older people PMV during summer situates between 0.14, and 0.2 under adults PMV.

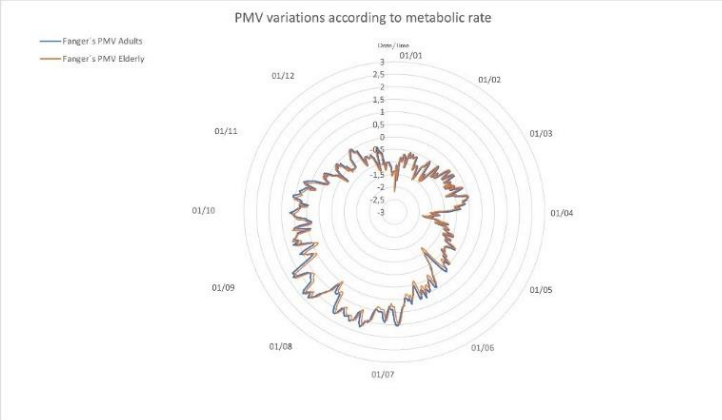

Figure 11. PMV variation

Solar gains produce an alteration in the sensation of comfort, having a more significant impact in winter, when low solar gains produce sensations of discomfort up to 3% lower in the older population compared to adults. While high solar gains occur in winter, the difference in PPD between the older residents and adults is smaller. In summer, the impact of solar gains in both age groups is low, producing comfort differences of less than 1% while high solar gains occur and 0.3% and 0.4% lower in the older residents when gains occur. The combined use of natural cross ventilation during summer (figure 10) and hybrid ventilation (figure 11) can provide a good renovation of air with a cooling sensation during summer and a limited loss of heat during winter. Hybrid ventilation reduces air contamination 28% respect mechanic ventilation.

5. Conclusions

In conclusion, building performance must be different when occupied by older residents compared to younger adults. Based on this simulation they require higher temperatures to reach comfort during winter and they adapt better than adults to warm temperatures.

It also has been shown that cross ventilation is the most recommendable system to reduce air contamination and to improve the thermal sensation during summer. Meanwhile, in winter, hybrid ventilation renovates air without lowering interior air temperature in excess compared to the other ventilation systems and dissipates better high CO2 concentrations.

Solar gains have a greater impact in winter than in summer. While in winter, days with little light may cause an increase in the feeling of discomfort in the older residents, in summer the solar gains have similar effects on the older residents and adults.

Further investigations are recommended to achieve a deeper understanding of older people’s thermal comfort issues regarding local climate and nursing homes.

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HISTORIC BIM WORKFLOW RUSSBOROUGH HOUSE INTERIORS – A CASE STUDY

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Abstract. Using the interior of Russborough House, an Irish Neo-Classical Building as a case study, a prototype for a Historic Building Information (HBIM) workflow was developed from data capture using laser scanning and also including a WEB dissemination tool for the virtual representation of the building. Laser scanning was used for automated data collection which is now accepted as a standard part of surveying alongside other techniques for historic building recording. Because of time and resource limits, a set of sample elements were developed in HBIM and not the full building. The modelling of partial elements of the historic structure confirms the use of existing workflows and illustrate the possibilities for producing conservation documentation from both the point cloud and HBIM. This study proposes an addition to existing HBIM workflow based on the use of Faro-Web for dissemination and access to the point cloud and laser scan data with the addition of access to conservation and project drawings.

1. Introduction

1.1. OVERVIEW OF STUDY

Historic Building Information Modelling (HBIM) is an extension of BIM that is specifically used for digitally managing and conserving architectural heritage and archaeology. HBIM involves the digital recording of historical buildings using remote sensing technologies such as laser scanning and digital photogrammetry, or a combination of digital surveying and manual techniques. The acquired survey data is then processed to improve data organisation and intelligence using BIM software platforms. The production of a virtual representation of a historic structure or object using HBIM workflows creates a digital repository and database which allows for wider dissemination. This study examined the existing workflow of HBIM as well as potential additions to the workflow as future work. Using the interior of Russborough House as a case study, the proposed workflow was followed from start, data capture, to developing a partial Historic Building Information Model (HBIM). The research methods used in this study consisted of mainly primary data capture using laser scanning and converting the point cloud using BIM platforms to a Historic Building Information Model. In the case of damage or destruction of Russborough House, an important Irish Neo-Classical Building no digital or 3D record data existed and in addition the existing survey information available was minimal.

1.2. AIMS AND OBJECTIVES OF STUDY

The aim of this study is to develop a prototype workflow for a partial Historic Building Information Model for Russborough House which can be used for the creation of documentation and as a digital record for use in the conservation of the historic structure. The HBIM workflow in this case consisted of a series of steps:

1. Carry out a laser scan survey of a part of Russborough House and establish a set of surveying procedures.

2. Develop and present a prototype HBIM workflow.

3. Propose a wider dissemination addition to the HBIM workflow based on open-source Faro Web platforms.

4. Outline as a discussion and for future work for a set of procedures for creating a 3D print from the survey data.

1.2. RESEARCH METHODS

In consultation with the Head of Collections and Conservation at Russborough House, three areas selected for scanning were the Entrance Hall, Saloon and Main Staircase. A full survey was outside the scope of this study. A survey of these rooms was carried out using a laser scanning instrument (Faro Focus 3D-S 120). Internally it took 24 scans and 4 hours to capture the rooms selected. All data capture took place on Monday February 13th, 2023, in Russborough House. The rooms were chosen for their particularly high level of plasterwork detail on the walls and ceiling. The laser scan survey data was cleaned and further processed within FARO software suite and imported into HBIM platforms described in the paper. A partial HBIM was produced for elements of the building because of time and resource limitations. Sample engineering and conservations drawings and documentation was developed from both the laser scan survey data and the HBIM. The use of Faro-Web platform was tested for dissemination and access to the point cloud and laser scan data with the addition of access to conservation and project drawings.

2. Laser Scanning Survey

2.1 LASER SCANNING

Laser scanning automatically records environments, structures, and elements of a building with high accuracy. Terrestrial laser scanning (TLS) is used for automatic collecting of survey data for modelling of existing buildings (Allen et al., 2003, Boehler and Heinz, 1999, Barber and Mills, (2007), Bernardini and Rushmeier, 2002).

TLS can automatically record millions of three-dimensional points on an object in near real time, collecting distances and angles from the sensor. Based on laser scan survey and recording of the interiors of Russborough House, a sample best practice is outlined. Russborough House was chosen as a case study, in particular the interior, the Entrance Hall, the Saloon and the Main Staircase. These parts of the house were identified as the rooms of most note at present by head of Collections and Conservation of Russborough House. There is no existing scan data for Russborough House therefore this survey will also exist as a survey and record of these parts of the structure to assist with future conservation. The data collected at Russborough House explores the possibilities for newer technologies in conservation.

2.2. PROCESSING LASER SCAN DATA

Although laser scanning captures 3D point clouds directly a number of pre-processing steps are still required. As most objects cannot be scanned from one single scan position, individual scans must be accurately combined and referenced together. This stage is called registration. This requires common targets or points to be identified in different scans. Developments in laser scan processing software have led to increased levels of automation for this step which includes automatic and semi-automatic target detection in separate scans. Automatic triangulation of 3D points can also be carried out to create a mesh surface model from the 3D point cloud. This 3D mesh surface model can then be used to generate orthographic images by combining the 3D surface model with 2D images. 3D mesh models can also be textured using referenced image data. 2D cut sections and 3D vectors can also be generated from the 3D point cloud or 3D surface model.

2.3. LASER SCAN SOFTWARE AND PROCEDURES

Processing of laser scans requires computing power; a desktop computer is preferable to a laptop allowing for overnight processing and avoiding work on the computer at all while it is processing. Faro's proprietary software is Faro Scene, which was used to process the scans. Cloud-to-cloud registration is where the software uses common points between scans to automatically place the scans correctly in relation to each other. If an area being scanned is very bare or if scanning outside, for example as part of a topographical survey, it is essential to use targets to help the software to correctly connect the scans. Even with targets the software is not guaranteed to match up all scans correctly and this process must be checked. In Figure 1, the range of scans are illustrated, whereby the software uses automatic registration, visual registration, and manual registration. Visual checks must be carried out to finalise scan registration to ensure that the data has been processed correctly.

Once, the initial processing has taken place, the data needs to be reviewed to check if the scans are registered correctly. It is important to check the scans in plan and section view as sometimes the plan can look correct, but the elevation of a scan may be off which will cause it to not register correctly. If it has not registered correctly, the scans can be manually moved in any direction including being rotated and then attempted to process again. This can be done in smaller batches, adding scans as each set is registered. Individual scan positions can be viewed in figure 2, the view from the exact position of the scanning instrument is illustrated with magenta circles.

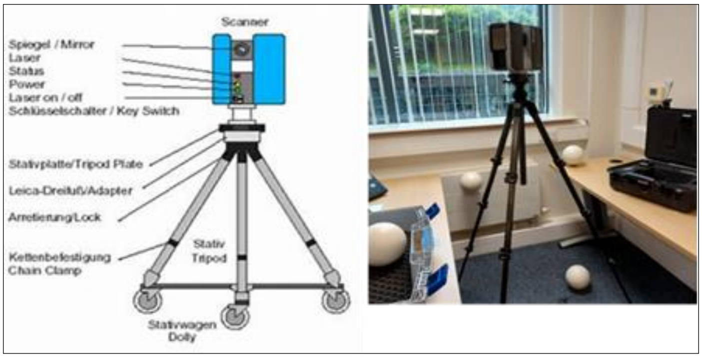

Figure 1. Diagram of Laser Scanner (left in figure) and Faro Focus 3D scanner.

Figure 2. Position of spheres showing scan positions

3. A Prototype Historic BIM Workflow

3.1. HBIM DEFINITION

The process of applying Building Information Modelling (BIM) for historic structures begins with capturing data on the geometry and texture of the building using laser scanning or digital photogrammetry. This captured data is then converted into solid Building Information Models (BIM), which is referred to as Historic BIM in the case of historic structures. BIM refers to a virtual representation of a building, which includes information related to its design, construction, and future lifecycle, also known as metadata. This information can range from geometric and spatial to material, structural, environmental, cultural, and economic. The BIM model consists of intelligent objects that represent the elements of a building structure and are organised within a 3D virtual environment (Banfi et al. 2017, 2018, 2019, 2020)

Historic Building Information Modelling (HBIM) is an extension of BIM that is specifically used for managing and conserving architectural heritage. HBIM involves the digital recording of historical buildings using remote sensing technologies such as laser scanning and digital photogrammetry, or a combination of digital surveying and manual techniques. The acquired survey data is then processed to improve data organisation and intelligence using BIM software platforms. However, accurately representing the complex and irregular objects present in historic buildings can be challenging, and existing BIM libraries of parametric objects may need to be rebuilt and coded. Additionally, systems have been developed to map intelligent library objects onto digital or other survey data to overcome these challenges (Murphy et al. 2019, 2012, 2013; Fai et al. 201; Oreni et al 2014;). A current limitation of HBIM is the lack of modelled parametric families available. In the Figure 3 below, an example of the Historic BIM of Leinster House the Irish House of Parliament is illustrated (Murphy et al 2019, Dore et al. 2017). The inputs which are the Laser Scan Survey of the building and the associated historic data which can consist of historic drawings, text, surveys, and maps relating to the building. This data set is imported into BIM and plotted to create a solid 3D model. in addition to the geometric data and texture of the building structure. The initial output is the Historic BIM of Leinster House which can be associated with the historic data as a repository of information. The final output is the documentation and record of the building in the form of orthographic drawings plans, elevation, sections and 3D details which in this case include the laser scan point cloud of the internal parts of the building which is merged with the external part of the building which is a solid HBIM (Figure 3).

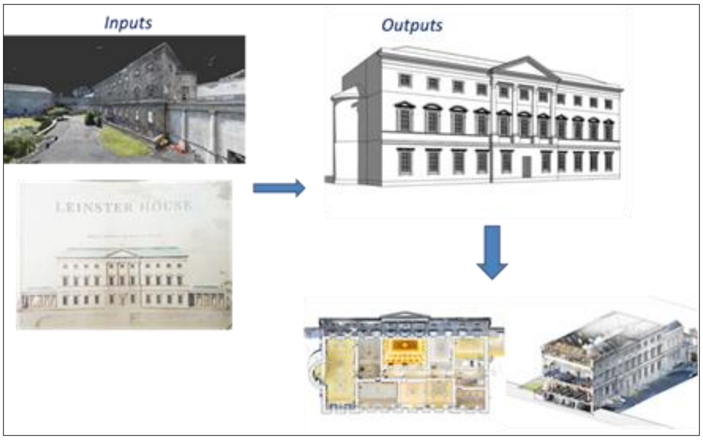

Figure 3. Laser Survey and Historic BIM of Leinster House

Figure 4. Fully Registered Point Cloud External and Internal

3.2. POST PROCESSING POINT CLOUD FOR HBIIM

Proprietary software for laser scanning instruments carries out much of processing the point cloud in terms of registration, quality and colour and if required meshing and texturing of the point cloud. it is also necessary to use additional software platforms for post processing for developing Historic BIM. In the case of this project Autodesk ReCap was chosen for post processing. The stages for preparing the point cloud for developing Historic BIM are as follows:

1. Registering all scans from different positions (Figure 4 above).

2. Isolating scan areas from the whole data set see (Figure 5).

3. Removing unwanted data described as noise see (Figure 6).

4. Exporting the point cloud as native file types suitable for BIM platforms.

5.

ReCap an Autodesk software platform is an acronym for reality capture and is used for processing point cloud data to prepare it for use in 3D CAD and BIM applications. The software facilitates filtering the point cloud to get rid of unnecessary data and work with the large data sets reducing their size to make them more manageable. Management of the data can also include breaking the data into building elements or parts of a building (floors, blocks etc.). The native ReCap file format can be used in Autodesk BIM software Revit or in 3D CAD for plotting parts or the whole building or elements of the building. The level of accuracy and detail in the point cloud will depend on the level of detail required for a project. Point clouds start as binary files directly from the scanner and when registered the file is exported as a suitable file format from the registration software. The scan files are further processed in ReCap software platform and exported as specialist point cloud files for developing a Historic BIM. This process is carried out by selecting the unwanted points and deleting them. Once the scans have been registered and processed further in ReCap they can be exported into BIM in this case the software platform Revit. It is important to sample the point cloud when exporting from the laser scan processing software as the file size can be very large and unmanageable. By sampling the point cloud, a suitable resolution can be established, which is determined by the number of points and the distance between the points in the data.

Figure 5. Isolating Parts of the Point Cloud in ReCap.

Figure 6. Removing Unwanted Data from the Point Cloud in Autodesk ReCap

3.3. HBIM WORKFLOW

Revit BIM software which has an option specifically for importing point cloud is used to develop the HBIM. The point cloud when imported into Revit can be viewed and library or 3D objects plotted onto it in 3D or 2D whereby locating various correct orientations of the point cloud. In 3D, a section box can be used to view segmented areas. Section and elevation views can be added and edited in the plan view again for various orientations of the point cloud. Revit is primarily a modelling tool for parametric and geometric shapes. It is possible to model the curved surfaces such as the stucco work on the walls and ceiling by modelling in place with specialist tools inside or outside of the software platform. It is important to consider the purpose of the survey data when choosing the level of detail for a HBIM. A survey for building maintenance does not require the same level of detail as one for detailed building records.

Objects can be built from the existing BIM libraries or where deformations or irregular geometry exists, meshes built from the digital survey data can be employed. The

variety of complex and irregular objects found in historic buildings are not available in existing BIM libraries. Therefore, parametric library objects need to be rebuilt and coded for Historic Structures. Original and early HBIM research concentrated on developing reusable parametric library objects (Baik et al., 2014, 2010, Fai and Rafeiro, 2014, Murphy et al., 2013, Diara and Rinaudo 2022 a and b, Dore and Murphy 2015). The complex parametric objects created by Fai & Rafeiro (2014) were developed for the Autodesk Revit BIM software. Baik et al. (2014), (also for Autodesk Revit BIM software) built parametric objects for heritage projects in the Al-Balad district of Jeddah City. A new process for developing a library of parametric objects was created by Chaw et al. (2015) for the Canadian Parliament buildings in Ottawa. The earliest work on HBIM parametric libraries were initiated by Murphy et al. (2012, 2013). The focus of this research was the modelling of classical architectural. The form and detail for the library of architectural elements were based on details from historic manuscripts and architectural pattern books using an embedded programming language within the ArchiCAD BIM software called the Geometric Description Language (GDL). Also included with this library of objects is a system for mapping objects to survey data.

In Figure 7 a series of steps are illustrated for processing the point cloud in ReCAP and mapping library objects onto the point cloud to create a partial HBIM from the scan data. In Figure 8, a sample produced in Revit for the automatic production of documentation such plans, elevations etc. are developed from the point cloud. In Figure 9, the automatic production of external and internal scaled elevations from the point cloud in HBIM is illustrated, a sample of internal and external elevations are automatically produced from HBIM.

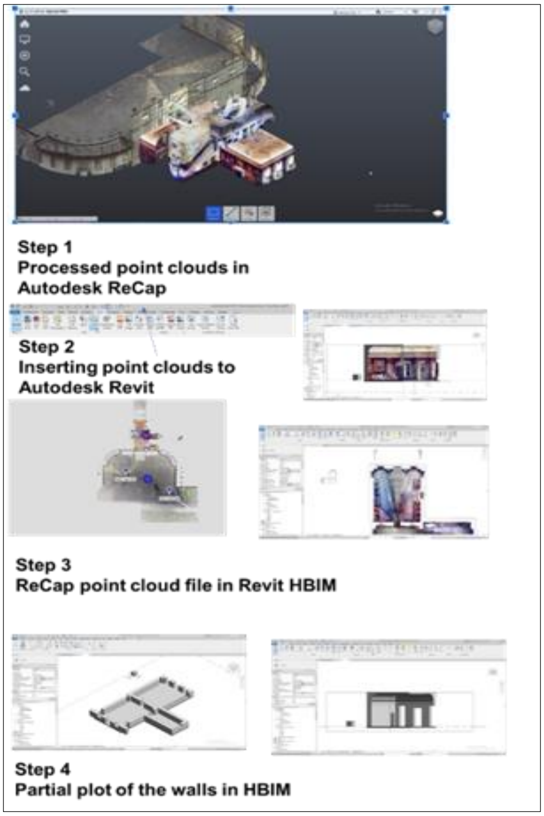

Figure 7. Steps in the development of HBIM from point cloud, part of the walls is plotted onto the point cloud giving the option of producing both a scaled point cloud plan (bottom right) and a vector plan (bottom left).

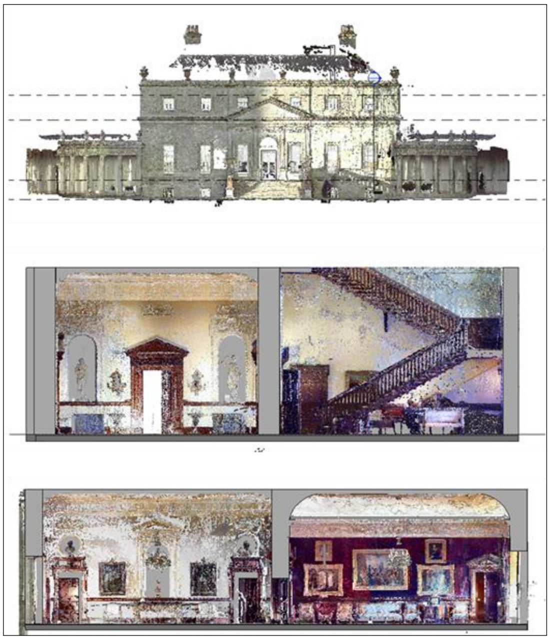

Figure 8. A sample of internal and external elevations from point cloud

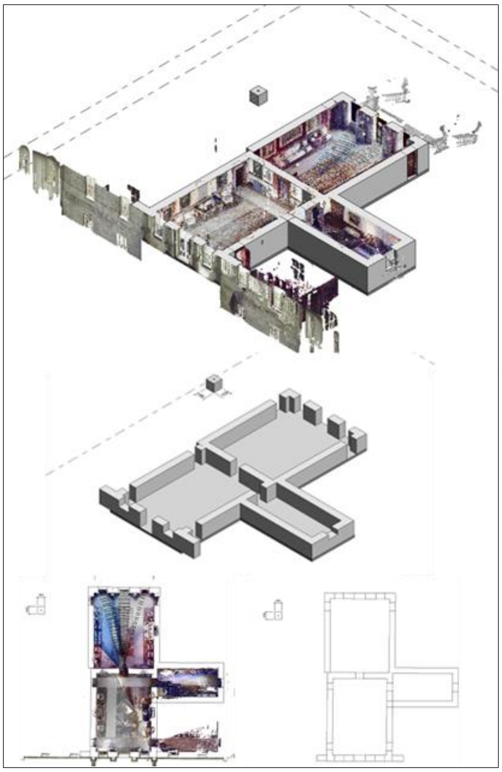

Figure 10. Plans and 3D Details from HBIM

The top figures in Figure 10 are 3D details which are also useful for conservation documentation.

3.4. HBIM **WEB FOR WIDER DISSEMINATION**

It is not always possible for wider dissemination of laser scan data, 3D models and their semantic attributions because HBIM is based around expensive software platforms, long training periods and powerful computing. Several solutions are available which range from dissemination of 2D and 3D conservation drawings as PDF or native CAD formats to using open-source software (Diara and Rinado 2020 a and b). The manufacturers of the laser scanning instrument used, Faro have their own WebShare software called Faro WebShare (Faro Sphere) which provides an online viewer for the point cloud. This means that anyone with an internet connection can view the point cloud without the need for specific software or a high spec computer. The WebShare also allows the taking of measurements, viewing where the scans were taken from exactly and showing both colour and black & white data (if it was captured). As Faro WebShare supports 3D viewing of the point cloud and other 3D makes it accessible to anyone with Web access (see Figure 11). Faro Webshare provides many of the capabilities to exploring the data as their proprietary personal computer software (Faro Scene) once the scans have been processed and uploaded.

Both colour and black and white point clouds, panoramic photographs and scan positions can be viewed. It is possible to move between scans by selecting another scan location and choosing the view required. By selecting the 'i' icon the information for that particular scan is shown on screen which also includes title, panoramic image and scan position and selecting the 3D icon displays the point cloud data for the scan area selected. A map icon shows the location of the scan in orthographic plan view to assist with navigation around the data in 3D.

See overview of scan data from Russborough House as viewed in Faro Sphere, Faro proprietary web-based point cloud viewer at:

https://russborough.websharecloud.com/?v=om&t=p:default,c:overviewmap,h:f,m:t,pr:t&om=om1&om1=auto:t&p=p:russborough-house

A second option for wider dissemination is to convert the laser scan point cloud to a textured mesh object which involves joining the points in the cloud with polygons which recognise and create a correct surface which is then textured with associated image data. The process is complex using a series of algorithms which can implement these procedures. MeshLab is an open-source software platform which can convert the point cloud to a solid 3D object which can then be viewed and further processed in a wider collection of open-source or low-cost 3D software platforms such as Sketchup (see Figure 12).

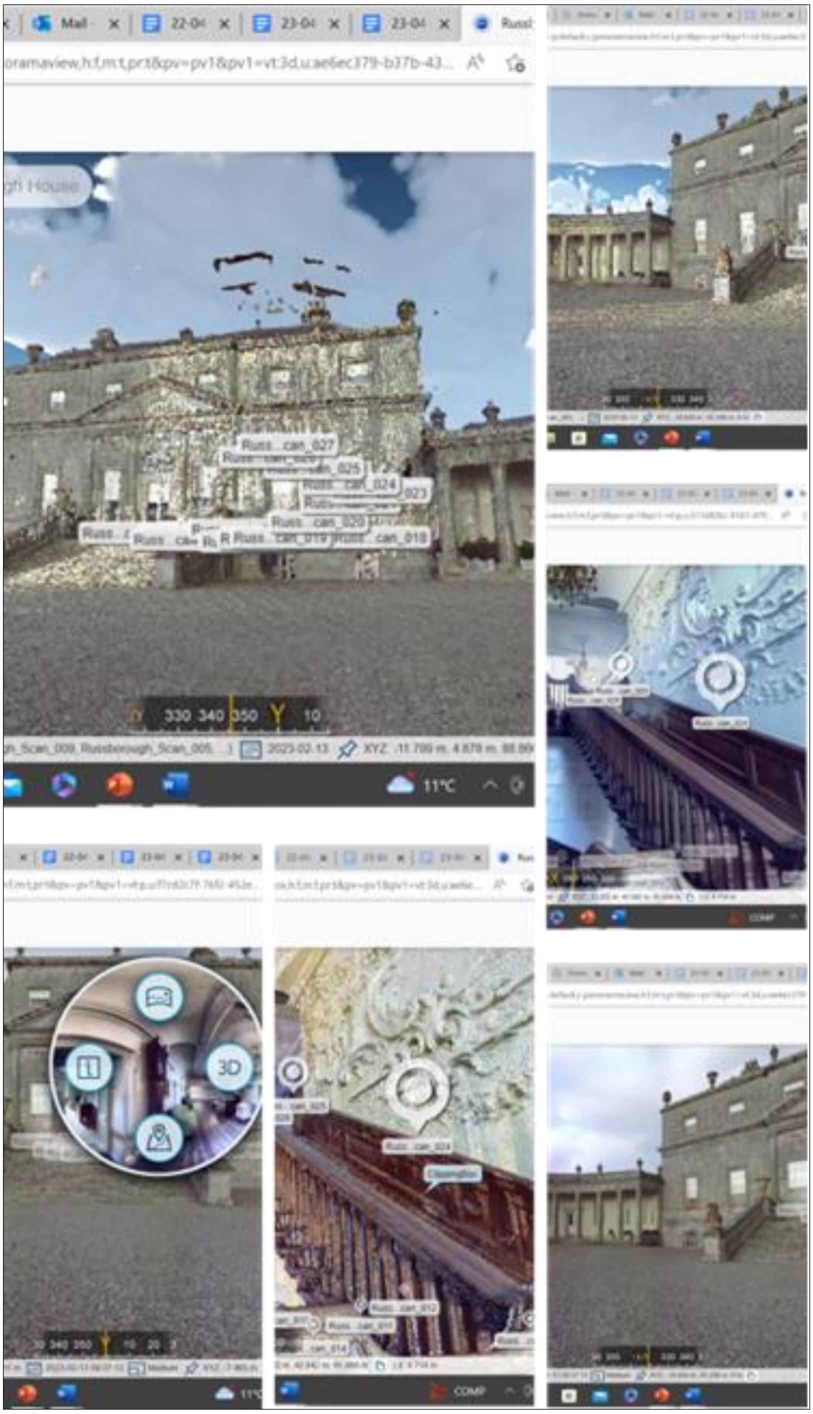

Figure 11. Web-share Dissemination Software (Faro Sphere) Provides an Online Viewer for The Point Cloud.

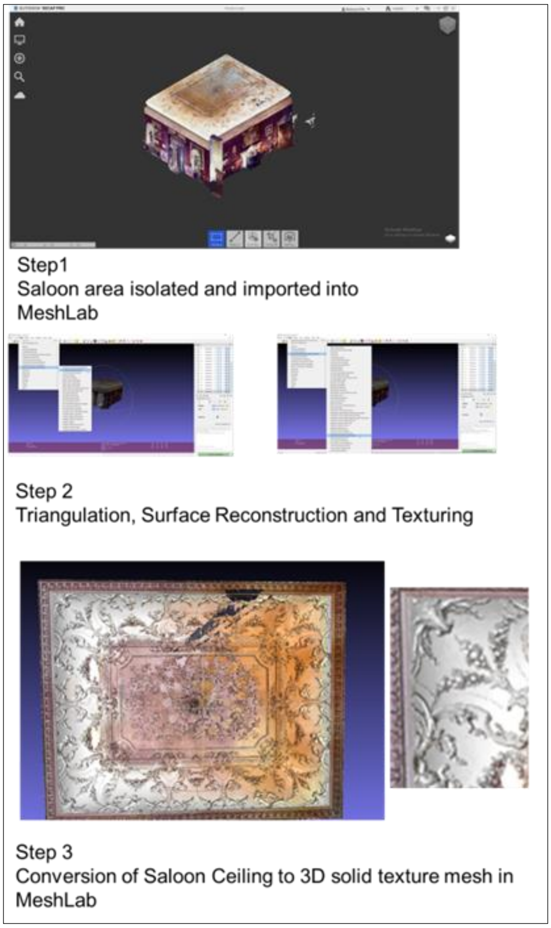

Figure 12. Steps in Converting Laser Scan Point Cloud to Solid Object in MeshLab

4. Conclusion

4.1 DISCUSSION

In addition to laser scanning digital photogrammetry can be used to capture the existing objects or structures but was outside the scope of this project. The wider area for producing a detailed digital twin of a historic building was outside the scope of this study but should be considered for future research and perhaps as an addition to the HBIM workflow. The role of HBIM can add greatly to the digital twin as a repository containing the physical form, texture and geometry and all other historic text, drawings, maps and film for historic structures and objects. The wider dissemination using open-source Web or modelling platforms provides a new level of accessibility to this information and the space for collaboration between professionals that was not previously possible. The fire and the damage to Notre Dame Cathedral resulted in the loss of much of the structure and its decoration and detail. Notre Dame was surveyed and scanned and a HBIM was created, see Figure below.

4.2. HBIM ACCURACY

The level of detail required for surveying and modelling historic structures is influenced by the use, requirement and intention of the model. Challenges during the survey and analysis stages, may not be attainable until after these stages are completed. For historic buildings, this task can be particularly labour-intensive, as the irregular shapes and varying conditions of the building's components may not easily conform to the rigid presentation requirements of HBIM. A guide to accuracy of Laser Scanning and Resolution in relation to drawing scale is detailed in the tables below to assist with establishing Level of Detail (LOD) (Historic England 2018).

TABLE1. Precision requirements for producing scaled drawings and documentation from HBIM as recommended by English Heritage [10].

Precision

Required maximum tolerance for precision of detail

scale	*acceptable precision (1 sigma)*
1:10	+/- 5mm
1:20	+/- 6mm
1:50	+/- 15mm
1:100	+/- 30mm
1:200	+/- 60mm
1:500	+/- 150mm

TABLE 2. Accuracy of Laser Scanning and Resolution in relation to drawing scale

	Scale	Effective point density	Precision of measurement
Close-range	1:5	0.5mm	0.5 mm
	1:10	1.0 mm	1.0 mm
Terrestrial	1:20	2.5 mm	2.5 mm
	1:50	5.0 mm	5.0 mm
	1:100	15.0 mm	15.0 mm
Aerial	1:200	30.0 mm	30.0 mm
	1:500	75.0 mm	75.0 mm

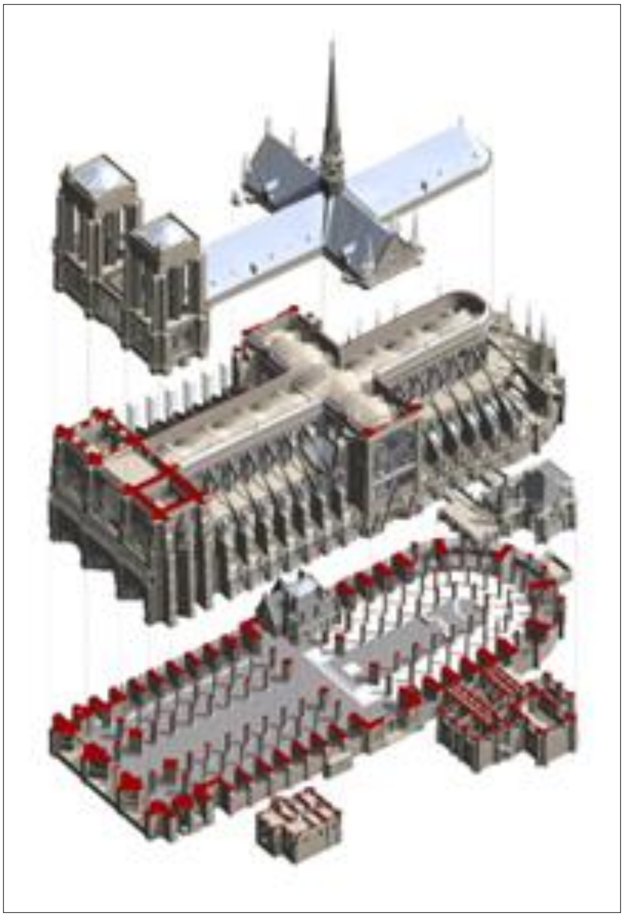

Figure 1.: HBIM of Notre Dame

4.3. CONCLUSION AND RECOMMENDATIONS

The existing HBIM workflow consists of data capture of the existing structures, creating a 3D virtual model and repository of existing related information (see Figure 14). A final stage is dissemination using HBIM dedicated or open-source software. The accuracy for data collection demonstrated in this study confirms laser scanning as a suitable standard for historic building surveying and recording. The sample elements developed in HBIM illustrate the possibilities for producing conservation documentation from both the point cloud and HBIM. Faro Web-based dissemination allowing access to the point cloud and laser scan with access to project drawings is an addition to existing HBIM workflows.

4.4. FUTURE WORK - DIGITAL FABRICATION

3D printing, or additive manufacturing, is the process of making a solid object using a digital 3D computer model and can be considered as a future element within the HBIM workflow. In the early 19th century, conservation experts popularised the method of taking plaster casts to record important but vulnerable ancient sculptures in situ (Payne 2017). Laser scanning can replicate the geometry and texture information of architectural features, a mould for a plaster cast can be produced from the laser scan data using digital fabrication. Much like the project undertaken in the restoration of the capitals at the Four Courts in Dublin, there is most definitely still a place for skilled artisans in these projects. In the case of the digital fabrication of the Corinthian capital of the Four Courts Dublin (Unpublished Work Office of Public Works 2018) the capital were digitally manufactured as a basic shape representing the regular geometry and the detail of the leaves and other elements were finished by hand by stone carvers (see Figure 15).

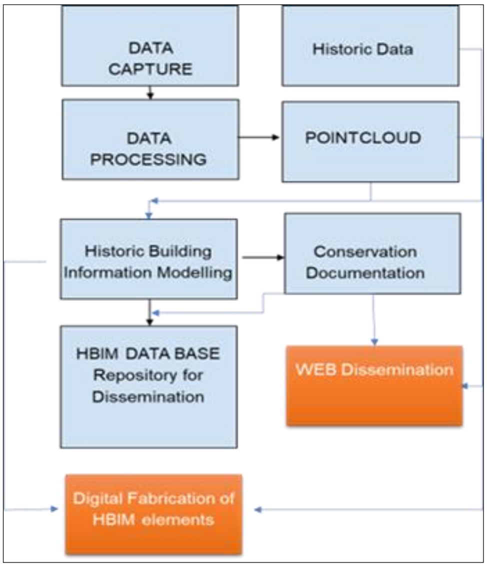

Figure 14. Proposed addition to HBIM workflow in orange and existing workflow in blue

Figure 15. Digital Fabrication of Corinthian Capitals Four Courts Dublin

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ReCap Software | Get Prices & Buy ReCap Pro 2023 | Autodesk
Revit Software | Get Prices & Buy Official Revit 2023 (autodesk.com)
SOLIDWORKS

ANALYSIS OF THE PERCEPTION OF THERMAL COMFORT IN SPANISH SHOOL CHILDREN COMPARED TO ADULTS

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Abstract. Thermal comfort is an essential factor when designing or remodelling an educational centre, since it helps to improve the school environment, while contributing to wellbeing and academic performance. However, little attention has been paid to the assessment of thermal comfort level in school children. Previous studies have mainly focused on the perception of adults, extrapolating their results to all ages. This research aims to determine whether children and adults perceive thermal comfort similarly. To achieve this objective the Fanger Method was used, and school children of different ages were surveyed to discover how factors such as air temperature, humidity, the activity they are doing, clothing and solar radiation in the classroom influence their perception of thermal comfort. Comparing the survey results to those obtained by the Fanger Method highlights a difference between how adults and children perceive thermal comfort.

Keywords: Thermal comfort; Fanger Method; Education; Children Comfort.

1. Background

Thermal comfort is the state of mind that expresses satisfaction with the thermal environment and is assessed through subjective evaluation (ASHRAE, 2020). It is a factor that influences the design of buildings and conditions the design and operation of mechanical conditioning systems (HVAC). Interest on the part of the agents involved in the construction process is increasing (Nicol and Roaf, 2005; Nicol and Humphreys, 2002) and has its origin in the studies carried out by Baruch Givoni (Givoni, 1992), P.O. Fanger (Fanger, 1967) and Victor Olgyay (Olgyay et al., 1963) .

Numerous studies have been conducted to understand how factors such as air temperature and speed, humidity, solar radiation, activity, and level of clothing influence thermal comfort (K. E. Charles, 2003; Hudie, 2016; Roghanchi et al., 2016; Srivajana, 2003). There is a general agreement that adequate thermal comfort has a positive impact on people's health. Additionally, new research has established that extreme temperatures can cause fatigue, sleep problems, and heat stress. Conversely, inadequate thermal comfort may have a negative impact on cognitive efficiency, work productivity and user satisfaction (Frontczak and Wargocki, 2011).

It follows that there must be a direct relationship between thermal comfort, sustainability and energy efficiency, with architectural design being a key factor to achieve harmony. In this way, bioclimatic designs, the use of natural cross ventilation and the integration of renewable energies have become very common strategies that are applied in different types of architecture (d'Ambrosio Alfano et al., 2013; Muñoz, 2018).

Despite efforts to improve thermal comfort in all types of buildings, it is considered that little attention has been paid to the evaluation of the level of thermal comfort in children and their work in schools. Most of the existing research has studied thermal comfort in adults, the results of which have been extrapolated to children. However, the physiological and behavioural characteristics are different between adults and children, so it can be concluded that their perception of thermal comfort will be different (Naidin et al., 2015).

It has been confirmed that children have a greater tolerance to lower temperatures than adults (Antoniadis et al., 2020), they have a greater range of temperatures in which they feel comfortable (Chen et al., 2022) and their limits to comfort levels can be up to 2 degrees lower than in adults (Teli et al., 2012). Moreover, the interest has been demonstrated not only in understanding the differences between how adults and children perceive thermal comfort but also between children of different ages (Teli et al., 2013). On the other hand, it has also been explored how natural ventilation benefits the development of children and influences their thermal comfort (Lala and Hagishima, 2022).

Therefore, it is considered that research on thermal comfort in children should be deepened with the aim of understanding the child's needs and applying this knowledge in new architectural designs and strategies to provide children with an ideal environment in which to study.

2. Methodology

The method is based in an iterative process in which on-site measurements and surveys are carried out in relation to a case study building. With this method it is intended to evaluate if thermal comfort is perceived differently by adults and children. The steps of this study are described as follows:

1. Definition of the case study. The primary school "Nuestra Señora del Carmen" was selected due to the need to improve energy performance under public funding calls. It is located in Orihuela, a warm-weather area of the south-east part of Spain where

cross-ventilation and thermal mass are responsible for providing thermal-comfort in the warmer part of the academic period.

2. Definition of the real case study construction data and existing HVAC systems.
3. On-site measurements of temperature, radiant temperature and relative humidity in different classrooms.
4. Surveys by age groups were carried out to evaluate the children's thermal comfort levels.
5. The results were analysed to establish the perceived thermal comfort of the different age groups.

2.1 THE CASE STUDY

The Nuestra Señora del Carmen school is located in the historic centre of Orihuela. It was built in the 1950s and its construction characteristics are in accordance with the techniques used at its time. In the southeast of Spain, priority has traditionally been given to the behaviour of the building in the warm period of the year, entrusting its operation to natural ventilation and energy loss through the building envelope. Thus, the building was designed and built without mechanical air conditioning or thermal insulation. To guarantee comfort in the cooler winter months the building has a boiler and radiators to provide radiant heat to the interior.

Figure 1. North Façade

Figure 2. Floor Plant

2.2 EVALUATION OF THERMAL COMFORT

To evaluate the children's thermal comfort levels in the school the Fanger Method scale and comfort limits was used. This method is widely recognized in the field of thermal comfort assessment. It is based on calculating the Predicted Mean Vote (PMV) index. A metric that quantifies occupants' perception of thermal comfort based on various parameters, such as operative temperature, humidity, clothing level, the level of physical activity the subjects are engaged in, etc. The PMV scale ranges are -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), +2 (warm), +3 (hot). The values closer to 0 indicate higher comfort defining the thermal comfort limits between +0.5 and -0.5 (Fanger, 1967).

To compare results, the limits established by ASHRAE 55 Adaptive Method were also considered, which range from -1 to +1. This method is very useful in the evaluation of buildings where people are able to interact with construction solutions that improve thermal comfort (ASHRAE, 2020).

2.3 SURVEYS

Surveys were conducted once a month from February to June to include students aged between six and 16 years. Surveys were anonymous and reached a total of 467 students. This represented approximately 87% percent of the school's student population. A total of 1,309 surveys are carried out, of which 95% of the surveys are valid. The remaining 5% are discarded due to inconsistencies in the answers. Children under the age of six were excluded due to their limited understanding of the questions and thermal sensations. The research design was approved by the ethics committee of the University of Alicante.

The surveys were adapted to various comprehension levels based on the students age and are divided as follows:
a) Children aged 6 to 8 years – Survey A (Fig. 3)
b) Children aged 9 to 11 years – Survey B (Fig. 3)
c) Children aged 12 to 13 years – Survey C (Fig.4)

d) Children aged 13 to 16 years - Survey D (Fig. 5)

All surveys asked identical questions, but the language and explanatory illustrations were adapted to the age of the respondents. Additionally, Type C and D surveys were conducted online, allowing students to respond via their laptops and smartphones.

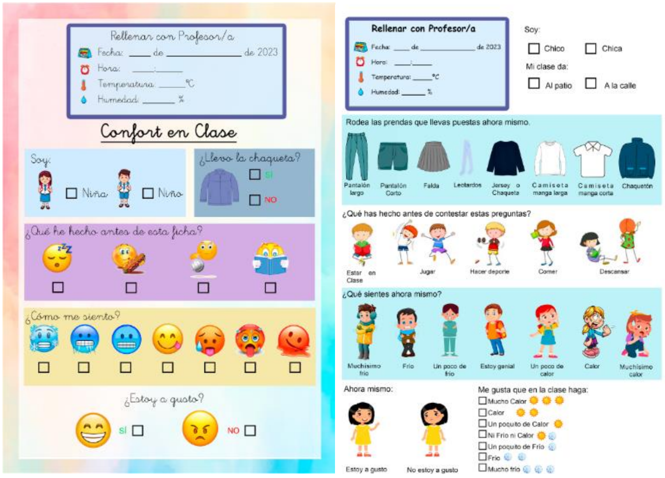

Figure 3. Surveys A and B

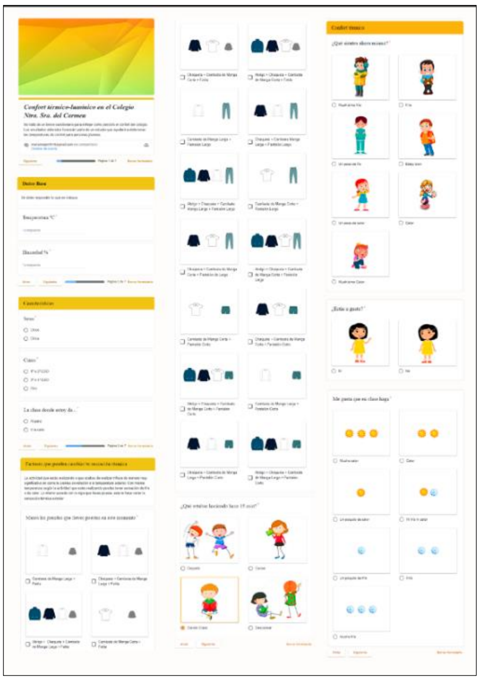

Figure 4. Survey C

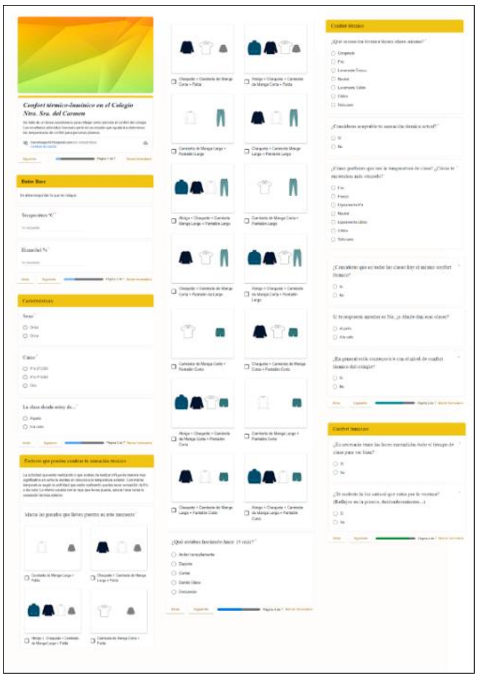

Figure 5. Survey D

The surveys comprised two parts. The first part included the interior conditions of the building, which were recorded by the interviewer supported by on-site measurements (Fig. 6). The instruments were turned on for five minutes before taking measurements to ensure that they were calibrated. Measurements were taken in the centre of the classrooms, far from direct sunlight to avoid any external influence. (see Table 1).

TABLE 1. Summary of measuring instruments and their characteristics

Measuring Instrument	**Model**	**Measuring Range**	**Accuracy**
a) Thermal Transmitrance Flow Meter	Testo 435-2	-20ºC to 50ºC	
b) Humidity/Temperature Probe	Testo	-20ºC to 70ºC	± 0.3ºC
		+10% to 100%	±2%HR
c) Black globe temperatura probe	Testo	+0 to-+120 ºC	Class 1(EN 60584-1)

The second part of the survey asked children about the factors that significantly influence thermal perception. The Fanger scale was adapted to ensure that the children could comprehend it. Students indicated their thermal sensation, as seen in Fig. 6, which was subsequently translated to the corresponding level on the Fanger scale.

Figure 6. Measurements and Surveys

2.4 DATA PROCESSING

The results of the student's thermal sensations were analysed and ordered according to the Fanger scale and related to the operative temperatures recorded in the classrooms. To achieve the operative temperatures, the method defined in Appendix A of ASHRAE 55 was used (ASHRAE, 2020). Table 2 shows the relationship between the operative temperatures and the thermal sensations of the students. This table reflects the thermal sensation of the different age groups, as well as the percentage of children who are under each thermal sensation. A trend line is defined to predict the thermal sensation for each operative temperature.

3. Results

Table 2 shows the ideal thermal comfort level in green, the lower thermal comfort limit in blue, and the upper thermal comfort limit in red. In those ages in which percentages do not appear, it is because surveys have not been carried out with those temperatures. This table also shows that regardless of the temperature, the majority of children are above the thermal sensation of 0 defined by the Fanger method.

The trend lines are calculated that allow a greater range of operative temperatures to be covered. Fig. 7 shows the operative temperatures on the horizontal axis and the thermal sensations on the vertical axis. The different colours used represent each of the age groups. The points are the average thermal sensation for the recorded operative temperature. The dotted lines are the trend lines indicating comfort levels depending on the operative temperature. And finally, the hatched lines are those that indicate the limits of the comfort zone, +-0.5 according to the Fanger Method and +-1 according to the ASHRAE Adaptive Method 55.

TABLE 2. Relation between Operative Temperatures and Thermal Comfort

Percentage of person in each comfort range — Operative Temperature

Thermal Sensation	18 to 19ºC						19 to 20ºC						20 to 21ºC					
	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults
3	--	--	--	--	0%	--	--	--	--	--	--	--	--	--	--	--	--	--
2	--	--	--	--	12%	--	--	--	--	--	--	--	--	--	--	--	--	--
1	--	--	--	--	28%	--	--	--	--	--	--	--	--	--	--	--	--	--
0	--	--	--	--	52%	--	--	--	--	--	--	--	--	--	--	--	--	--
-1	--	--	--	--	8%	13%	--	--	--	--	--	--	--	--	--	--	--	--
-2	--	--	--	--	0%	69%	--	--	--	--	--	--	--	--	--	--	--	--
-3	--	--	--	--	0%	18%	--	--	--	--	--	--	--	--	--	--	--	--

Percentage of person in each comfort range — Operative Temperature

Thermal Sensation	21 to 22ºC						22 to 23ºC						23 to 24ºC					
	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults
3	12%	--	--	--	0%	--	0%	6%	0%	7%	0%	0%	--	0%	0%	0%	--	0%
2	18%	--	--	--	24%	--	35%	6%	0%	13%	10%	0%	--	10%	6%	13%	--	0%
1	6%	--	--	--	29%	--	18%	39%	42%	13%	48%	0%	--	52%	28%	41%	--	5%
0	59%	--	--	--	41%	--	35%	50%	58%	60%	43%	18%	--	38%	67%	38%	--	41%
-1	6%	--	--	--	6%	43%	12%	0%	0%	7%	0%	67%	--	8%	0%	5%	--	47%
-2	0%	--	--	--	0%	50%	0%	0%	0%	0%	0%	15%	--	0%	0%	0%	--	7%
-3	0%	--	--	--	0%	7%	0%	0%	0%	0%	0%	0%	--	0%	0%	0%	--	0%

Percentage of person in each comfort range — Operative Temperature

Thermal Sensation	24 to 25ºC						25 to 26ºC						26 to 27ºC					
	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults
3	0%	--	22%	0%	0%	0%	7%	5%	0%	14%	0%	0%	26%	0%	9%	29%	3%	0%
2	10%	--	9%	11%	5%	0%	0%	15%	4%	19%	24%	0%	11%	16%	27%	18%	28%	0%
1	155	--	26%	21%	25%	4%	27%	45%	28%	36%	33%	12%	11%	44%	32%	47%	38%	36%
0	70%	--	35%	63%	60%	50%	53%	35%	63%	32%	38%	75%	53%	40%	32%	6%	26%	57%
-1	5%	--	9%	5%	10%	43%	7%	0%	2%	5%	5%	13%	0%	0%	0%	0%	5%	7%
-2	0%	--	0%	0%	7%	3%	7%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
-3	0%	--	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Percentage of person in each comfort range — Operative Temperature

Thermal Sensation	27 to 28ºC						28 to 29ºC						29 to 30ºC					
	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults	6-8 yrs	9-10 yrs	11-12 yrs	13-14 yrs	15-16 yrs	Adults
3	14%	4%	8%	24%	16%	0%	16%	5%	27%	13%	0%	0%	--	16%	30%	38%	16%	0%
2	8%	15%	25%	20%	67%	8%	25%	38%	14%	67%	43%	7%	--	25%	25%	32%	88%	27%
1	11%	50%	25%	24%	7%	44%	15%	48%	45%	7%	57%	78%	--	15%	30%	12%	13%	68%
0	68%	35%	33%	24%	7%	45%	56%	10%	14%	7%	0%	15%	--	56%	15%	15%	0%	5%
-1	0%	0%	8%	0%	7%	3%	0%	0%	0%	7%	0%	0%	--	0%	0%	3%	0%	0%
-2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	--	0%	0%	0%	0%	0%
-3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	--	0%	0%	0%	0%	0%

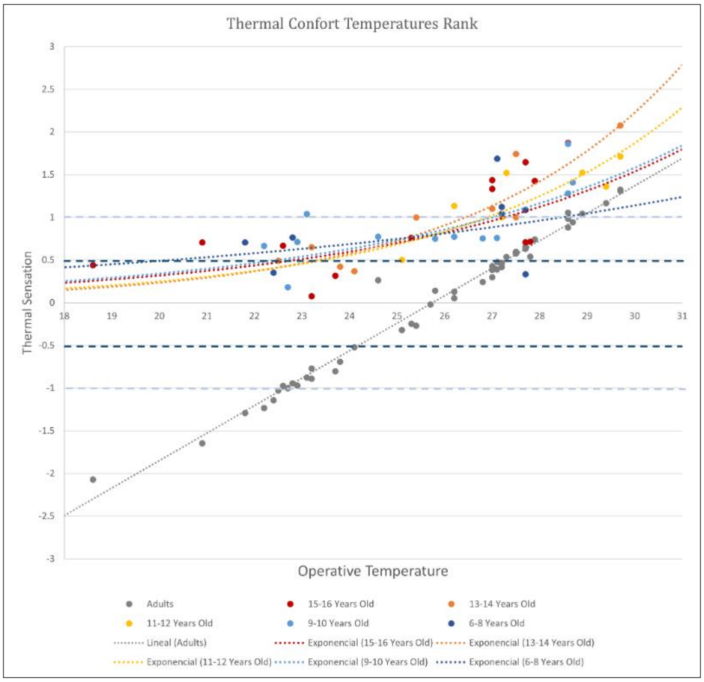

Figure 7. Thermal Comfort Ranks

Adults have the comfort temperature limits between 24.28ºC and 27.29ºC if the Fanger method is considered, and between 22.63 and 28.64ºC if the ASHRAE 55 method is considered (see Fig.7 and Table 3). Students aged 15 to 16, where their lower limits of comfort temperatures are not known due to research limitations, define the upper limit as 22.46ºC according to Fanger and 26.99ºC according to the Adaptive Method. Children aged 13 to 14, for whom the lower limits are not known, define an upper limit of 23.40ºC according to Fanger and 26.48ºC according to the Adaptive Method.

TABLE 3. Comparative Thermal Comfort Limit Temperatures.

	Fanger		Adaptative Method	
Age	Lower Acceptability Temperature Limit	Upper Acceptability Temperature Limit	Lower Acceptability Temperature Limit	Upper Acceptability Temperature Limit
6 to 8	<18ºC	20.23ºC	<18ºC	28.45ºC
9 to 10	<18ºC	22.46ºC	<18ºC	26.99ºC
11 to 12	<18ºC	23.48ºC	<18ºC	26.92ºC
13 to 14	<18ºC	23.40ºC	<18ºC	26.48ºC
15 to 16	<18ºC	22.46ºC	<18ºC	26.99 ºC
Adults	24.18ºC	27.29ºC	22.63 ºC	28.84ºC

4. Discussion of Results

A detailed analysis of the results demonstrates the initial hypothesis that adults would exhibit a greater capacity to endure warmer conditions compared to children. Fig. 7, confirms that children leave the comfort zone at lower temperatures than adults. This indicates that children are more sensitive to higher temperatures, resulting in lower comfort temperatures compared to adults.

However, it has been demonstrated that the range of thermal comfort temperatures is wider for children than for adults. The thermal comfort range for children is between 5 and 9ºC while the thermal comfort range for adults is between 3 and 7ºC depending on the method used, Fanger or Adaptive Method, to establish the comfort limits. This shows that children are much more tolerant to low temperatures than adults. This is because children have higher metabolic rates than adults in relation to their body surface area.

This research has also confirmed that children's age influences comfort temperature ranges. It is observed that they are not the same at all ages. This is because metabolic rate levels vary as the child grows (Havenith, 2007) and that the metabolic rate is one of the most influential factors in thermal comfort and comfort temperature ranges (Charles, 2003).

The children with the greatest width in the comfort range are the youngest, however, for this same reason they are the least credible in their responses. According to the surveys carried out, they are able to withstand almost the same temperatures as adults, leaving the limits of adaptive comfort at 28.45ºC, only half a degree less than adults.

Children with a lower range of comfort temperatures are those aged 13 to 14 years, followed by those aged 11 to 12. Both age groups leave the comfort zone around 26.5ºC according to the Adaptive Method. This is logical because at these ages the greatest changes in metabolic rates occur. These changes are due to the child's hormonal development (Güemes-Hidalgo et al., 2017). Taking into account that the metabolic rate is the factor that most influences the perception of the thermal environment, it is logical that these ages are the ones that tolerate high temperatures the worst (Charles, 2003).

Finally, there are the 9- and 10-year-old group and the 15- and 16-year-old group. Both ages share very similar comfort ranges, since those who are younger have not yet entered the puberty stage and those who are older have already balanced. Both groups continue to demonstrate a lower tolerance to high temperatures than adults, with the limits according to the adaptive method being 26.9ºC.

Furthermore, although the results confirm the hypothesis that adults tolerate higher temperatures better than children, there are limitations to this study that should be addressed in future research. The study should be enhanced by conducting new questionnaires in colder weather conditions. Furthermore, studies in other schools would help to determine the lower thermal comfort thresholds in children. This research was focused on a building located in an area of Spain with a Bshs climate, which has an average annual temperature of 18 ºC (Chazarra Bernabé et al., 2022). Therefore, it has not been possible to carry out surveys with lower temperatures as it is in a temperate climate area with consistently higher indoor temperatures.

Future research may consider other factors, such as differences in heat tolerance by gender, individual physical condition, or long-term adaptation to hot environments, which have not been evaluated. These factors could add layers of complexity to the relationship between age and heat tolerance.

5. Conclusions

This study validates the hypothesis that a difference exists between thermal comfort in children and in adults. Moreover, it has been observed that thermal comfort differs depending on the age of the children. This underscores the substantial influence of the metabolic rate factor on thermal sensation, as it is the only aspect that significantly changes across different age groups.

The metabolic rate remains stable throughout adulthood, leading to consistent and stable comfort temperatures for adults. In contrast, during the growth stage, the metabolic rate undergoes constant changes, causing thermal comfort to change until they become adults.

This finding holds significant importance in educational architecture as educational buildings should take this factor into consideration and adjust the operative temperature ranges accordingly.

At the same time, the differences in thermal comfort among the different children age groups should condition the planning and design of spaces in schools distributing students according to operative temperature in the different building spaces.

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BUNGALOW RETROFIT: THE ENERPHIT IN THE ROOM
OPPORTUNITY FOR SCALE

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Abstract. The Irish bungalow is an iconic affordable housing solution that quickly became a quintessential Irish phenomenon. They first came to prominence in the 1970's following a series of easy-to-follow design catalogues which flooded the country and became the peoples' housing solution, allowing a new generation of families to build their own homes for the first time. Despite the success of the bungalow bliss era, many have fallen out of love with the humble bungalow. Today in Ireland they represent 15% or 300,000 of all homes, 80% of these existing bungalows have a Building Energy Rating (BER) of a low D or E. Considering that the built environment contributes to 39% of global greenhouse gas emissions, there is a clear need to retrofit at scale and utilise existing embodied carbon within existing buildings. An opportunity to, once again, create a scaleable and repeatable solution. This paper presents an innovative solution to the dark, poor performing and dated homes. The design concept is to transform these humble bungalows and reimagine them into beautiful high performance bespoke homes, fit for today's lifestyle. Thus, demonstrating not only the transformative effect good architecture can have but also the effect high performance buildings can have on healthy environments and energy costs. This proposition has the potential to be a repeatable and scalable solution for 15% of Ireland's low performing housing stock.

Keywords: Passive house, Enerphit, Retrofitting, IAQ.

1. Introduction

On the 9th of May 2019, the Irish government declared a climate and biodiversity emergency (BBC, 2019). Globally the built environment accounts for 39% of all emissions, of which 11% is from embodied carbon (UNEP, 2017). The Republic of Ireland national retrofit plan targets 500,000 energy upgrades to a B2 energy rating. This represents an unprecedented €8 billion available to support residential upgrades by 2030 (SEAI, 2022). The Irish bungalow is a well-known and affordable housing option that has become a distinctively Irish phenomenon. It gained popularity in the 1970s when easily accessible design catalogues flooded the country, offering a housing solution for people who wanted to build their own homes (DUNCAN,2022).

Over the past 53 years, the popularity of the bungalow in Ireland has soared, with the humble dwelling now accounting for 15% of all homes in the country (SEAI, 2022). The catalyst for these homes was the rise in catalogues of home designs the most famous titled ‘Bungalow Bliss’ by Jack Fitzsimmons. Over the course of time, ‘Bungalow Bliss,’ sold an impressive 250,000 copies The Sustainable Energy Authority of Ireland (SEAI) estimates that approximately 300,000 bungalows can now be found scattered throughout the Irish countryside. This project has evolved from a design concept to a practical approach, providing a revised version of the bungalow that meets the needs of modern families and could become a template for replication and adoption at scale.

The paper aims to outline the design concept and delve into the technical aspects of this project. Additionally, the paper will present pre and post project data on indoor air quality (IAQ) monitoring, detailed project costs, and actual and predicted energy costs. Furthermore, accurate projections of future running costs will be provided. This will be discussed within the larger context of the urgent need for retrofitting in the face of an energy crisis and already outlined climate emergency (IPCC, 2018).

The Environmental Research Institute (ERI) at University College Cork reported that in December 2022, consumer electricity prices were 62.7% higher year-on-year. According to the Central Statistics Office, from December 2021 to December 2022, the price of gas rose by 86.5%, liquid fuels were up 39.9% and solid fuels were up 46.9% (MaREI Centre/ERI, 2023).

Today, the Irish bungalow remains an integral part of the country's architectural landscape. It has evolved and adapted over time to meet changing housing needs, yet still retains its charm and appeal. Residing in picturesque rural settings or as part of suburban neighbourhoods, the Irish bungalow continues to hold a special place in the hearts of the Irish people, representing a quintessential aspect of their housing history and cultural identity (DUNCAN,2022).

Frank Lloyd Wright, one of the most influential architects of the 20th century, played a significant role in the development and popularisation of the bungalow style in the United States. His innovative architectural philosophy and designs had a profound impact on residential architecture, including the bungalow form (DUNCAN, 2022).

Wright's interest in the bungalow stemmed from his belief in creating homes that were functional, affordable, and well-suited to the needs of its inhabitants. The bungalow was seen as an ideal solution to meet these requirements, and he sought to redefine and elevate the concept of the bungalow through his designs. Wright's Prairie style houses are often located in rural areas, where they can take advantage of the natural landscape. They are typically one-story, with a low-pitched roof and large windows. The interior of a Prairie style house is open and spacious, with a focus on natural light.

Usonian homes, conceived as a response to post-war American architectural challenges, were single-story structures ranging from 90 to 140 square meters and designed to fit within a budget, typically with at least one acre of surrounding land. They featured a simple palette of materials. Wright's Usonian homes notably influenced Fitzsimmons' work, particularly in their shared belief that providing adequate space for a family was a democratic right.

Fitzsimmons' ‘Bungalow Bliss’ movement drew inspiration from elements like whitewash, rubble wash, small windows, direct entry doors, thatched roofs, and the incorporation of two communal rooms. This approach aimed to create better living conditions, filling a void in the domestic housing market.

The historical context of Irish housing development included the Irish Land Commission transferring ownership of 13.5 million acres in 1920, the emergence of standardized labourer’s cottages as the first modern houses, and the construction of 40,000 uniform rural houses between 1920 and 1940. The 1950s saw the introduction of Georgian bungalows, and the emergence of town planning initiatives, exemplified by Frank Gibney's work at Bord na Móna (DUNCAN, 2022).

The 1960s marked the commencement of free secondary education in Ireland, bringing changes to the education and industry sectors. This era witnessed increased standardisation, modular design, and state support for the ‘Bungalow Bliss’ movement, however; there was also criticism from the architectural establishment and the media regarding the proliferation of bungalows, particularly along the western seaboard (Irish Times, 2020).

The 1960s was marked by a shift toward interval operation, rooms organised in zones, ergonomic interconnectivity, and a significant development in 1969, when estate standard house plans were made available to the public for just one pound each. Houses were often oriented toward the road to showcase wealth, often disregarding the path of natural sunlight from the south that was so important to Frank Lloyd Wright’s designs.

‘Bungalow Bliss’ represented not only an aspiration for better living but also contributed to the design education of the modern Irish state. It aimed to eliminate issues like cottage darkness and dampness, emphasising scalability and buildability, representing a newfound autonomy within the broader modern republic. It also coincided with the financial instrumentation of mortgages in Ireland (RTE, 2021).

In summary, Jack Fitzsimmons' influential book and architectural designs, played a pivotal role in shaping Irish housing and design principles. ‘Bungalow Bliss’ addressed issues of practicality and accessibility, filling a housing gap, and transforming architectural education; however, it was met with both support and criticism, leading to a significant shift in Irish housing development and design.

2. EnerPhit Standard

2.1 THE ENERPHIT STANDARD

The EnerPHit Standard, a variant of the Passive House standard, focuses on retrofitting existing buildings to achieve high energy efficiency and comfort levels like new Passive House constructions. It specifically tackles the challenges associated with upgrading older structures. The key aspects of the EnerPHit Standard include:

2.1.1 Energy Efficiency

The primary objective of the EnerPHit Standard is to achieve substantial enhancements in the energy efficiency of pre-existing buildings. Although the precise energy targets can vary depending on factors such as climate and building type, the overarching aim is to achieve a minimum reduction of 75% in energy consumption for heating and cooling compared to the building's original condition (Passive House Institute, 2016).

2.1.2 Retrofit Strategies

To achieve compliance with the EnerPHit Standard, retrofitting an existing building necessitates a comprehensive approach that includes upgrading insulation, enhancing airtightness, and installing efficient mechanical systems. Retrofit strategies typically involve adding extra insulation to walls, roofs, and floors, improving windows and doors, and meticulously sealing and insulating the building to enhance airtightness. These measures collectively contribute to the successful retrofitting of the building to meet the EnerPHit Standard (Passive House Institute, 2013).

2.1.3 Quality Assurance

Similar to the Passive House Standard, the EnerPHit Standard places a significant emphasis on maintaining quality assurance throughout the retrofit process. To ensure the energy efficiency objectives are achieved, certified professionals and meticulous planning, design, and construction methodologies are employed. Various diagnostic tools such as blower door tests, thermal imaging, and other assessments are commonly utilised to verify the effectiveness of airtightness measures and insulation performance. These rigorous measures contribute to the successful implementation of the EnerPHit Standard and ensure the desired energy efficiency outcomes are attained (Passipedia, 2023).

2.1.4 *Indoor Comfort and Health*

Apart from focusing on energy efficiency, the EnerPHit Standard places a high priority on enhancing occupant comfort and health. The retrofit measures aim to improve indoor air quality by integrating efficient mechanical ventilation systems that incorporate heat recovery mechanisms. Adequate thermal insulation and airtightness measures contribute to maintaining consistent indoor temperatures, minimising drafts, and overall enhancing comfort levels for occupants (ISO, 2005). These considerations ensure that the EnerPHit Standard not only achieves energy efficiency but also prioritises the well-being and comfort of building occupants (Foster, 2016).

2.1.5 Long-Term Sustainability:

The EnerPHit Standard considers the long-term sustainability of retrofit projects. Its objective extends beyond immediate energy efficiency improvements, encompassing the durability and long-lasting performance of the building. The retrofit strategy incorporates high-quality materials, well-defined maintenance plans, and a lifecycle perspective. By considering these factors, the EnerPHit Standard ensures that the retrofit project not only achieves energy efficiency goals but also guarantees the sustained performance and longevity of the building over time.

The EnerPHit Standard offers a comprehensive framework for retrofitting existing buildings, enabling significant reductions in energy consumption and improvements in comfort levels. By adhering to this standard, older buildings can undergo a transformative process, becoming highly energy-efficient and sustainable structures.

This transformation contributes to the reduction of greenhouse gas emissions and promotes a more sustainable built environment.

Furthermore, retrofitting a specific housing typology can be scalable and repeatable. When retrofitting a particular housing typology, such as a standardised design or a common building style, scalability can be achieved through various factors including:

2.1.6 Standardised Design

Retrofitting becomes more straightforward and replicable when the housing typology being renovated adheres to a standardised design. In such cases, it becomes easier to devise retrofit strategies that can be applied consistently across multiple buildings. For instance, if the housing typology shares common architectural features, construction materials, or layout patterns, retrofit solutions can be standardised and implemented with greater efficiency. This standardisation streamlines the retrofit process, ensuring consistent and effective improvements across a range of buildings within the same typology.

2.1.7 Replicable Retrofit Techniques

Retrofitting a specific housing typology greatly benefits from the establishment of replicable retrofit techniques. These techniques encompass standardised processes, technologies, and materials that can be consistently utilised in diverse buildings of the same typology. This standardisation enables a streamlined approach, facilitating faster implementation across multiple projects. By employing replicable retrofit techniques, the retrofit process becomes more efficient and effective, ensuring consistent and reliable outcomes in various buildings within the typology (Cotterell, 2012).

2.1.8 Economies of Scale

Retrofitting a particular housing typology unlocks the potential for economies of scale. When multiple buildings of the same typology undergo retrofitting simultaneously or in a coordinated manner, cost savings can be achieved through bulk material procurement, shared expertise, and streamlined project management. This results in a more cost-effective and scalable retrofit process. By capitalising on economies of scale, the overall expenses of retrofit projects can be reduced, making energy-efficient upgrades more accessible and financially viable for a larger number of buildings within the typology.

2.1.9 Knowledge Transfer and Training

Scaling up retrofit projects for a specific housing typology requires knowledge transfer and training. This entails providing education to architects, engineers, contractors, and other stakeholders on the standardised retrofit solutions and techniques tailored to the typology. By enhancing capacity and expertise, the retrofit process can be effectively replicated across various locations and projects. Empowering professionals with the necessary skills and knowledge enable the successful implementation of retrofit initiatives, facilitating widespread adoption and consistent results across different contexts (Passive House Institute, 2013).

2.1.10 *Policy and Financial Incentives*

Supportive policies and financial incentives are pivotal in promoting the scalability and replicability of retrofitting projects for a housing typology. Government initiatives, grants, and subsidies can encourage building owners to undertake retrofitting projects, fostering a greater likelihood of scalability. Furthermore, the implementation of policies mandating energy efficiency enhancements and streamlined permit processes can contribute to the facilitation of scalability. These measures create a favourable environment for widespread adoption and effective implementation of retrofit projects, resulting in substantial energy savings and sustainable transformations across the housing sector.

The leveraging of these factors has the potential to enable the scalability and replicability of retrofitting projects for a specific housing typology. Standardised retrofit solutions, replicable techniques, economies of scale, knowledge transfer, and supportive policies collectively facilitate the efficient and extensive implementation of retrofit initiatives. This comprehensive approach results in significant energy savings, environmental advantages, and an overall enhancement of the housing stock. By capitalising on these factors, the retrofitting process becomes more accessible and effective, leading to a sustainable and resilient built environment (Passipedia, 2023).

3. Bungalow Retrofit

3.1 EXISTING BUNGALOW

This paper focuses on a bungalow constructed in 1969. It received a D2 Building Energy Rating in 2011 and 2022. It is a very typical example of the common Irish bungalow. The bungalow consumed 290 kWh/m2/year and incurred energy expenses of €3,711 in 2020/2021 and €4,773 in 2021/2022. An annual average energy expense of €4,242 for the 2-year period. During the demolition phase, areas of the building exhibited mould and signs of prolonged condensation.

Figure 1. Existing Bungalow Before Retrofit.

3.2 BUILDING ENVELOPE

3.2.1 Floor

To improve the thermal performance of the building, the existing floor build-up was enhanced by reducing the U-Value from 0.57 W/m2K to 0.11 W/m2K. This was achieved by installing a 180mm PIR insulation board beneath a new 100mm sand cement floor screed.

3.2.2 External Walls

Furthermore, the external walls were upgraded from a U-Value of 0.57 W/m2K to 0.11 W/m2K, by implementing a 200mm EPS external wall insulation system, with the existing cavity filled with EPS beads.

3.2.3 Roof

The new roof comprised a concrete tile finish, cross batten, and a 35mm wood fibre insulation layer on the outside. This was followed by a 220mm deep layer of pumped cellulose recycled newspaper, matching the depth of the pre-manufactured roof truss rafters. A 50mm service void filled with sheep wool insulation was added underneath. As a result, the U-Value improved from 0.147 W/m2K to 0.125 W/m2K.

The choice of insulation materials for the roof was primarily based on decrement delay. A total of 252 bags (3.15 tonnes) of cellulose were used, which contrasted with a typical lightweight warm roof insulation system of 1.3 tonnes using PIR insulation.

3.2.4 Thermal Bridging

To address thermal bridging, aerated concrete thermal blocks were used in over one-third of the new external walls and in the internal walls beneath the floor level. The external wall insulation system effectively addressed most of the remaining 290 total meters of thermal bridging by providing a consistent layer of insulation that enveloped the entire building. Window installation was also optimised to reduce thermal bridging, with the windows placed within the EPS insulation layer, resulting in a flush alignment with the exterior wall.

3.2.5 High Performance Windows

The retrofit project incorporated passive house suitable triple-glazed windows and five glazed roof windows. The building assessment using design PH and passive house planning package (PHPP) for overheating indicated a rate of 1%, meaning that the building would not exceed 25°C for more than 88 hours (1%) of the year. The glazed area accounted for 16% of the treated floor area, below the recommended guidance of 20% (UKPHT, 2021). The cost of high-performance windows averaged €800 per square metre.

3.2.6 Airtightness

The airtightness strategy for the building was typical of best practice with the plaster layer and airtightness paint being implemented on the masonry elements of the fabric. Airtightness tapes and membranes were employed in the roof area and around the windows. The first airtightness result conducted at the completion of the building envelope came in at 0.67 air changes per hour at 50 pascals. The final airtightness test yielded a result of 0.53 air changes per hour at 50 pascals of pressure, facilitating the implementation of an 84% efficient mechanical heat recovery system.

3.2.7 Balanced Mechanical Heat Recovery Ventilation

The balanced mechanical heat recovery system is a Passive House certified system for airflow rates of 56–352m3/h. It also meets the Passive House criteria of electrical efficiency with a specific electric power 0.25 Wh/m3. The ducting which uses semi-rigid radial ducting is easy to install and can provide excellent performance. The system is based on one extract and one supply manifold with continuous hoses into the various supply and extract rooms. The ducts are polyethylene hoses, which are relatively smooth on the inner surface and therefore almost as efficient as spiral ducting. The ducting has a 90mm exterior and 76mm interior diameter. Flow speeds were kept to the best practice of 2.m/s, one duct per room was sufficient. The system was commissioned and balanced in line with passive house best practice at less than 3% on the positive pressure side (MC CARRON, 2021). These improvements resulted in an overall heating load of 10 W/m2 per year, meeting the international certified passive house standard. The building's energy rating improved from a D2 rating to an A1.

3.2.8 Embodied Carbon

An embodied carbon assessment was conducted, using the PHPP plug in Passive House Ribbon demonstrating positive results with 86.7 tonnes or 461.4 kgCO2e/m^3 gross internal area, comfortably within the RIAI 2030 Climate Challenge target of 625 and 304.6 kgCO2e/m^3 GIA against the LETI standard. The use of cellulose and wood fibre materials contributed to the carbon-negative outcome.

3.1.9 Air to Water Heat Pump

The heating system is a Monoblock Air source heat pump with natural refrigerant (R290). The greenhouse effect associated with the use of propane gas as a refrigerant, is about 700 times less than that of the most common refrigerant gases in some current systems (Ecoforest, 2023). The unit is a modulating unit from 1-7 kW. It has an efficiency up to 400%. In a Passive House it is common to base sizing of the heating generation to the domestic hot water over space heating demand due to domestic hot water being typically twice the space heating demand. The installation was optimised by coupling the system with a large 500 litre domestic hot water tank. The heat emitter is underfloor heating employed specifically in a 100mm sand cement floor. This was chosen as this thickness will provide more thermal mass, thus heating up more slowly and cooling down slowly providing a more stable, consistent heat output. Monitored heat pump performance from June to October had a Seasonal Performance Factor (SPF) of 4.2; however, this was exclusively domestic hot water heating as no space heating was required until after October 2023.

3.1.10 Solar Photovoltaic System

Finally, a 5.92 kWp Solar PV was installed, consisting of 16 modules at 370W each. The system includes 12 modules on the south-east roof plane and 4 on the south roof plane, with a projected output of 4217 kWh per annum. This system is connected to the heat pump system to further enhance efficiency so when there is excess solar energy, the heat pump will utilise the power generation. Monitored solar generation to date is in line with the projected outputs for a 3-month period August to October 2023.

3.1.11 Annual Energy Costs

As a result, the estimated total energy (Space Heating, DHW and Electric) running costs of the EnerPHit retrofit reduced to €1320 per year. The current projected basic energy savings over the mortgage period of 28 years amounted to €84,748. The future projected total running costs of the project will be reduced further to €844 per year if excess solar generation was captured in the form of battery storage. The current projected savings with battery storage over the mortgage period would project to €98,528. This represents savings of €2,922 - €3,397 per year.

The comprehensive build costs for the deep retrofit were provided, totalling €1,950 per square metre, with an additional estimated expense of €14,800 for Passive House extras, equivalent to a maximum of 5% or €80 per square metre of floor area. The payback period is 5 years for passive house standard.

Figure 2. Bungalow after Retrofit.

4. Indoor Comfort and Health Performance

4.1 INDOOR AIR QUALITY MONITORING

The indoor air quality of the home was monitored between June 2023 and September 2023 over 78 days with 15,000 data points. Five-minute Indoor Air Quality data was collected for the house, using the commercially available Netatmo monitoring equipment, see Table 1:

TABLE 1. Netatmo monitoring equipment.

Metric	Range	Accuracy
indoor temp	0 °C to 50 °C	± 0.3 °C
indoor RH	0 to 100%	± 3 %
indoor CO_2 conc.	0 to 5000 ppm	± 50 ppm/± 5%
noise level	35 to 120 dB	n/a
outdoor temp	−40 °C to 65 °C	
outdoor RH	0 to 100%	± 3 %

The Netatmo's inbuilt optical CO_2 sensor automatically self-calibrates, baselining at 400 ppm and has a stated accuracy of ± 50 ppm or ± 5%. The actual range was found to be wider in some individual units (possibly up to ± 250 ppm) (Colclough, 2019).

4.2 POST AND PRE-INDOOR AIR QUALITY RESULTS

The findings were as follows:

4.2.1 kitchen

In the new kitchen, carbon dioxide (CO2) levels reached 543 parts per million (PPM), relative humidity (rH) was at 59%, and the average temperature was 22.9°C. *This contrasted with the old kitchen, carbon dioxide (CO2) levels reached 1050 parts per million (PPM), relative humidity (rH) was at 61%, and the average temperature was 17.8°C.*

4.2.2 Living Room

In the new living room, CO2 levels were recorded at 560 PPM, rH at 61%, and the average temperature at 22.4°C. *In the old living room, CO2 levels were recorded at 1166 PPM, rH at 47%, and the average temperature at 22.1°C. The living room experienced temperature highs of 32°C and CO2 levels of 2300 parts per million (PPM).*

4.2.3 Master Bedroom

Finally, in the new master bedroom, CO2 levels measured 659 PPM, rH was at 57%, and the average temperature was 23.3°C.
In the old master bedroom, CO2 levels measured 1365 PPM, rH was at 62%, and the average temperature was 18.7°C. The data also showed the master bedroom had elevated CO2 levels reaching 2800 PPM.

4.2.4 Overheating Performance

The bedroom experienced temperature highs of 25°C which calculates 4.72% overheating; however, there are currently no blinds on the Velux windows. The highest recorded CO2 levels were 1530 parts per million (PPM) with over 20 people in the house at a family occasion, while the bedroom had a maximum elevated CO2 levels reaching 1259 PPM.

5. Conclusion

A comprehensive overview of a bungalow retrofit project in Ireland has been outlined, with a focus on achieving energy efficiency, indoor comfort, and long-term sustainability. The study addresses the urgent need for retrofitting existing buildings to combat climate change and reduce energy consumption, as emphasised by the Irish government's declaration of a climate and biodiversity emergency.

The retrofit project, based on the EnerPHit Standard, successfully transformed a typical Irish bungalow constructed in 1969 from a D2 BER to an A1 BER. The project focused on improving insulation, airtightness, and ventilation systems, resulting in a 75% reduction in energy consumption for heating and cooling. The incorporation of high-performance windows, a heat recovery system, and solar PV panels further enhanced the energy efficiency of the building. The embodied carbon assessment also revealed that the project achieved carbon-negative results, contributing to sustainability, and reduced environmental impact.

In addition to energy efficiency, the paper highlights the importance of indoor comfort and health. The findings demonstrated that the project not only achieved energy savings but also prioritised the well-being of the occupants The retrofit significantly improved indoor air quality, reducing CO2 levels, and providing consistent temperatures throughout the home.

Furthermore, the paper discusses the scalability and replicability of retrofit projects for specific housing typologies. By standardising retrofit solutions, employing replicable techniques, capitalising on economies of scale, providing knowledge transfer and training, and implementing supportive policies, the efficient and extensive implementation of retrofit initiatives can be realised. This approach contributes to substantial energy savings, environmental benefits, and an overall enhancement of the housing stock.

Overall, the presented case study of the bungalow retrofit project serves as a valuable example of how retrofitting existing buildings can play a pivotal role in addressing the climate and energy crisis. It demonstrates that with the right strategies and standards in place, older buildings can be transformed into energy-efficient, sustainable, and comfortable spaces, providing a template for future replication and adoption. As Ireland strives to achieve its ambitious energy and climate goals, the lessons learned from this project can serve as a model for similar efforts in the country and beyond.

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AN EVALUATION OF THE PHYSICAL AND MECHANICAL PROPERTIES OF CONCRETE USING EGGSHELL WASTE AND GLYCERINE

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Abstract. Concrete, being one of the most widely used construction materials, has long been subjected to exploration and experimentation in search of innovative solutions that enhance its performance and sustainability. As the world grapples with the urgent need to reduce carbon emissions of construction practices, researchers are constantly seeking ways to optimise concrete production. In this context, this research investigates the effects of using eggshell powder (ESP) and glycerine as partial replacements of the cement and water, respectively, on the concrete's physical and mechanical properties. In the experimental samples, ESP replaced the cement in quantities of 5-20% in 5% increments and glycerine replaced water in a constant quantity of 15%. The test results obtained were compared with control specimens of equivalent size. Early compression test results indicated lower compressive strengths in the ESP-glycerine concrete than the results of the control after 7 days from the day of casting. Compressive strength tests conducted after 28 days showed significant strength gain in these samples, with the most promising experimental sample exhibiting about 5 times higher strength than the 7-day results. However, the compressive strength values remained lower than the control. Workability test results found that the slumps of the ESP-glycerine concrete samples increased between a range of 31-46% compared to that of the control. From this, it can be concluded that glycerine can be used in concrete mixes to aid with increasing the workability of the mixes without increasing the total liquid quantity whilst ESP has shown to be a potential alternative to cement in concrete mixes.
Keywords: Concrete, eggshells, glycerine, compressive strength, workability.

1. Introduction

Second only to water, concrete is the most used material on the planet and is the leading material used in the construction industry worldwide, with its recorded use greater than all other building materials combined (Gagg, 2014). Concrete's impact on the environment is colossal. As of 2018, the construction industry accounted for approximately 39% of global energy and process-related carbon emissions (International Energy Agency, 2019) with cement production accounting for nearly 8% of this total (Andrew, 2019). Two key ingredients in concrete production are cement and water. Cement production alone emitted 1.5 gigatonnes, of CO_2 into the atmosphere in 2018 (Andrew, 2019). This alone clearly indicates that the current method of concrete production is unsustainable and is causing a detrimental impact on our planet. Urbanisation is an expanding global subject with 55% of the world's population currently living in urban areas according to the United Nations (2018). It is estimated that approximately 68% of the world's population will be urban zone dwellers (UN, 2018). Urbanisation has previously been shown to boost concrete production and is being the most used building material across the construction industry (Kisku et al., 2017). It is fair to predict that concrete will play a significant part in future development. Consequently, there is a growing emphasis on the immediate need to develop sustainable building materials, which is gaining significant attention as a critical aspect of preserving the planet for future generations.

Cement is a primary part of concrete production and its main purpose in concrete is to act as the hydraulic binder between aggregates (Global Cement and Concrete Association, 2023). This cement and water reaction is known as hydration and C-S-H-gel and calcium hydroxide ($Ca(OH)_2$) are formed from the silicate phases (Govindarajan & Gopalakrishnan, 2012). When C-S- H gel hardens, it forms the primary strength of the cement and allows the paste to bind the aggregates together.

In the case of the traditional cement and concrete manufacturing process, there are three key areas where innovation can be applied in response to the ongoing climate issues; 1) sources of energy used for extreme heating, 2) methods of raw material extraction, and 3) choice of materials used. This research focuses on the third key area and is inspired by the idea of using alternative sources of calcium carbonate as potential cement replacements to develop more sustainable concrete.

1.1 LITERATURE REVIEW

Today, research has proven that biobased materials can have a positive impact on the construction industry's carbon emissions and recycling waste from agricultural products is considered the most environmentally friendly way of tackling the negative environmental impact of cement manufacturing (Ngayakamo & Onwualu, 2022).

The use of eggshells in concrete provides an interesting focus as they are composed of approximately 94% calcium carbonate (Stadelman, 2000, as cited in Faridi & Arabhosseini, 2018; Razali, Azizan, Pa'ee, Razali & Jumadi, 2020), the same compound limestone is made of. Evidence of the use of eggs in construction can also date back to the 15th century in the Philippines (Collett, 2019) where the spread of Catholicism due to Spanish colonisation led to a construction storm of churches. The process of burning materials such as waste eggshells does not require as much energy as limestone does to allow for calcination to occur as in the case of eggshells, this process can occur at temperatures as low as 900°C for as little as 120 minutes (Razali et al., 2020). This alone is a significant reduction of energy used and carbon emissions released.

Research into the use of eggshell powder (ESP) as a partial cement replacement has shown strength increases in reinforced concrete slabs (Mahmood et al., 2022). Razali et al. (2020) proved that replacing 40% of fine aggregates with ESP accelerated the rate of carbonation and increased the compressive strength of the biobased concrete. Alagarsamy et al. (2018) investigated the use of eggshells as a partial cement replacement. This study used ESP at a size of 75µm in quantities of 2.5-10%, with 2.5% increments. Result showed that compressive strength values higher than the control with 5% replacement proving to be most effective. Similarly, Tan et al. (2018), investigated ESP (size -60µm) as a partial cement replacement in quantities of 5-20%.

An optimum of 15% ESP recorded a compressive strength increase of 51% when compared to the control.

Currently, it is estimated that approximately 900 tonnes of eggshells are wasted in Ireland per year (Attard & O'Connor, 2022). Developing an alternative concrete form that includes eggshells not only has the potential to reduce total carbon emissions emitted from concrete production by reducing cement content but also offers a beneficial use for waste material, improving sustainability. Additionally, workability, which is one of the key properties of concrete that can be improved by using water-reducing admixtures. Introducing sustainable admixtures into concrete to reduce the water content provides many global benefits, especially in countries where potable water required for concrete production is already scarce. Mbugua et al. (2016) used Acacia karroo gum as a water-reducing admixture in concrete. Results showed that workability increased when gum was used in dosages of +0.7% of the weight of the cement used.

Another water-reducing element in water-concrete admixture is Glycerine. Abu-Nawareg & Zidan, (2020) revealed that the use of glycerine in concrete increased the cohesiveness and handling properties of fresh concrete. This highlighted the potential that glycerine provides to increase the workability of concrete as a water replacement.

Based on the reviewed literature, this study aims at investigating the workability, compressive strength and material savings properties of concrete containing ESP and glycerine in comparison to a conventional concrete mix.

2. Material and Methodology

2.1. PREPARATION OF ESP

The creation process of the ESP is displayed in Figure 1. Firstly, the eggshells were added to a bucket of water and cleaned using an electric drill and stirrer. Then, they were left to air-dry for five days. After this, the eggshells were crushed using a mallet before being added to a pestle and mortar where they were ground down further. This material was then added to a blender to further blend it into a powder known as ESP. The ESP was sieved to achieve a consistent maximum powder size and remove any particles in excess of this size. As calcination was excluded from the scope of this research, no additional heat or burning was included in the creation of the ESP.

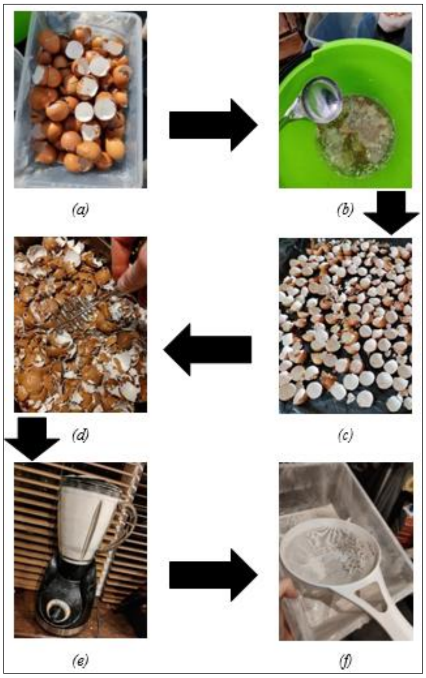

Figure 1. ESP Creation Process, (a) collection of eggshells, (b) washing and cleaning of eggshells, (c) eggshells air-drying, (d) crushing of eggshells with a mallet, (e) blending of eggshells, (f) eggshells are sieved.

2.2. MIX DESIGN

The mix design was created using the Design of normal concrete mixes as detailed by Teychenne et al. (1997). Five different mixes were designed and created to provide eleven samples in total. Table 1 refers to the total quantities of all materials used in each mix and overall. Mix 1 created samples of a chosen conventional concrete mix and was labelled as a control group in all testing. Mixes 2, 3, 4 and 5 were tested under the label of the experimental group and contained the remaining nine samples. These samples contained 5%, 10%, 15% and 20% ESP, respectively, as a cement substitute. Each experimental group mix contained glycerine in a quantity of 15% as a water substitute.

TABLE 1. Mix Quantities

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Cement (%)	100	95	90	85	80
ESP (%)	0	5	10	15	20
Water (%)	100	85	85	85	85
Glycerine (%)	0	15	15	15	15
W/C Ratio	0.5	0.5	0.5	0.5	0.5

Cement (kg)	3.60	5.13	3.24	3.06	2.88
ESP (kg)	0	0.27	0.36	0.54	0.72
FA (kg)	4.76	7.14	4.76	4.76	4.76
CA (kg)	8.88	13.32	8.88	8.88	8.88
Water (L)	1.80	2.30	1.53	1.53	1.53
Glycerine (L)	0	0.41	0.27	0.27	0.27

Out of 11 samples, ten samples were used for testing and were categorised into the control concrete group and the experimental concrete group based on the mix as indicated in Table 2. Specimen 2C was kept as a proof of concept and was not tested.

TABLE 2. Total Mix Quantities of ESP and Glycerine

Mix Number	Sample Number	Group Type	Percentage of cement replaced by ESP (%)	Percentage of water replaced by Glycerine (%)
1	1A	Control	0	0
1	1B	Control	0	0
2	2A	Experimental	5	15
2	2B	Experimental	5	15
2*	2C	Experimental	5	15
3	3A	Experimental	10	15
3	3B	Experimental	10	15
4	4A	Experimental	15	15
4	4B	Experimental	15	15
5	5A	Experimental	20	15
5	5B	Experimental	20	15

*proof of concept and not used for physical and mechanical testing

2.3. MIX CREATION, CASTING AND CURING

The creation of the concrete mixes was carried out in accordance with the standards *I.S. EN 12390-1* and *I.S. EN 12390-2* (International Organization of Standardization, 2019: International Organization of Standardization, 2021). Irish Cement CEM I Portland was used as the cementitious component. Sand was used for fine aggregate and was graded with 70% passing through a 600μm sieve. The coarse aggregate consisted of both 10mm crushed gravel and 20mm crushed stone. All dry materials were placed into the mixer. Glycerine and water were combined prior to contact with the dry materials to form a liquid mix and half of the quantity was added to the mixer. Mixing began and the second half of the liquid mix was added after two minutes and mixed for a further two minutes. Eleven cube moulds measuring 150 x 150 x 150 mm were prepared prior to mixing.

Each mix was cast into cube moulds after conducting its workability test and was labelled for clear identification. After 40 hours of setting time, the samples were demoulded, and their weights were recorded. The samples were then placed into a water bath set to a constant temperature of 23°C and left to cure. 3. Construction Issues

3. Physical and mechanical tests

3.1. WORKABILITY

To test for the workability of the concrete mixes, the Slump Test was carried out in accordance with the standard *I.S. EN 12350-2* (International Organization for Standardization, 2019a). The slump test cone was filled in 3 layers with each layer approximately one-third the height of the cone. Each layer was compacted with a tamping rod. The cone was lifted off vertically within 5 seconds and placed upside down next to the slump. The slump height was measured by determining the difference between the cone's height and the highest point of the slump using a ruler.

3.2. COMPRESSION TEST

All tests were carried out in accordance with I.S. EN 12390-3 (International Organization for Standardization, 2019b). The first set of compressive strength tests was conducted seven days after the cube samples were cast. This set of testing was labelled as 'Testing Set 1'. Testing Set 1 consisted of testing five samples, one from each of the five mixes created, as indicated in TABLE 3. Each specimen was loaded perpendicularly to the direction of casting until the failure. The second set of compressive strength tests carried out was labelled as 'Testing Set 2' and was conducted 28 days after the sample casting date in a similar manner.

TABLE 3. Testing set sample identification.

Testing Set 1	Testing Set 2
1A	1B
2A	2B
3A	3B
4A	4B
5A	5B

4. Results and Discussion

4.1. WORKABILITY TEST

Workability test results are shown in TABLE 1. Results identified that the glycerine increased workability between a range of 31-46% to that of the control mix. This noticeable increase is caused by the glycerine increasing lubrication between the aggregates and particles.

TABLE 4. Workability test results

Mix Number	Value of Slump (mm)	Slump increase from control (%)
1	130	-
2	180	38
3	170	31
4	190	46
5	180	38

4.2. COMPRESSION TEST

TABLE 5 and Figure 2 show the results of Testing Set 1 and Testing Set 2, respectively. Results of Testing Set 1 (7 days) highlighted a significant difference in the compressive strength between the control group and the experimental group, with the experimental group performing significantly lower than the control group. Sample 1A (control) recorded the highest compressive strength overall with a result of 41.36 MPa. Sample 2A was recorded as the highest-performing experimental group sample with a compressive strength of 12.10 MPa and Sample 3A was recorded as the lowest-performing experimental group sample with a compressive strength of 6.40 MPa. Whilst Sample 2A was recorded as the highest-performing experimental group sample, this sample still recorded a value 70% lower than the control sample.

In the case of Testing Set 2 (28 days), the compressive strength of the control sample (Sample 1B) was measured at 52.49 MPa. The testing of Samples 2B, 3B, 4B and 5B recorded results of 24.82 MPa, 32.35 MPa, 23.4 MPa and 19.61 MPa, respectively. From this, it is clear that all samples from the experimental concrete group performed less than that of the control concrete sample. Sample 3B was the highest-performing sample of all experimental concrete samples but it was 38% lower than Sample 1B.

Positives of this test were still evident in the experimental group's total percentage strength gain between Day 8 and Day 28. As indicated in TABLE 5, the strength increase in these samples was far higher than the control sample. Mix 3 displayed the highest recorded strength gain with a 405% increase and Mix 2 recorded the lowest strength gain with 105% of 7th day strength.

TABLE 5. Comparison of Compressive strength test results between 7 and 28 days

Mix number	Compressive strength after 7 days (MPa) – Testing set 1	Compressive strength after 28 days (MPa) – Testing Set 2	Increase (%)
1(c)	41.36	52.49	26.91
2	12.10	24.82	105.12
3	6.40	32.35	405.46
4	10.10	23.40	131.68
5	9.40	19.61	108.61
*(c) control			

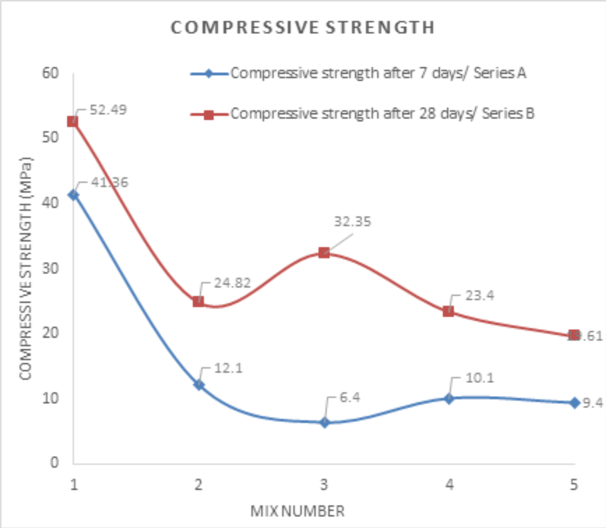

Figure 2. Comparison of compressive strength between the 7th day and 28th testing

From both Testing Set 1 and 2's results, several solutions were formed as to why there was a significant difference in the total compressive strength of all mixes as well as the total strength increase in all mixes.

The four main components of cement are calcium, silica, alumina and iron. These materials are mixed together and sent into the kiln where they are burned. In the kiln, all of these substances combine and form 4 main products: C3S, C2S, C3A and C4AF. C3S and C2S are the two substances responsible for providing the strength in concrete with C3S accounting for initial strength gain and C2S accounting for long-term strength. When C3S and C2S react with water they form a substance known as calcium-silicate-hydrate (C-S-H) gel. This gel is the main product of the hydration of OPC, and it is the material responsible for binding the aggregates together to provide the strength of concrete. From this, a number of different scenarios are identified as possible reasons why the compressive strengths of the experimental samples were lower than the controls.

Scenario 1 identifies an inadequate amount of C-S-H gel created as the cause of lower compressive strength. From this, two reasons evolve: Reason A is probably a lack of liquid in the mix which resulted in a reduced amount of C-S-H gel formation. This means that there was an excess of silicates left in the mix that did not undergo hydration and the amount of C-S-H gel that was created was lower than required. This reduced amount of C-S-H gel decreased the strength of the concrete. Reason B is formed from a decrease in silica content in the mix. Cement provides silica to the mix meaning that the reduction in cement content due to the ESP resulted in a reduction in the total silica content. ESP does contain silica but in a significantly lower amount than that of cement. Due to this, the C-S-H gel was affected as there was an inadequate amount of silica in the mix to react with the liquid thus reducing the total amount of C-S-H gel formed. As this gel is responsible for binding the aggregates together to provide the concrete's strength, the reduced amount of C-S-H gel resulted in a weaker bond between the aggregates.

Scenario 2 is formed around the idea that the glycerine may have delayed the hydration process which led to a delay in the formation of C-S-H gel. This meant that the cement and ESP were unable to react with the liquid in the mix at the same rate as water alone, as evident in the control sample. This delay in C-S-H gel formation would have resulted in a delay in the concrete's hardening and reduced its initial strength as result.

Scenario 3 is formed from the size of the ESP. This substance may not have been as fine as cement powder to behave as a cement powder replacement and could have behaved as a fine aggregate due to its size. From this, it would show that the ESP used did not replace the cement powder but in fact reduced the cement powder content altogether and increased the fine aggregate content thus increasing the voids between the particles at a grain of cement-sized scale and reducing the concrete's strength.

Scenario 4 is formed from the exclusion of calcination from the ESP creation process. Calcination is a key part of cement manufacturing. The purpose of calcination is to alter a substance's physical or chemical composition using heat. By excluding this process from the creation of the ESP, the calcium oxide (lime) was unable to bond with silica correctly and hindered its ability to C3S and C2S.

The significant increase in strength gain of the experimental samples compared to the control sample came as a result of the delay in hydration in the experimental samples due to the glycerine delaying the C-S-H gel binder from hardening.

4.3. MATERIAL SAVING

The use of ESP as a partial cement replacement saved a total of 1.89kg of cement and use of glycerine as a partial water replacement saved 1.22L of water from use in the mix design. These results reduced the cement and water contents by 9.5% and 12%, respectively.

5. Conclusion

In conclusion, glycerine increased the workability of the experimental mixes compared to the control up to 46% as it hindered water absorption by the aggregates and allowed for more liquid to remain in the mix outside of these aggregates to act as a lubricant between the particles. The overall compressive strengths of the experimental samples were lower than the control with the most promising sample obtaining a strength 38% lower than the control. This was due to the ESP being too large in size, an inadequate amount of C-S-H gel formation and the exclusion of calcination from the ESP creation process.

However, the strength gain of the experimental samples between days 7 and 28 was significantly higher than the control and this was a result of the glycerine causing a delay in hydration in the experimental samples and delayed the hardening of the C-S- H gel binder.

In total, the use of ESP and glycerine in the concrete mixes reduced the cement and water contents by 9.5% and 12%, respectively, saving 1.89kg of cement and 1.22L of water.

Due to the lower initial compressive strength of this material, increased quantities of this material would be required to function in the same manner as conventional concrete. This would essentially cancel out the environmental benefit and lead to other design challenges such as thicker columns for example. However, the increased strength gain over time and increased workability of this material show potential for it to be applied to areas where the initial strength of the concrete is not the priority but where it is required in bulk amounts such as in the case of mass concrete. Other areas where this can be included are in non-structural elements where a workable concrete that has enough strength to hold its shape over time is required.

6. Future research

One obvious limitation of this research was small sample size. Further research into this material with a larger sample size is needed to ensure the accuracy of results. Also, the particle size of the ESP may be created as fine as the cement particles to enhance the mechanical performance. A third direction of focus could be calcination in the ESP creation process and comparing the results to those of this study. Additionally, to establish the potential of this material in the construction industry, further analysis should be conducted into the environmental and economic impact of this material.

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AN INVESTIGATION AND ANALYSIS OF SOLAR GAINS AND DAYLIGHT STRATEGIES

An Investigation into the Solar Analysis of Columban Hall Galway to Implement Good Daylight Solar Strategies and Solar Gains using a Range of Software Tools.

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Abstract. Many elements of a building project require investigation and analysis to ensure an optimum construction. One such element is the recent emergence of the use of digital applications to visualise 'daylighting' in buildings. This investigation aimed to show the implementation of good daylight strategies and solar gains to a building with the use of solar analysis software. Using a number of research methods, results showed that there is capacity in the overall design of a building for optimisation and use of daylight and solar gains. The research was carried out using Case-study Methodology preceded by a literature review. Results were gathered to show that designing a building utilising strategy to incorporate as much daylight and solar gain as possible can greatly increase the standard of build.

Keywords–Daylight Strategies; Solar Gains; Orientation; Human Comfort; Glazing.

1. Introduction

1.1 INTRODUCTION

There are many aspects in the modern world of construction to consider ensuring that a building reaches its full potential and utilises not only the most basic but also the more intricate forms of building methods, to support improvements to the overall standard of living. In an ever-depleting environment, measures must be taken to ensure the housing industry strives to become more environmentally friendly and promotes a world of green living. Currently the building sector accounts for approximately 40% of all CO2 emissions (Stockstrom & Zilbauer, 2021).

This is where using the planets greatest resource comes into focus: the sun. The sun is an everlasting reusable source of energy that needs to be exploited. The decision to select this topic was taken due to the author's interest in the area of environmental sustainability.

Every building should be utilising reusable resources as much as possible.

Sunlight can light up buildings and heat them, decreasing the amount of artificial light and heating needed (McAuliffe, 2022). This is becoming a major part of construction requirements in attempting to get houses to nZEB and EnerPHit standard and daylighting is a huge factor in this (spacious, 2015).

It is also stated in the literature that good daylighting in a building contributes greatly to the well-being of the occupants of the building both mentally and physically. In schools and workplaces, it supports a higher level of focus and work. In dwellings daylight helps the mood and overall healthiness of residents. Daylighting creates an overall atmosphere of happiness (McAuliffe, 2022).

In the author's opinion, using advancements in technology and software, the advantages of the use of daylight can be shown to design a more optimal form of building.

1.2 AIM

The aim of this research was to highlight the implementation of good daylight strategies and solar gains with the use of solar analysis software to the Columban Hall, Galway.

1.3 OBJECTIVES

1. Investigate requirements and processes for good daylight strategies and solar gains.
2. Implement, with the use of modelling, these strategies to achieve the requirements necessary for good daylight and solar gains.
3. With the use of solar analysis software show the results of the daylight strategies implemented to achieve the optimal requirements.

1.4 SCOPE AND LIMITATIONS

1.4.1 Scope

This research ascertained how different aspects of a site and building affect the daylighting strategies and solar gains. This was done using different software tools such as Revit 2022 to analyse a site and find ways to implement good daylighting strategies. Secondary research was done to gain knowledge of other studies on this subject, and this was used to structure the primary research.

1.4.2 Limitations

- Results and findings from the research are limited by the technology available at the time with factors e.g. glare or weather could not be factored into the results.
- This research was based on one site and all aspects may not apply for other sites.
- Much of the research is from international sources so may not be entirely relevant to the Irish construction industry.
- For primary research the software tools used were limited to Revit 2022, Insight analysis and Enscape.

2. Methodology

2.1 SECONDARY RESEARCH

A review of the literature using Google and Google Scholar focused on the essential elements required to understand the requirements for implementing good daylight strategies and solar gains to a building. The research was categorised according to the topics which related most closely to the title of this research. The literature review consisted of peer reviewed articles and publications, government publications, industry journals, websites and other research papers. Many of these documents were sourced internationally due to a gap in the body of research in Ireland.

2.2 PRIMARY RESEARCH

Case-study Methodology included qualitative and quantitative research.
The qualitative research consisted of semi-structured interviews with professionals holding a broad knowledge and industry experience in this field to gain a full understanding of this topic. All interviewees were asked the same open-ended questions to facilitate elaboration on each question which allowed for greater understanding and a wider range of knowledge and strategies for use in modelling.

The quantitative research consisted of modelling the Columban Hall, Galway by performing a daylight analysis to achieve compliance with research –based standards. The model requirements integrated data collected from research to achieve the optimum amount of daylight. Solar analysis software Revit 2022 was used to create the model, Insight analysis plug-in software to analyse the Revit model and Enscape visual software was used for 3D Renders for conclusive results.

3. Research Findings

3.1 SECONDARY RESEARCH FINDINGS

The literature resulted in the investigation of a number of topics including Orientation, Human Comfort, Daylight Factor and requirements, Over-heating and Cooling, Shading, Glazing and Software Modelling.

3.1.1 Orientation

The orientation of a building has a major impact not only for daylighting strategies and the overall energy efficiency of a building but also for the creation of a space that is comfortable. The orientation of the building saves money on heating, lighting and cooling costs. Availing of natural light, winds and sun can give the warmth of the sun in the winter and cool breezes in in the summer (Design, 2019).

When considering daylight strategies with the orientation of a building there are 4 main exposures, Southern, Northern, Eastern and Western.

Southern exposures provide warm, ambient, consistent light throughout the day. This light should be used for the areas that are most used. Southern exposures must deal with high amounts of overheating and glare which can be controlled with a shading system.

Northern exposures have mostly indirect lighting meaning it is always in a shadow. This means it does have to use more artificial lighting and larger openings to acquire more light. This orientation does not require any form of shading.

Eastern exposure consists of a lot of direct light in the morning. This can cause issues with overheating and glare in the early hours when the sun is low requiring specific types of shading systems. This face will be cooler in the evening.

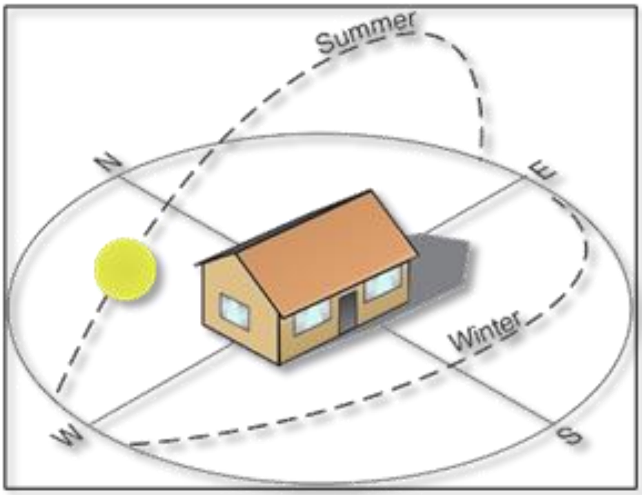


Figure 1. Orientation of a building. (Gromicko & Gromicko, 2023)

Western exposure is the opposite to Eastern in that it gets direct light in the evenings causing glare and overheating then and would require specific shading systems to accommodate the low sun angle. This face does not achieve consistent light and is greatly affected by irregular shadows (Mahoney, 2018)

3.1.2 Human comfort

Human comfort is an essential element when designing a building and the daylighting strategy has a huge impact on it. Visual comfort performance is very important in the form of glare protection, view to outdoors or indoor illuminance. It has a big impact on the occupant's well-being psychologically and physiologically.

Figure 2. Designing for visual comfort. (Franco, 2019)

Psychologically, visual comfort has major influences on productivity as well as circadian daily rhythm. Lack of proper light results in a psychological illness called Seasonal Affective Disorder (SAD). In addition to lighting benefits through windows, interest in utilising views has emerged from research studies in psychology and environment that supports the concept of providing windows as a significant element for improving individual well-being and performance. Later research confirmed the importance of visual connection for people in windowless workstations by creating surrogate windows as posters of natural scenes, a view mitigates stress particularly if the work requires doing details at close distances. (Amir Tabadkani, 2021)

Physiologically, the human body reacts to light through human eye and the skin. Visual and thermal comfort impact seemed to be pleasant when the light source was daylight. (Amir Tabadkani, 2021).

3.1.3 Daylight Factor and Requirements

As defined in I.S EN 17037:2018 (NSAI Standards, 2018) daylight factor is the ratio of the illuminance at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, excluding the contribution of direct sunlight to both illuminances.

From the literature the author has read and the feedback from the interviews carried out, it suggests that people who have a dwelling can spend approx. 80% of their time in the dwelling. This leads the author to believe that this amount of time spent indoors can have a lasting effect on their health and wellbeing, one of those factors can be exposure to daylighting while in the dwelling.

Average Daylight factor can be calculated using the formula below (Fabric First, 2019):

$$\frac{W}{A} \qquad \frac{T\theta}{(1-R^2)}$$

Minimum average daylight factor

Room type	**Minimum average daylight factor** %
Bedrooms	1
Living rooms	1.5
Kitchens	2

Figure 3. Daylight standards (Standards, 2008)

The most widely used standards for daylighting are ISO 8995:2002, EN 12464-1:2002 and BS8206-2. The British Standards give a minimum average daylight factor of 2% for kitchens, 1.5% for living rooms and 1% for bedrooms (Littlefair, 2012). Daylight factor varies within a room/space, most light tends to be near the windows or directly below roof openings and decrease the further away you are from the daylight source. This is why a daylight average is taken into account when calculating the daylight factor (Halliday, 2019). For most spaces the optimum daylight average is between 2-5%.

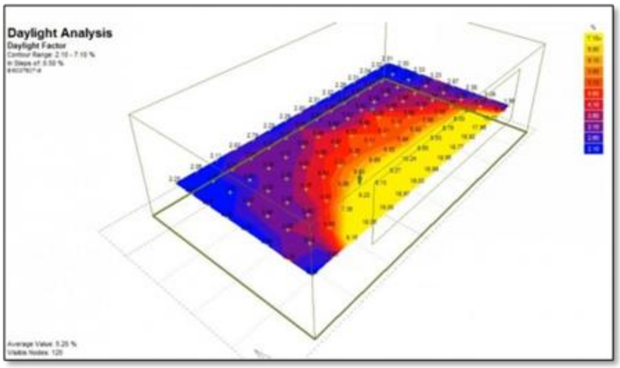


Figure 4. Daylight factor analysis (Strong, 2022)

3.1.4 Overheating/ Cooling

While glazing a building façade is a great way to introduce more light and heat into a building, it can also cause issues with overheating resulting in human discomfort. This has to be resolved by a cooling method such as ventilation systems, openable window sections and overall orientation and layout design of a building (Phelan, 2022).

3.1.5 Shading

The most effective way to control the amount of light penetrating a building is by shading, either a natural form of shading or by installing an interior or exterior form of shading system. In a year if the east and west sides of a building let in the most amount of sun whereas the south facing façade lets in the most during winter, this must be considered when locating the solar shading (Shrestha, 2011).

Shading devices can be categorised into fixed shading systems and movable shading systems (Hossein Omrany, 2015). Fixed shading systems are Canopies, Overhangs, Louvres or Brise soleil, light shelves and solar controlling glazing and also trees and other natural vegetation (Designing Buildings, 2021). These devices can serve as great architectural features. They don't provide the most effective sun protection for low angled morning and afternoon sun from the east and west (Enviroscreen Systems, 2020).

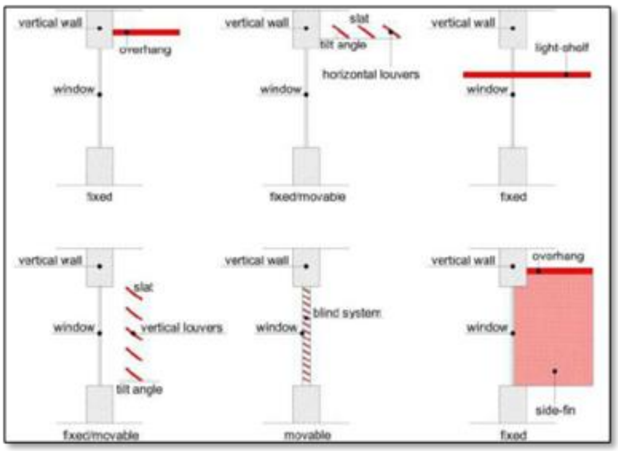


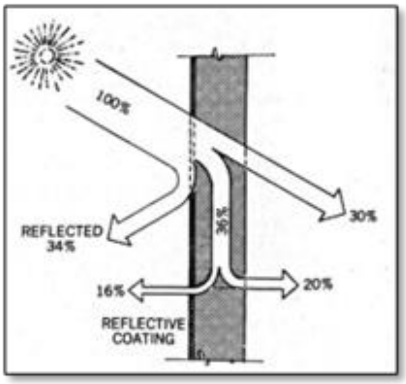
Figure 5. Shading Example. (Bellia, et al., 2014)

Movable shading systems can let in useful daylight when shading is not required and allow all solar gains to enter the building (Designing Buildings, 2021). These devices can be operated manually which can cause problems with overheating and glare due to incorrect use, or it can be electronically powered and timed to move automatically (Enviroscreen Systems, 2020).

3.1.6 Glazing

The European Commission called THERMIE (Energy Research Group, 1994) states that a conventional window, single glazed with clear float glass will transmit about 85% of light that hits it and this drops to 70% and 60% when using double or triple glazing. Glazing can control the amount of solar radiation entering a building. The radiation from the sun is either absorbed or reflected depending on the additives and thickness of the glass and can affect the light and heat in a building in different ways:

- Tinted glass: reduces heat gain in a building, however it reduces the amount of daylight entering the building and changes the colour of the landscape outside.
- Heat absorbing glass: doesn't reduce daylight but reduces the amount of heat gain by about 10% as much of the heat is re-radiated into the building.
- Reflective glass: effectively blocks solar radiation but also blocks much of the daylight entering the building.



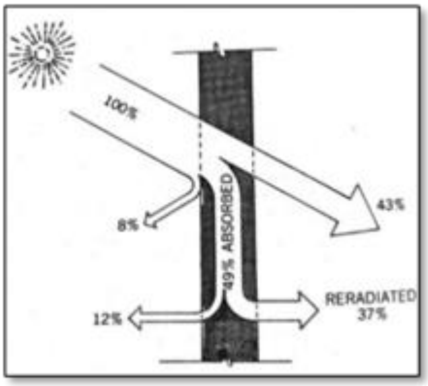


Figure 6. Tinted or heat absorbing glass. *Figure 7.* Reflective Glass (Lechner, 2015)

3.1.7 Modelling Software

For this project the best tool to use to model the Columban Hall, in the author's opinion, was Autodesk Revit 2022. Revit is a type of BIM design software that goes beyond 2D drawings to 3D modelling. The software supports the creation of floor plans, elevations, sections, 3D views and more. Based on the design specifications it allows the optimisation of building performance outcomes by analysing materials, quantities, sun position, and solar effects (Autodesk, n.d.).

Insight analysis software can be used for the design of more energy efficient buildings through advanced simulation engines and building performance analysis data. This software was used to calculate daylight factor levels in the case study (Autodesk, n.d.).

Enscape provided a more visual form of modelling through rendering. It allows anyone to be able to see the results of this research through the use of its lighting rendering tool.

3.2 PRIMARY RESEARCH

Semi-structured interviews with Subject Matter Experts took place 11-04-2022.

3.2.1 Interviews

Question 1: Have you much experience with designing for good daylight strategies and solar gains to a building?

Interviewee 1 was working in the company for a year when they decided to start doing solar analysis which they have now been doing for the last 7 years and has created a whole new revenue stream for the company as daylighting has taken off across the industry. He gave an example of a hospital building describing how they did a daylight analysis on the building which passed but failed an overheating analysis also as the windows weren't opening up far enough because of health and safety restrictors standards and stated how it's necessary to get a balance between daylight and overheating to achieve a perfect design.

Interviewee 2 had approximately 2 years' experience in doing daylight analysis between placements and working full time mostly focused daylight factors for buildings in design stage. He described his work in planning applications - he has to show analysis for proposed daylight to the new build and ensure that existing buildings surrounding the site will maintain the same daylight access as before. If this is not proved the project won't go past planning.

Interviewee 3 worked in multiple consultancies working on daylight analysis for approximately 3 years very much focusing on analysis for planning applications.
All interviewees have worked on projects such as public sector hospitals and residential apartment blocks.

Question 2: Have you any experience working with daylight and solar gains for a protected structure?

Interviewee 1 doesn't have much experience with protected structures, mostly new builds. They say that the planning authorities for the protected structures would be less stringent on the daylight factors and provisions because you can't mess around with the facades of the building if its protected and retaining stained glass or original windows.

Interviewee 2 described how they were currently working on a protected structure, a train station built in 1844 that's being renovated, and they must do an overheating analysis. They showed the project drawings and the progress of the analysis so far. He also described how they also do energy modelling for BER and NZEB compliance but for protected structures there's a line in the documents stating, *as it's a protected structure it doesn't need to comply with NZEB or BER*. Similarly, they usually don't need to do daylight analysis for these rooms, but feel it is good practice.

Question 3: How much of a role does the layout and orientation of a site play for optimum daylighting?

Interviewee 1 For layout you can put your main rooms in the corners because you can get dual aspect in on a corner and where there is high massing of surrounding buildings you would put the less important rooms such as the bathrooms.
Orientation is not as important for daylight factors because the average daylight factor is based on a standard sky that everyone has to use which is an overcast sky for comparability between projects so different projects aren't using more sunny climates for their research giving deterred results.
While orientation isn't important for daylight factors it is important for sunlight studies which is the amount of direct sunlight getting into the building which needs to be tested also under the standards. For this south facing the important rooms is key.

Interviewee 2 & 3 also described how orientation does not affect a daylight analysis because of the standard sky but does affect a sunlight analysis and the fact that south facing will give the most amount of sunlight. However, this can bring problems with overheating so it's all about the balance. A solution discussed for this would be to lower the G-value of the glass to obtain less solar gain and darken the window to tackle the overheating issue.

Interviewee 2 also discussed how a congested site such as the Columban Hall will produce high levels of shading which must be considered in terms of orientation and layout.

Question 4: What standards do you work towards in terms of reaching a daylighting level goal for a new and existing building?

Interviewee 1 stated the targets for anything outside of residential, they would usually say between 3 to 5% of hours of daylight factor is needed and in housing and apartments the targets are 1% for a bedroom, 1.5% for a living space and 2% for a dining space. These numbers can be really hard to achieve when considering large room depths and balconies and also with constrained sites where you need to fit in certain rooms and certain layouts into the building while being surrounded by other buildings. Interviewee 1 stated they maximise the glazing as much as possible fitting in as much as possible on the façade. They also reduce the depths of the rooms while increasing the widths to be able to fit in more glazing and decrease the distance the light has to travel into the building to achieve these standards. Another standard they look at is reflections so if you paint a room black and run a simulation and then paint it white, you're going to see huge differences in results. So, the standard reflectance for modelling is 70% reflectance on the walls, 50% reflectance on the ceiling and 20% reflectance on the floor. However modern paints will go up 80% on the walls and ceilings and 40% on the floors.

Interviewee 2 & 3 stated the EN standard 17037 and the BR209 guidance document from the BRE in the UK would be the two main documents. The EN standard is currently not written into the Irish standards yet, it still references BR209 so at the moment both have to be used in reports until the new guidance is issued.

Question 5: What applications to a building are most useful in your opinion for daylight strategies and solar gains?

Interviewee 1 stated they maximise the glazing by increasing the width and decreasing the depth, however he states how just targeting daylight in a building can lead to a completely inefficient scheme that wouldn't work because there are many other important factors that must be taken into consideration so there needs to be a balance. He also advised that for the case study of the Columban Hall, Galway, that the important rooms for daylighting are the meeting rooms in the building and the bathrooms and circulation areas are not.

Interviewee 3 says using as much glazing as possible and also a long deep room will struggle for daylight so designing the rooms in such a way that the glazing can have as much of an effect as possible is very important. Roof lights are also a great way to provide great daylight to a room.

Interviewee 2 states these depend on the types of roofs being used and the overall aesthetic of the building. For interviewee 2 maximising the openable sections is very important for the large amount of glazing. Using automatically opening windows at the high parts and manually operated openings at the lower parts is the optimum solution for having high amounts of glazing while controlling overheating.

Question 6: What kind of software do you use to carry out a solar analysis and how do these benefit the study?

Interviewee 1, 2 and 3 stated they use the IES VE software tool for all their daylight analysis of buildings and recommended the student version of the software for this research. This software gives the most data in terms of a daylight analysis and goes very depth while giving accurate figures.

Question 7: How have you dealt with negative effects of daylight to a building such as overheating, glare and comfort inside a building?

Interviewee 1 stated it's another balance you have to strike, with so much glazing you'll have issues with overheating in the summertime and because the u-value of the glass is much higher you'll also have heating issues in the winter.

Interviewee 2 stated there are elements of spandrel that you can put in in-lieu of glazing. So, some architects swap glazing for spandrel which can help with reducing solar gain as it's not see-through. Also using blinds in the windows, however, this is used as a last resort as a lot of guidelines ask not to use blinds.

Interviewee 3 said louvres or brise soleil are a good way to stop excessive solar gain and does usually have a good impact. Also, the G-value of the glass and high-performance glass can be helpful for negative effects of daylight.

3.2.2 Case Study

3.2.2.1 Introduction

The case study for this research analysed the Columban Hall, Galway. The Columban Hall is a former congregational church built in 1863. It is now a protected structure used as an art exhibition Hall. As part of this case study an extension was designed to the building to reflect the research.

This case study shows that using good daylight strategies helps to provide a building that complies with daylighting guidelines and is comfortable and efficient to occupy.

Figure 8. Columban Hall Photo (NIAH, 2008)

3.2.2.2 Design and Layout of Building

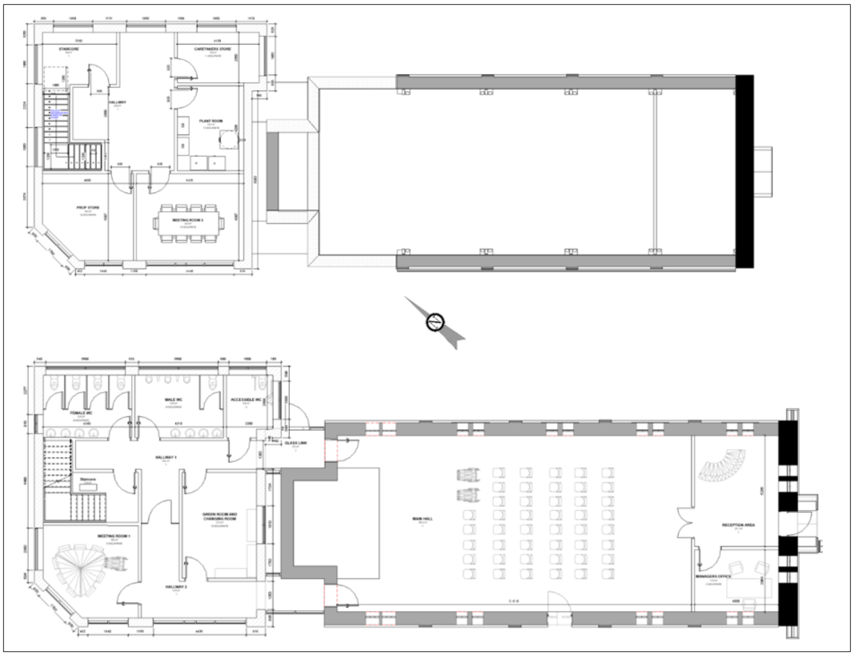


Figure 9. Ground floor Plan *Figure 10. First Floor Plan*

Within the Columban Hall there were a number of rooms that must have good daylighting and rooms that did not. Meeting rooms which require a daylight factor above 2% were designed to the south facing side of the building to maximise the amount of sun exposure. Rooms such as bathrooms, stair cores and circulation areas do not need to meet requirements and were designed to the north facing side of the building requiring artificial lighting The facades were maximised with glazing to allow for maximum daylight and solar gains into the building.

In order to strike a balance between obtaining enough daylight in the building and dealing with overheating because of the large amounts of glazing, openable window sections were designed into the curtain walling on the south most facing façade.

3.2.2.3 Daylight Analysis

This is a protected structure; therefore, this part of the building did not need to meet any requirements for daylighting. It was however considered good practice to complete a daylight analysis. This building can only take on minor upgrades and changes e.g. replacement of windows, added ventilation and insulating materials to maximise daylighting and solar gains and comfort in the building because conservation of the building must come first.

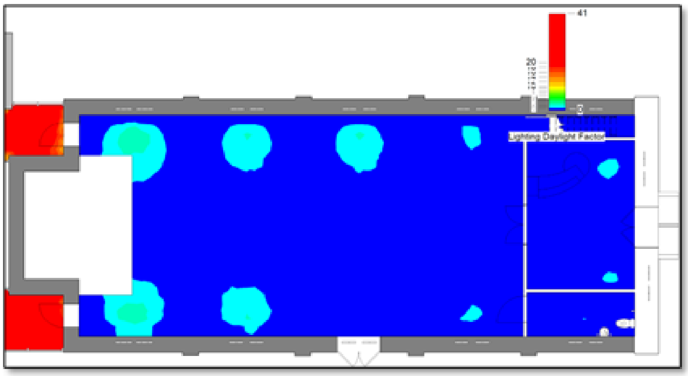


Figure 11. Main Hall Daylight Analysis

The Daylight analysis for the extension focused on compliance with regulations for the most important rooms. Using Revit, the building was modelled and with the use of the Insight analysis plugin tool detailed images were created showing the daylight entry into the building. This gives daylight factor for each room as well as the building as a whole. Enscape was used to produce a 3D representation of the light entering the building.

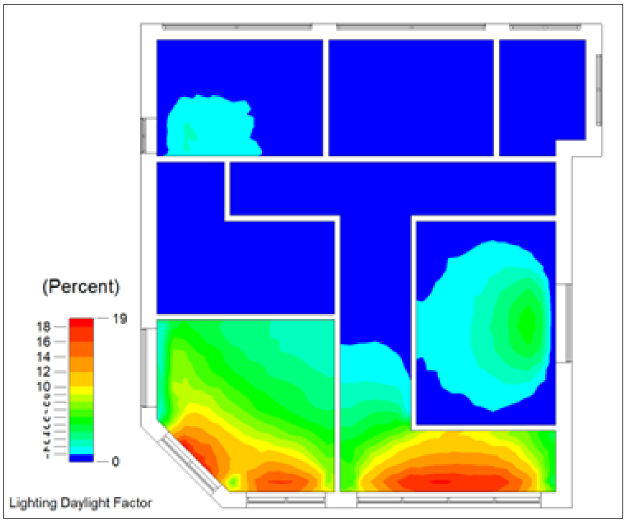


Figure 12. Ground Floor Plan Daylight Analysis

3.2.2.3.1 Ground Floor Plan

100% of points are between 0.0-20.0% (Building ADF is 2.5%)												
Daylight Factor Sky (unshaded horizontal 100%)												
A	B	C	D	E	F	G	H	I	J	K	L	M
						DF Sky threshold results						
						within threshold		above threshold		below threshold		
Level	Name	Number	Area	Include in Daylighting	Automated Shades	%	Area	%	Area	%	Area	ADF %
Ground Floor Plan	Female WC	2	12.6 m²	☑	☐	100	13 m²	0	0 m²	0	0 m²	0.7
Ground Floor Plan	Male WC	3	12.5 m²	☑	☐	100	12 m²	0	0 m²	0	0 m²	0.3
Ground Floor Plan	Accessible WC	4	6.2 m²	☑	☐	100	6 m²	0	0 m²	0	0 m²	0.3
Ground Floor Plan	Meeting Room 1	5	18.2 m²	☑	☐	100	18 m²	0	0 m²	0	0 m²	6.9
Ground Floor Plan	Green Room	6	18.5 m²	☑	☐	100	19 m²	0	0 m²	0	0 m²	1.6
Ground Floor Plan	Staircore	7	13.4 m²	☑	☐	100	13 m²	0	0 m²	0	0 m²	0.0
Ground Floor Plan	Hallway	8	29.8 m²	☑	☐	100	30 m²	0	0 m²	0	0 m²	3.5

Figure 13: Daylight factor figures – Ground Floor Plan

Figure 14: Daylight Factor Render 1

From the analysis of the ground floor plan the main rooms such as the meeting room achieves over 2% daylight factor, and the green room achieves over 1.5% daylight factor. Overall, this gives the ground floor plan an average daylight factor 2.5%. Rooms such as the bathrooms don't need to meet these standard and will require artificial lighting.

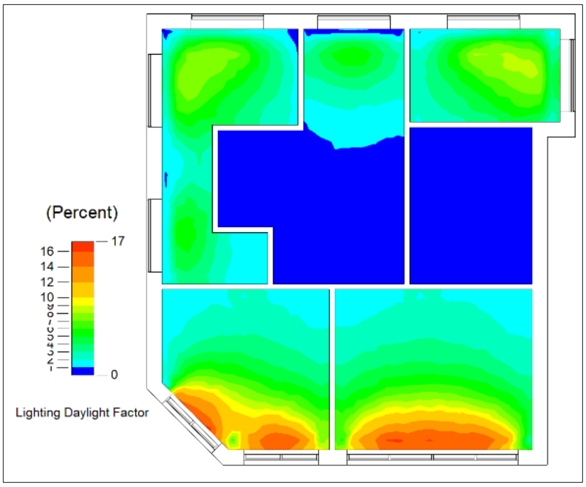


Figure 15. First Floor Plan Daylight Analysis

3.2.2.3.2 First Floor Plan

100% of points are between 0.0-20.0% (Building ADF is 3.3%)												
Daylight Factor Sky (unshaded horizontal 100%)												
A	B	C	D	E	F	G	H	I	J	K	L	M
						DF Sky threshold results						
						within threshold		above threshold		below threshold		
Level	Name	Number	Area	Include In Daylighting	Automated Shades	%	Area	%	Area	%	Area	ADF %
First Floor Plan	Staircore	2	18.1 m²	☑	☐	100	18 m²	0	0 m²	0	0 m²	3.6
First Floor Plan	Hallway	3	26.9 m²	☑	☐	100	27 m²	0	0 m²	0	0 m²	1.0
First Floor Plan	Caretakers store	4	10.6 m²	☑	☐	100	11 m²	0	0 m²	0	0 m²	4.7
First Floor Plan	Plant Room	5	14.4 m²	☑	☐	100	14 m²	0	0 m²	0	0 m²	0.0
First Floor Plan	Meeting Room 2	6	23.9 m²	☑	☐	100	24 m²	0	0 m²	0	0 m²	5.3
First Floor Plan	Prop Store	7	18.5 m²	☑	☐	100	19 m²	0	0 m²	0	0 m²	5.4

F*igure 16.* Daylight Factor Figures – First Floor Plan

Figure 117. Daylight Factor Render 2

From the analysis of the First Floor Plan, the main rooms achieve a daylight factor of over 2% giving the First Floor Plan an average of 3.3% daylight factor. This was achieved using the research results of this study.

4. Results

The main aim of this research was to show the implementation of good daylight strategies and solar gains to a building using solar analysis software. The objectives were described in 1.3.

Objective 1 was to investigate requirements and processes for implementing good daylight strategies and solar gains to a building. This was led by the secondary research identifying the topics which gives a clear understanding of this area of study. This resulted in clear figures and standards required for daylighting as well as providing insights into what can aid in the design to reach these standards.

Using a case-study methodology, interviews were conducted as part of the primary research which also supported the completion of the first objective. By talking to professionals who have expertise in designing with good daylight strategies, clarity of requirements for daylighting and the effects it has on people within a building and the optimal methods for best design was obtained.

The second objective was to implement the strategies discovered in objective one to achieve good daylight and solar gains in the Columban Hall using modelling. During this research it was found that Revit is a fantastic tool for bringing all aspects of a building together. Using this tool facilitated the building design for optimum daylighting and solar gains.

The final objective was to show the results of the implemented daylight strategies and with the use of Insight analysis software and the Enscape rendering tool results were seen. All aspects of the building that required to meet standards, excelled beyond them giving the whole building an optimum standard of daylight and solar gain.

5. Conclusions and Recommendations

5.1 CONCLUSIONS

Daylighting for buildings has become a huge aspect of design and planning as more discoveries and research has found its importance in terms of wellbeing and the overall usage of a buildings. Daylighting has created whole new revenue streams for constructions companies in the last number of years because of these discoveries.

All buildings need to incorporate the use of the sun to improve building efficiency. There are so many ways to do this and from the research undertaken in this study the best way to make use of the limitless resource is to have a well-planned balanced scheme taking every aspect of design into account to optimise the use of the sun for daylighting and solar gains and for many other aspects of the build.

5.2 RECOMMENDATIONS

More research is required in this field as evidenced by the lack of Irish research and publications in the Irish context.

For further investigation into this field more advanced software should be used to achieve a more in-depth result taking into account natural occurrences such as glare and weather and how this can affect the daylighting and solar gain in a building.

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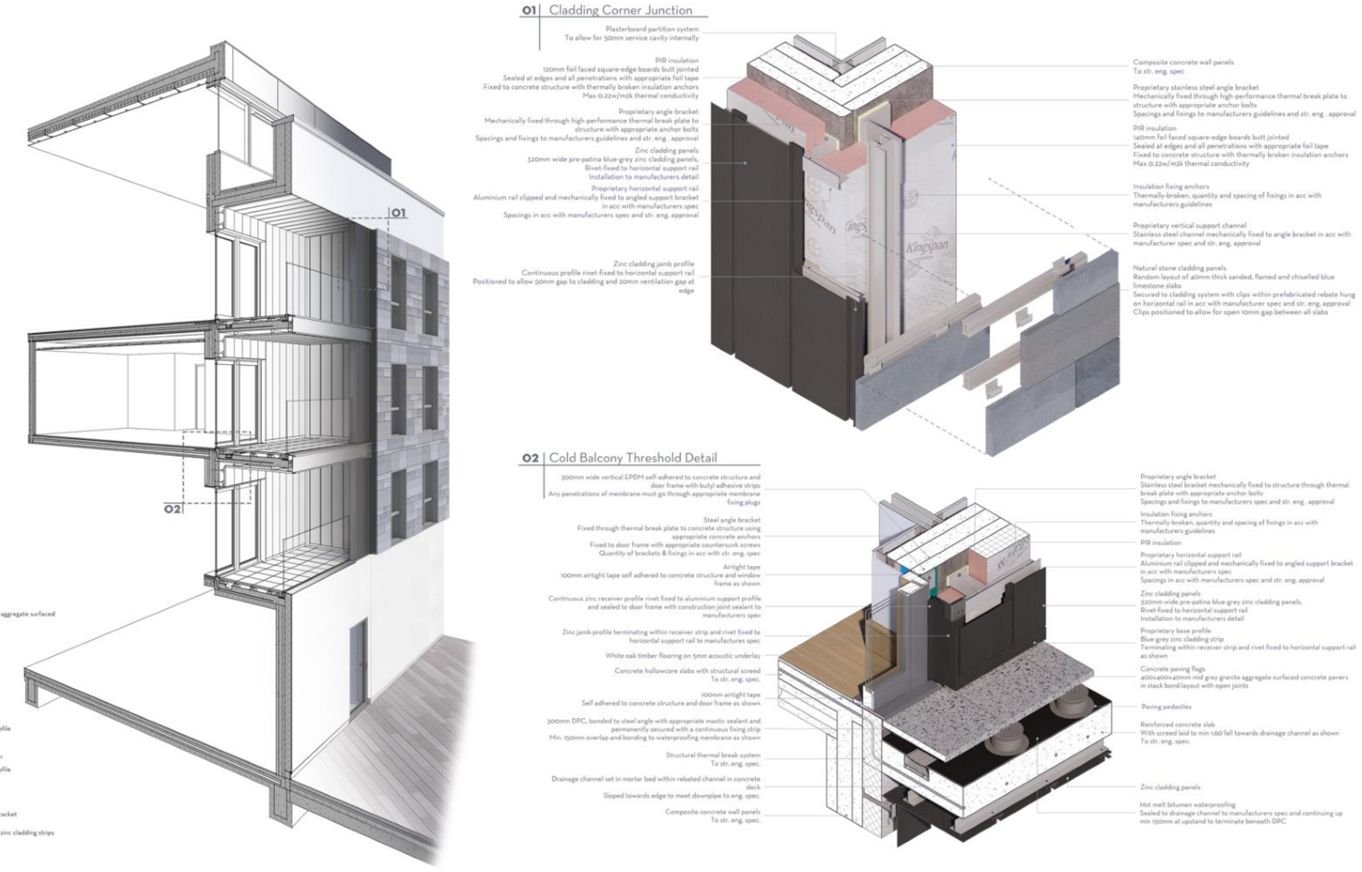

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