Optimised evaluation of environmental impact using homegrown wood fibre materials in housing construction.

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Abstract:

Purpose
The Scottish Government promotes the use of homegrown, wood fibre-rich products in the construction industry as a key feature of a wider sustainability strategy that aims to decarbonise the sector. This strategy also promotes the use of Building Information Modelling (BIM) as a means to digitalise the built environment, enabling key metrics to be visualised, evaluated and continually monitored. This study, which involved the creation of a BIM optioneering tool to evaluate the impact of specifying homegrown, wood fibre-rich products in the design and construction of housing is therefore intended to complement this national strategy.

Design/methodology/approach
This paper investigates the environmental benefits of BIM in designing a low-rise residential dwelling meeting the Scottish Building Standards' Bronze Sustainability Standard. A BIM tool was developed to assess the structural, thermal, and environmental aspects of various construction products and assemblies. Two house designs were created: a benchmark (V1) and an alternative using wood fibre-rich products (V2). Both versions were analysed using imported (V1a, V2a) and locally sourced (V1b, V2b) wood fibre-rich materials. This research demonstrates the potential of BIM to optimise material selection and improve the environmental performance of residential buildings.

Findings
The research demonstrated that opting for a wood fibre-rich build-up (V2b) resulted in greater total carbon sequestration within the superstructure, shifting from -4,315 kg/CO2eq to -13,802 kg/CO2eq. This translates to a 220% reduction in Global Warming Potential (GWP) relative to the benchmark build-up incorporating imported wood fibre-rich products (V1a). These findings emphasise the potential of digital tools to optimise the selection of construction details and materials, focusing on minimising environmental impact without compromising performance.

Originality/value
This study enabled the following insights to be gained: (1) The environmental impact of specifying a wood fibre-rich alternative to the industry-standard benchmark, and (2) Evaluation of the environmental impacts of specifying homegrown, wood fibre-rich products in both versions. The results from this study demonstrate that specifying homegrown, wood fibre-rich products led to significant carbon savings that help the housing construction industry recognise the added benefits alongside achieving operation energy and carbon commitments.

Keywords: BIM; Construction; Embodied Energy; Global Warming Potential; Housing; Low-carbon; Timber; Wood Fibre-rich.

1. Introduction

In the UK, 23% of greenhouse gas emissions are directly attributable to the construction industry i.e., emissions coming from construction-related activities (Climate Change Committee, 2020). In Scotland, the built environment is responsible for approximately 40% of carbon emissions annually, accounting for both embodied and operational emissions (GCF-2022).

One approach to reducing embodied carbon emissions is to select biogenic construction materials that have a lower environmental impact, compared to standard, conventional materials such as concrete and steel. This includes materials which can be categorised as 'wood fibre-rich' - a collective term that includes timber (in its natural form) and timber derivatives. Timber, a plentiful and renewable resource, can replicate the structural performance characteristics of standard construction products (Ramage et.al., 2017). Crucially, timber products are also able to sequester carbon for the lifecycle of the product – effectively 'locking up' carbon and preventing its release into the environment (Hawkings, 2021).

In Scotland, approximately 92% of all new-build homes are constructed using a timber frame system, which is assembled onsite (Department for Environment, Food and Rural Affairs, 2023). However, this aggregated figure does not differentiate between homegrown timber products (i.e., harvested and manufactured in Scotland) and those imported from outside Scotland. This issue of provenance is important as the transportation of products can contribute significantly to its carbon footprint. To highlight this issue, a study found that for every 1 tonne of material, transportation by road accounted for an additional 62kg CO_2, whilst rail and sea transportation methods accounted for 22kg CO_2 and 16kg CO_2 respectively (RICS, 2023).

Within this context, this study aims to investigate the environmental impact of selecting homegrown, wood fibre-rich products in the design and construction of housing in Scotland. In doing so, the following objectives provided the research framework for the investigation:

- Identify standard products found in the design and construction of an industry-standard house configuration (V1) and design an alternative version, utilising wood fibre-rich products (V2).

- Create a product database containing information on the structural, thermal and environmental attributes of the products found in each iteration (V1a, V1b, V2a and V2b).

- Develop a multifaceted BIM model capable of calculating the structural, thermal and environmental performance of each build-up, and perform a parametric analysis to determine the environmental impact of selecting homegrown, wood fibre-rich products.

2. Literature review

2.1. Policy background

The UK and Scotland have set ambitious targets to reduce greenhouse gas emissions and achieve net zero by 2050 and 2045, respectively (The Scottish Government, 2019). Buildings account for about a fifth of global carbon emissions and in 2019 the UK construction industry was responsible for 23% of the total sum (Climate Change Committee, 2020). Therefore, decarbonising the building sector is essential for meeting the net zero goals.

A key challenge in decarbonising the built environment is to transition from fossil fuel heating systems to low and zero-emission heating methods, such as community district heating, heat pumps, and other innovative technologies. By 2037, the UK government has set a target of reducing greenhouse gas emissions by 75% from public buildings and has announced investment into energy efficiency measures and low-carbon heating solutions. The Scottish Government has recently consulted on a Heat in Buildings Strategy, which sets out the vision for more than 1 million homes and an estimated 50,000 non-domestic buildings to transition to low and zero-emission heating systems by 2030 (The Scottish Government, 2021 & The Scottish Government, 2023). The strategy also outlines the actions and policies to support the transition, such as regulation, financial incentives, skills development, and consumer engagement.

To help reduce operational carbon emissions, insulation materials are used to enhance energy efficiency and reduce heat loss in the thermal envelope of a building. Increasingly, the installation of insulation products is integrated with modern methods of construction (MMC), where components are manufactured offsite to varying levels of completeness, and subsequently transported to the site for installation. In Scotland, the construction industry has been encouraged to modernise its delivery of buildings with panelised and volumetric timber off-site methods of construction (The Scottish Government, 2022).

2.2. Digital tools

MMC also incorporates the use of modern digital methods such as building information modelling (BIM), digital twinning (DT) and digital scanning methods. Efforts to highlight the full potential of BIM models have been discussed by Arayici *et al*. (2023) who consider its application as a tool to improve performance and productivity in the construction industry. The Scottish Government (2020) has produced guidance on applying digital tools to use available data and deliver end-to-end digital planning methods enhancing collaboration and engagement to promote digital innovation. This guidance promotes the use of tools such as BIM and DTs which contribute towards the adoption of design for manufacturing and assembly (DfMA), enabling the procurement, design and technical specification stages to be further integrated (Abrishami and Martín-Durán, 2021).

Similarly, DTs are sophisticated tools employed in construction processes to aid decision-making (Kaewunruen *et al*., 2018). A DT refers to a virtual twin or a digital representation of a physical asset and the data synchronisation between them. Although still in its academic infancy, several case studies demonstrate the usefulness of DTs across various sectors including manufacturing, aviation, engineering and the built environment (Bagireanu, A. *et al*., 2024).

It is the bi-directional data exchange, the potential live self-actualisation and self-optimisation that distinguishes DTs from BIM principles (Sepasgozar, 2021). For this reason, DTs can be employed for a variety of uses, such as assessing building performance, simulating what-if scenarios based on real-time data, supporting design options and decisions, forecasting process sequences, and hands-free maintenance through machine learning behaviour (Jones *et al*., 2020). With time, and as data accumulates and the twin becomes more complex, it can reach a level of self-optimisation that enables autonomous decision making.

Digital tools, such as BIM and DTs, can be used to calculate operational energy and carbon emissions across the full life cycle of the building, enabling key stages to be identified (Keyhani *et al*., 2023). For example, the emissions emanating from the construction stage are significant, and in some instances account for more than 50% of the carbon emissions over the life cycle of a building (Adams *et al*., 2019 & Parkin *et al*., 2020). The work undertaken by Bouhmoud *et al.* (2022) is also highly relevant to BIM and carbon accounting, having demonstrated the application of such tools in analysing life cycle performance.

2.3. Material properties

In domestic buildings, embodied carbon of materials contributes 51% of emissions, and operational, direct and indirect emissions a further 31% with in-use activities (maintenance & replacements) contributing a further 18% of emissions (Pomponi and Moncaster, 2016). This shows the importance of reducing the carbon emitted during the manufacture and transportation of building products, particularly as buildings get more efficient during the operational stage (Adams *et al*., 2019).

A method to lower the embodied carbon intensity is to select and procure materials that are sourced locally and manufactured from natural and replenishable materials. This includes most plant-derived fibres that can be categorised according to their source, predominantly from lignocellulosic materials, such as wood and non-wood plant-based fibres (Mohamed et al., 2018). In addition to their low carbon properties, these alternative materials are non-toxic with low, or zero, negative impacts on human health (Krueger *et al.*, 2019).

Natural fibre insulation, such as synthetic insulation, can act as a thermal barrier that resists the passage of heat through it. Most natural sources are those from seeds, bast, leaf, stalk, cane, grass and reed. Wood-derived natural fibre insulation includes different forms of tree bast, including wood itself (soft and hard wood species), hemp, jute and flax (Sutton *et al*., 2011). Such fibres are hair-like, continuous filament materials that can be pressurised and thermally bonded at varying densities to form insulation materials. The use of fibre products in buildings as construction materials and reinforcement has been widely explored in different forms and uses.

Wood fibre insulation is typically used in low-density batts and medium or high-density rigid boards using dry or wet processes; however, some have enhanced properties using radiant foils and convective air passage. In comparison with synthetic products, most natural fibre products demonstrate comparable thermal conductance properties, with a balanced temperature and humidity performance (Laborel-Préneron *et al*., 2016). However, if not treated properly, wood-derived fibres tend to degrade over time making them less durable than synthetic equivalents (Saha *et al*., 2015). Some efforts to make natural fibre products more durable involve converting the organic compounds in fibres into alcohols, to enhance their solubility in water (Mohajerani *et al*., 2019). Hemp shives, for example, are normally used as an alternative aggregate in lime, clay or magnesia binders but can also be used as an insulation product. Kosiński *et al*., (2022) obtained thermal conductivity values of between 0.049 – 0.052 W/mK in certain natural fibre insulation. Wood fibre has many products on the market with its primary application being in new buildings and the retrofit of existing dwellings (Bianco *et al*., 2017).

In conclusion, addressing the need to reduce the carbon intensity of our built environment requires not only the reduction of operational energy but also reducing the embodied carbon intensity of construction products. It is the intention of this study to further examine both of these metrics within the context of net zero.

3. Methodology

As previously stated, this study aimed to investigate the environmental impact of selecting homegrown, wood fibre-rich materials in the design and construction of housing in Scotland. Using the BIM optioneering tool developed (discussed in Section 3.5), this impact was investigated by comparing a standard construction build-up adopted by Scottish house builders (V1), with an alternative build-up that utilises homegrown, wood fibre-rich alternatives (V2). For this study, only the superstructure (walls, floors and roof) and foundations were considered, therefore excluding windows, doors, fixtures and fittings. Both versions of the build-up (V1 and V2) were designed to achieve the Bronze Sustainability Standard for domestic properties, as set out in the Scottish Building Standards. For comparison purposes, Table 1 shows the minimum space heating requirement to meet the Bronze, Silver and Gold Section 7 Sustainability standards in the Scottish Building Standards, along with the equivalent value to achieve Passivhaus accreditation. The space heating requirements outlined in Table 1 act as a reference point for the need to maintain similar thermal attributes of building insulation to limit heat loss from the building envelope. New materials developed for construction should increase thermal resistance (lowering thermal conductivity), so that components achieve lower thermal transmission values and that the operational energy required for space heating is minimised (as with the Gold Standard and Passivhaus).

Table 1. Comparison of building standards. Source: Table created by authors from data supplied by The Scottish Government (2024).

Standard	Energy for space heating (kWh/m2/yr)
Scottish Builing Standards, Bronze (domestic)	Compliance tool pass
Scottish Building Standards, Silver (domestic)	40 (houses) 30 (flats)
Scottish Building Standards, Gold (domestic)	30 (houses) 20 (flats)
Passivhaus	15

For this study, a standard 3-bedroom semi-detached house configuration was selected for the parametric analysis, enabling comparisons to be made between the different iterations. Drawings of the house type, including the first floor and elevation sections, are shown in Figure 1, with a gross floor area of 98.48 m^2.

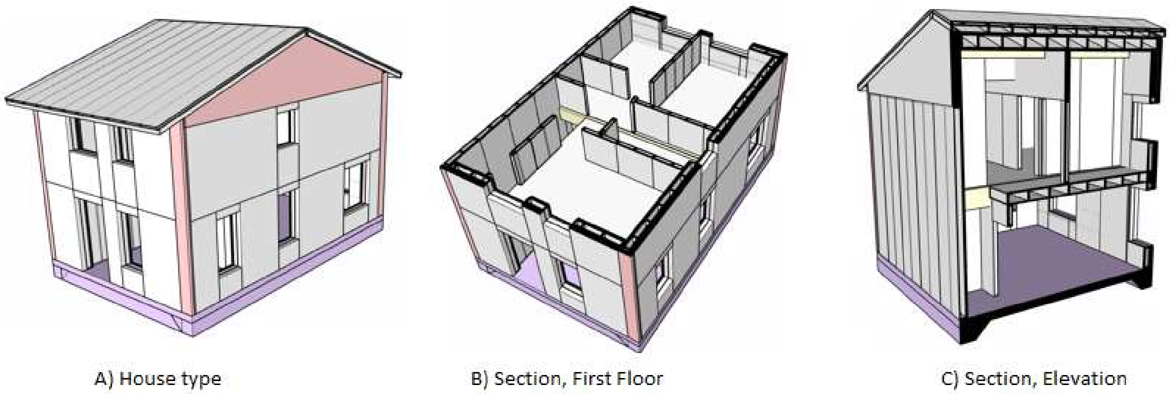

Figure 1. House configuration details. Source: Authors' own creation.

Having selected the configuration, this study adopted a 4-stage methodological approach, as outlined in Figure 2. Further explanation of Stages 1 to 3 is provided in this methodology section. The results from Stage 4, the parametric analysis, are discussed in Section 4.

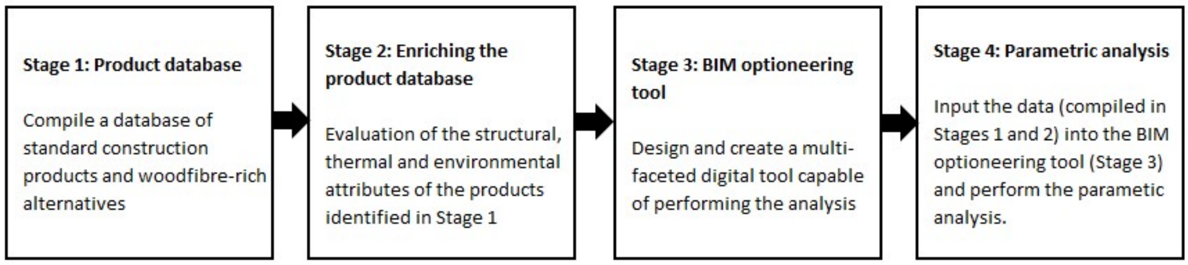

Figure 2. Outline methodology. Source: Authors' own creation.

3.1. Selection and development of a product database

For this study, four iterations of the same house type were developed; incorporating a standard, timber open-panel system designed to meet the Bronze Standard of the Scottish Building Regulations.

The first task was to identify the products typically found within a standard, timber open-panel, semi-detached house configuration (V1a). The method used to capture this information was through an online workshop with construction industry experts, which facilitated discussions on these products. The workshop attendees were all construction professionals and were split into: a) those involved in the design and specifications of buildings, and b) those who are involved in the delivery and construction of buildings. Questions and discussions were based on three topics: 1] Thermal performance of wood fibre-rich products, 2] Availability of products and supply chain in the UK and abroad, and 3] Challenges and innovation required. The outcomes of the workshop were incorporated into the study, enabling the BIM tool to assess and propose different wood-fibre-rich designs to optimise the optimal low-carbon house design.

Therefore, for this study, wood fibre-rich products in V1a were assumed to be sourced from the nearest manufacturer located outside of Scotland. To assess the impact of utilising homegrown wood fibre-rich products, V1b assumed that such products were sourced from within Scotland.

The workshop also enabled the experts to optimise the use of wood fibre-rich products in the build-up. For the study, V2a assumes that all wood fibre-rich products are sourced from the nearest manufacturer that is located outside Scotland. Similarly, V2b assumed that such products were sourced from within Scotland, where possible.

In substituting imported wood fibre-rich products for homegrown Scottish alternatives (V1b and V2b), a desktop study was undertaken to confirm that such products were commercially available. In each of the four iterations, non-wood fibre-rich products are sourced from the nearest manufacturer to the site.

The full product database for each iteration (V1a, V1b, V2a and V2b), including geographical provenance, is shown in Table 2.

The four iterations are as follows:

V1a – Benchmark House Featuring Imported, Wood fibre-rich products
V1b – Benchmark House Utilising Homegrown, Wood fibre-rich products
V2a - Wood fibre-rich House Featuring Imported, Wood fibre-rich products
V2b – Wood fibre-rich House Utilising Homegrown, Wood fibre-rich products

Table 2. Build-ups of Version 1 (the 'benchmark' house) and Version 2 (wood fibre-rich house). Source: Table created by authors.

			VERSION 1 (V1)		VERSION 2 (V2)	
			V1a BENCHMARK HOUSE FEATURING IMPORTED, WOODFIBRE-RICH PRODUCTS	V1b BENCHMARK HOUSE UTILISING HOMEGROWN, WOODFIBRE-RICH PRODUCTS	V2a WOODFIBRE-RICH HOUSE FEATURING IMPORTED WOODFIBRE-RICH PRODUCTS	V2b WOODFIBRE-RICH HOUSE UTILISING HOMEGROWN, WOODFIBRE-RICH PRODUCTS
WALLS	External wall	*External finish*	1 Brickwork External 102mm	1 Brickwork External 102mm	2 Timber larch cladding 25mm	3 Timber larch cladding 25mm
		External battens			4 Vertical and horizontal battens	5 Vertical and horizontal battens
		T/frame sheathing, ext	6 OSB 10mm	7 OSB 10mm	6 OSB 10mm	7 OSB 10mm
		Timber frame	8 140 x 38mm C16 @600mm ctr	9 140 x 38mm C16 @600mm ctr	8 140 x 38mm C16 600mm ctr	9 140 x 38mm C16 600mm ctr
		T/frame insulation, cavity fill	10 Glasswool	10 Glasswool	11 Blown cellulose	11 Blown cellulose
		Internal insulation	12 Polyisocyanurate (PIR) 25mm	12 Polyisocyanurate (PIR) 25mm	13 Rigid woodfibre 60mm	13 Rigid woodfibre 60mm
		Internal battens	14 Vertical timber battens	15 Vertical timber battens	14 Vertical timber battens	15 Vertical timber battens
		Internal finish	16 Platerboard 15mm	16 Platerboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm
	Internal wall	*Internal finish*	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm
		Timber frame	17 95 x 38mm C16 @400mm ctr	18 95 x 38mm C16 @400mm ctr	17 95 x 38mm C16 @ 400mm ctr	18 95 x 38mm C16 @ 400mm ctr
		T/frame sheathing, ext	6 OSB 10mm	7 OSB 10mm	6 OSB 10mm	7 OSB 10mm
		T/frame insulation, cavity fill	10 Glasswool	10 Glasswool	19 Loose wood fibre	19 Loose wood fibre
		Internal finish	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm
	Party Wall	*Internal finish*	20 Fire board, 2 @ 15mm (1hr)	20 Fire board, 2 @ 15mm (1hr)	16 Plasterboard 15mm	16 Plasterboard 15mm
		Timber frame	8 140 x 38mm C16 @ 600mm ctr	9 140 x 38mm C16 @ 600mm ctr	8 140 x 38mm C16 @ 600mm ctr	9 140 x 38mm C16 @ 600mm ctr
		T/frame insulation, cavity fill	10 Glasswool	10 Glasswool	11 Blown cellulose	11 Blown cellulose
		T/frame sheathing, ext	6 OSB 10mm	7 OSB 10mm	6 OSB 10mm	7 OSB 10mm
		Internal battens			14 Vertical timber battens	15 Vertical timber battens
		Sheeting			20 Fire board (1hr)	20 Fire board (1hr)
I'MEDIATE FLOOR		*Internal finish, top*	21 Chipboard 22mm	22 Chipboard 22mm	21 Chipboard 22mm	22 Chipboard 22mm
		Internal battens	23 25 x 55mm timber battens	24 25 x 55mm timber battens	23 25 x 55 timber battens	24 25 x 55 timber battens
		T/frame sheathing, ext	6 OSB 10mm	7 OSB 10mm	6 Osb 10mm	7 Osb 10mm
		Timber frame	25 245 x 63mm I-joist	25 245 x 63mm I-joist	26 245 x 45 mm C16 @ 600mm ctr	27 245 x 45 mm C16 @ 600mm ctr
		T/frame insulation	28 Rockwool 50mm	28 Rockwool 50mm	11 Blown cellulose	11 Blown cellulose
		Underside	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm
ROOF			*Upper:*	*Upper:*	*Upper:*	*Upper:*
		External finish	29 Concrete roof tiles	29 Concrete roof tiles	29 Concrete roof tiles	29 Concrete roof tiles
		External battens	30 Vertical timber battens 45 x 45mm @ 600 ctr	31 Vertical timber battens 45 x 45mm @ 600 ctr	30 Vertical timber battens 45 x 45 mm @ 600 ctr	31 Vertical timber battens 45 x 45 mm @ 600 ct
		T/frame sheathing, ext	32 OSB 18mm	33 OSB 18mm	32 OSB 18mm	33 OSB 18mm
		Timber frame	34 120 x 45mm C16 @ 600mm ctr	35 120 x 45mm C16 @ 600mm ctr	34 120 x 45mm C16 @600mm ctr	35 120 x 45mm C16 @600mm ctr
			Lower:	*Lower:*	*Lower:*	*Lowwer:*
		Internal insulation	36 Polyisocyanurate (PIR) 60mm	36 Polyisocyanurate (PIR) 60mm	37 Rigid woodfibre 80mm	37 Rigid woodfibre 80mm
		Timber frame	26 245 x 45mm C16 @ 600mm ctr	27 245 x 45mm C16 @ 600mm ctr	26 245 x 45 mm C16 @ 600mm ctr	27 245 x 45 mm C16 @ 600mm ctr
		T/frame insulation, cavity fill	10 Glasswool	10 Glasswool	11 Blown cellulose	11 Blown cellulose
		T/frame sheathing, internal	32 OSB 18mm	33 OSB 18mm	32 OSB 18mm	33 OSB 18mm
		Internal battens	14 Vertical timber batten	15 Vertical timber batten	14 Vertical timber batten	15 Vertical timber batten
		Internal finish	16 Platerboard 15mm	16 Platerboard 15mm	16 Plasterboard 15mm	16 Plasterboard 15mm
FOUNDATION			38 Scread	38 Scread	38 Scread	38 Scread
			39 Concrete	39 Concrete	39 Concrete	39 Concrete
			40 Steel r'ment @ 2% of concrete	40 Steel r'ment @2% of concrete	40 Steel r'ment @ 2% of concrete	40 Steel r'ment @2% of concrete
			41 EPS insulation	41 EPS insulation	41 EPS insulation	41 EPS insulation
			42 Sand	42 Sand	42 Sand	42 Sand
			43 Type 1	43 Type 1	43 Type 1	43 Type 1

KEY
- Manufactured in Scotland
- Manufactured in England/Wales
- Manfuctured in mainland Europe

3.2. Product database attributes.

Having created a database of products for all variants of the house, further information was needed to enhance the digital tool. This process involved adding structural, thermal and environmental attributes for each of the products identified. Adding these values into the digital tool provided a calculated function of the material volume. The products selected for this study and their corresponding attributes are shown in Table 3.

Table 3. Product database. Source: Table created by authors.

			Structural attributes	Thermal attributes			Environmental attributes					
							Global Warming Potential [GWP]			Embodied Energy (EE)		
REF.	Component	Functional Unit	Density (Pmean) [kg/m3]	Conductivity [W/(mk)]	Specific heat [KJ/KgL]	Vapour permeability factor [μ]	A1 - A3	Seq	A4	A1 - A3 Renewable	A1 - A3 Non-renewable	A4
1	Brickwork External	m^3	2000	—	—	—	244.90	—	58.62	90.37	4,355.50	837.44
2	Timber larch cladding	m^3		—	—	—	235.55	-896.00	43.01	9,770.00	902.00	614.41
3	Timber larch cladding	m^3	550	—	—	—	61.35	-834.00	3.39	10,700.00	1,570.00	48.37
4, 8, 14, 17, 23, 26, 30, 34	Structural timber C16 (Mainland Europe)	m^3	370	0.13	1.6	50	56.00	-742.00	43.01	9,770.00	902.00	614.41
5, 9, 15, 18, 24, 27, 31, 35	Structural timber C16+ Home grown	m^3	400	0.13	1.6	50	107.00	-764.00	3.39	10,700.00	1,570.00	48.37
6, 32	OSB imported from Mainland Europe	m^3	600	0.13	1.7	50	445.48	-1,386.00	63.49	12,947.67	3,008.10	906.99
7, 33	OSB manufactured from homegrown wood-fibre	m^3	600	0.13	1.7	50	408.20	-1,270.00	4.24	13,813.00	3,441.00	60.58
10	Glasswool	m^3	24	0.031	1	1	51.20	—	1.82	74.90	1,060.00	25.93
11	Blown cellulose	m^3	60	0.038	2.02 ±6%	2	36.96	-115.00	6.14	25.80	352.80	87.77
12, 36	Polyisocyanurate (PIR)	m^3	32	0.021-0.022	1.03	1	169.38	—	1.21	116.25	3,406.25	17.29
13, 37	Rigid woodfibre	m^3	110	0.038	2.1	3	81.00	-322.00	11.26	2,929.73	1,665.02	160.92
16	Platerboard	m^3	675	0.19	1	10	157.50	—	25.53	1,867.50	2,708.33	364.69
20	Fire board	m^3	800	0.19	1	10	157.50	—	25.53	1,867.50	2,708.33	364.69
21	Chipboard	m^3	600	0.14	1.7	50	315.63	-982.00	24.96	11,135.00	6,398.00	356.59
22	Chipboard	m^3	600	0.14	1.7	50	315.63	-982.00	4.66	11,135.00	6,398.00	66.64
25	I-joist	m	4.1	—	—	—	1.65	-6.08	0.03	57.70	28.00	0.41
28	Rockwool	m^3	136	0.035-0.039	1.03	1	16.33	—	1.82	26.83	221.67	25.93
29	Concrete roof tiles	m^3	2510	—	—	—	4.60	—	4.13	5.85	69.45	58.98
38	Scread	m^3		—	—	—	269.00	—	2.01	326.00	3,510.00	28.71
39	Concrete	m^3	2471	—	—	—	246.00	—	2.01	118.00	1,888.00	28.71

(green)	Manufactured in Scotland
(orange)	Manufactured in England/Wales
(red)	Manufactured in mainland Europe

3.2.1 Structural attributes.

When conducting a structural review, it is important to consider the permanent actions of the structure itself. The product database contains the mean density (ρ_{mean}) for each material, which is used with the geometry data to calculate the mass of the selected panels/elements of the superstructure.

3.2.2 Thermal attributes

To determine the hygrothermal properties of the products selected it was necessary to compile available data on the thermal conductivity (λ), specific heat capacity (c) and the water vapour resistance factor (μ). These hygrothermal attributes were obtained from product-specific technical documentation using certified laboratory-tested results, particularly those from established imported products used in this study. For the homegrown examples, their thermal attributes were benchmarked against those imported, assuming they would be of similar performance. Thermal conductivity is defined as the rate at which heat is transferred through a material via conduction, and combined with the material thickness a resultant thermal resistance is obtained which determines a component U-value (i.e. the rate of thermal transmittance). Table 4 shows the maximum U-values permitted in the Scottish Building Standards in their April 2024 Edition (The Scottish Government, 2024).

Table 4. Maximum U-values as specified by the Scottish Building Standards. Source: Table created by authors.

External wall	Roof	Party wall	Floor
0.17 W/(m^{2}K)	0.12 W/(m^{2}K)	0.0 W/(m^{2}K)	0.15 W/(m^{2}K)

Note: Any cavity separating wall should also be fully filled with a material that limits air movement, allowing a U-value of 0.0 to be assigned.

Specific heat capacity is used to determine the thermal capacitance or inertia of a product (i.e. how much heat it can absorb). It is useful to understand the material's thermal inertia and capacity to absorb heat considering also the time lag, decrement factor and admittance of temperature influencing the interior of the building.

The vapour permeability factor measures the behaviour of a material at the passage of moisture (i.e. the amount of water vapour that crosses the material). Products with a high vapour permeability factor, such as those which are primarily constituted from plastic or metal, tend to limit the passage of water vapour and can lead to problems such as dampness and condensation. Conversely, products with a low vapour permeability factor allow moisture to pass through their structure and are often referred to as being 'vapour-open' or as having 'breathable' qualities.

3.2.3 Environmental attributes

A key aim of this study is to demonstrate the environmental impact of specifying homegrown wood fibre-rich build-ups in the design and construction of housing. This data was obtained from existing product Environmental Product Declaration (EPD) documents which report on the environmental impact of a construction product. A standardised approach to determining the global warming impact of different greenhouse gases is to compare them in reference to carbon dioxide. This approach, referred to as the embodied carbon of a material or its global warming potential (GWP), adopts $kgCO_2$-eq as the unit of measurement, where the GWP for 1kg of carbon dioxide is equal to 1 $kgCO_2$-eq. Calculating the GWP for the construction products under consideration was deemed the most suitable approach for this study.

GWP of the construction products identified was extracted from the Environmental Product Declaration (EPD) reports of the selected products. These EPD reports are obtained by the manufacturer and independently verified, consider the lifecycle of a product and are undertaken in accordance with BS EN 15804 (BSI, 2020). This standardised methodology considers the lifecycle stages as 'modules' or 'boundaries', as shown in Figure 3.

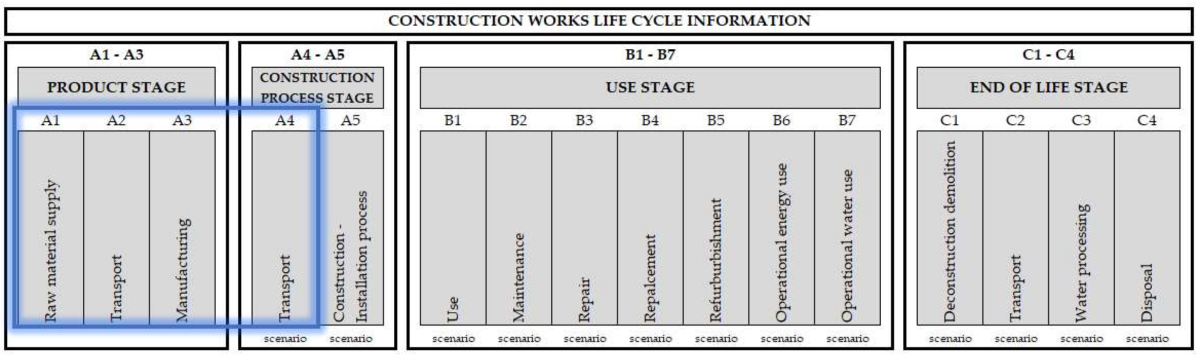

Figure 3. EPD stages and modules. Source: Figure courtesy of British Standards Institution, BS EN 15804:2012 & A2:2019, (2020).

For this study, information was extracted for modules A1 to A3, which constitutes the product stage of the lifecycle, and can be referred to as 'cradle to gate'. Where available, information relating to module A4 (transport) was also extracted and factored into the assessment. In addition to providing the GWP, an EPD also reports upon the embodied energy (EE) that is amassed at each stage of the lifecycle.

As shown in the Product Database (see Table 3), the construction products identified originated from one of three different geographies: (1) Scotland, (2) England/Wales, (3) mainland Europe. To calculate the GWP and EE of Stage A4 (Transport) for this study, it was necessary to apply some assumptions to input transportation distances. The first assumption was that the location of the construction site was the town of Pitlochry in Scotland, as it represents the (approximate) geographical centre of Scotland. The second assumption was that the manufacturing location of homegrown, wood fibre-rich products was in Edinburgh, located in the heavily industrialised 'central belt' of Scotland. A third assumption was that products originating from England/Wales were manufactured in Coventry, England, taken as an approximation for the centre of this geographical area. Lastly, the fourth assumption was that products originating from mainland Europe were manufactured in Hamburg, Germany, once again selected as the approximate centre of this geographical area.

To estimate the GWP and EE resulting from the transportation of each product from its manufacturing location to the site in Pitlochry, the distances travelled, and mode of transport were calculated.

For products originating from mainland Europe, it was assumed that the overland distances would be travelled by road, with the load temporarily transferred to rail when crossing the English Channel. For products originating from Scotland, or England/Wales, it was assumed that all products would be transported by road. The approximate distances for each scenario, and assumed transportation modes, are shown in Figure 4.

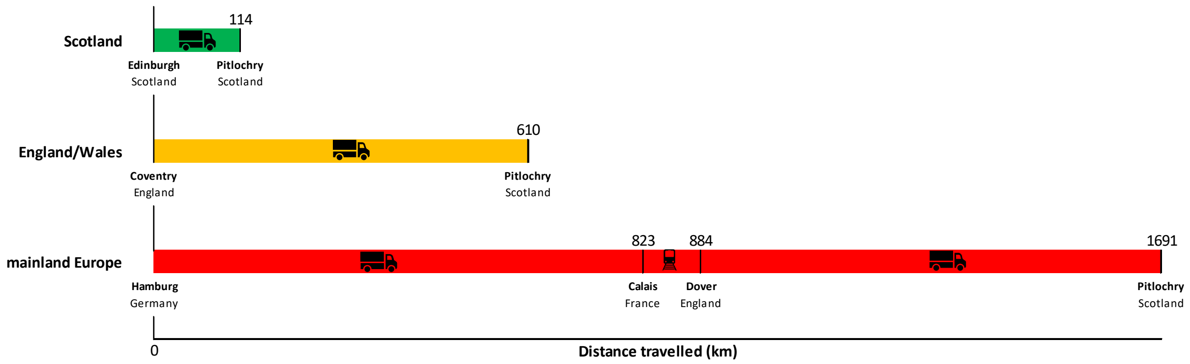

Figure 4. Origin and destination of construction products selected for the study. Source: Figure created by authors.

The GWP of the road and rail transport was taken as 62 and 22g CO_2/tonne-km, respectively, assuming a sub-optimal capacity of 80% for the outbound journey and 25% for the return journey (RICS, 2023). In obtaining the mass of the product being transported, and the distance travelled from the manufacturing facility to the site, it was therefore possible to calculate the GWP.

3.3. BIM optioneering tool

The multi-faceted digital model (subsequently referred to as a 'BIM optioneering tool') was developed using Trimble SketchUp Pro which integrated the BIM-enabled 3D modelling programme. The BIM optioneering tool allows the end user to model the build-up of a construction component – either a wall, roof, floor or foundation – from a variety of pre-specified options. Figure 5 shows the BIM modelling process, which can be considered in four stages.

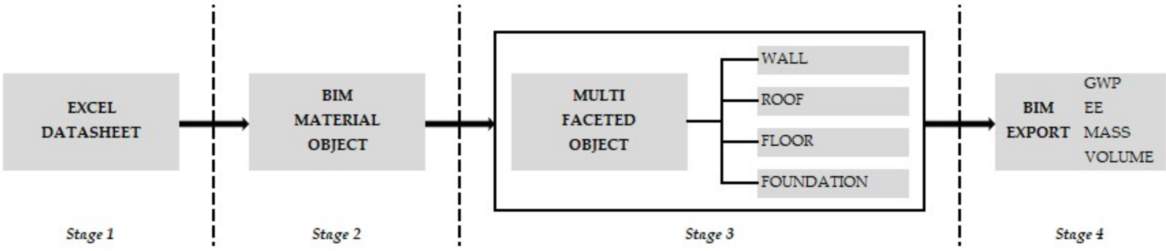

Figure 5. Flow diagram showing the BIM modelling process. Source: Figure created by authors.

In Stage 1, the product information is compiled in a database. The database contains the structural, thermal and environmental characteristics of the product (as discussed in Section 3.4).

Stage 2 involves transferring this information into the BIM material object library, as a list of attributes within SketchUp. In addition to the information contained within the datasheet, the geometry of the multifaceted BIM object is created. This component is created from sublayers of dynamic components that each represent a different part of a typical construction build-up.

In Stage 3, the material attributes are linked to the appropriate sublayer. When completed, the multifaceted BIM object can be used to design wall, floor, roof or foundation components, providing an almost limitless number of potential configurations. When complex geometries are required in the design, single dynamic components allow each product to be shaped appropriately. Figure 6 shows the interface of the BIM optioneering tool, where a drop-down menu allows designers to select from pre-specified options. In designing each component (wall, floor, roof and foundation), a full superstructure design can be generated within the BIM optioneering tool.

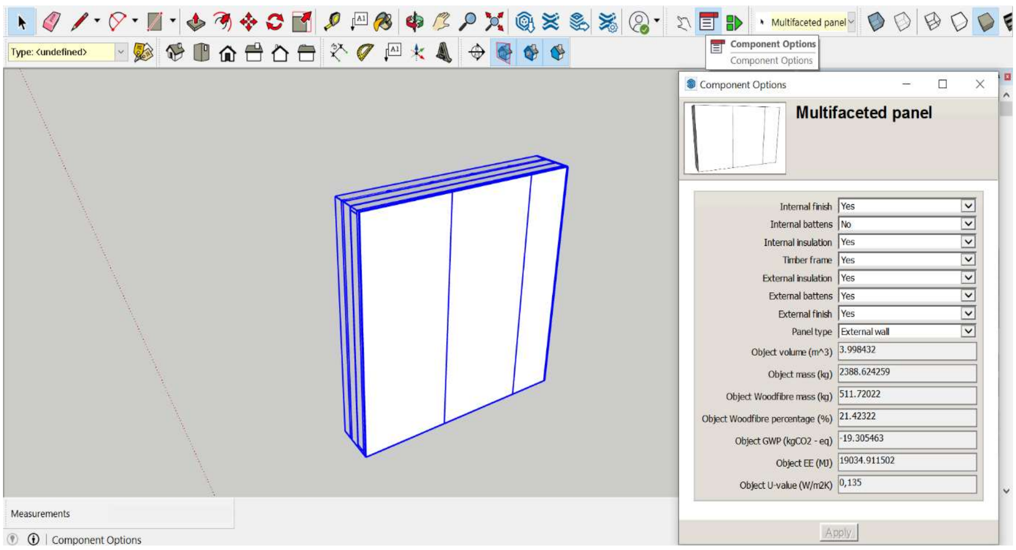

Figure 6. Interface of the BIM optioneering tool. Source: Figure created by authors while using Sketch Up Pro, Trimble software.

Finally, in Stage 4, the selected design can be exported into a spreadsheet format. This file contains the attributes of each product and build-up selected, including the environmental impact of the design (provided as GWP and EE). Information on each product selected is provided, including its volume and mass, allowing a bill of quantities to be compiled.

4. Parametric analysis

To demonstrate the environmental impact of increasing the percentage of homegrown, wood fibre-rich products in both versions (V1, the 'benchmark' and V2, 'wood fibre-rich house'), four design iterations were developed (V1a, V1b, V2a and V2b), with V2b representing the build-up containing the highest proportion of homegrown, wood fibre-rich products. Both versions (and all four iterations) of the design conform to the Bronze Standard, as set out in the Scottish Building Standards as the baseline level for sustainability.

In exporting the data from each design iteration, the BIM optioneering tool provided the following information that determines the environmental impact:

4.1. Composition of superstructure

Figure 7 shows the proportion of wood fibre products specified for the superstructure in each iteration. Here, wood fibre-rich products constitute 17.96% of V1 and 32.74% of V2.

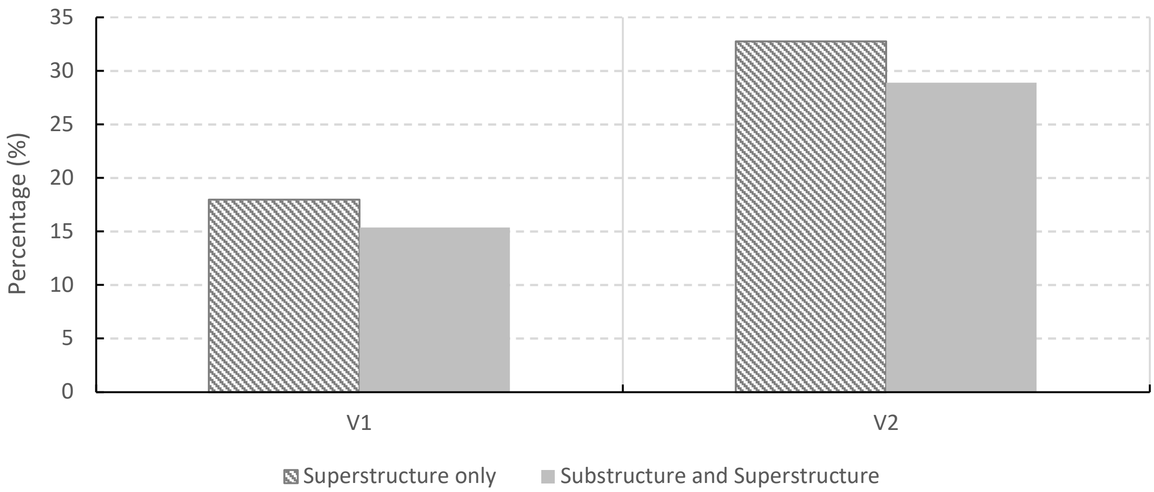

Figure 7. Proportion of substructure and superstructure made from wood fibre-rich products. Source: Figure created by authors.

4.2. Volume of material

The pre-manufactured volume (PMV) of all iterations is shown in Figure 8. The results show that the pre-manufactured volume of V1 is 74.26 m^3, and V2 is 87.94 m^3. In analysing the environmental impact of construction, PMV is an important factor as it dictates the proportion of construction that takes place offsite or near-site using any of the seven categories of Modern Methods of Construction (MMC). It can be achieved through a combination of off-site, near site and on-site manufacturing techniques, as well as through materials innovation and site-based process improvement and technology. A recent industry target sits at >55% PMV according to the Affordable Homes Programme from Homes England, launched in 2021 (Homes England, 2016 & Cast, 2021). Applying off-site timber manufacturing achieves a high PMV.

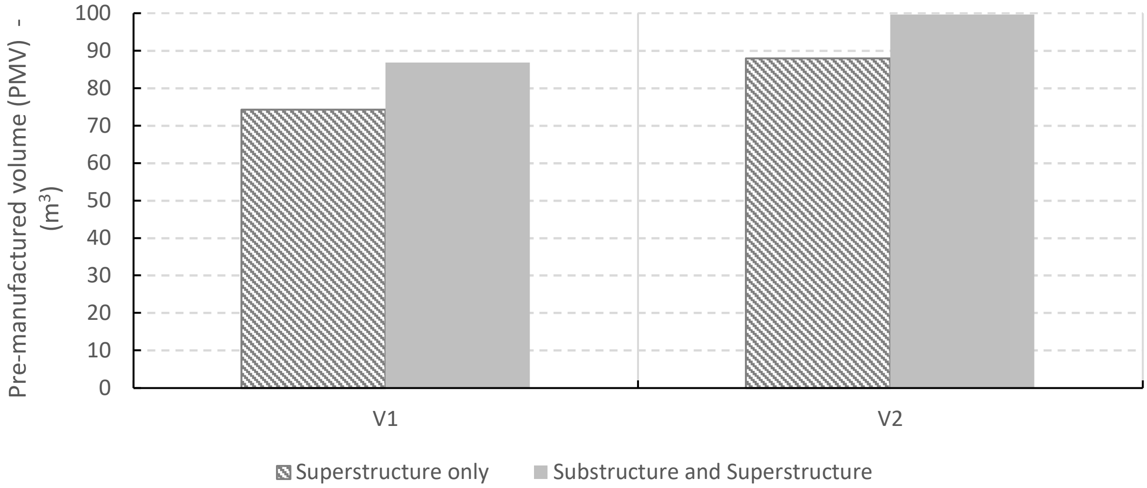

Figure 8. Pre-manufactured volume (PMV) - Total volume of V1 and V2. Source: Figure created by authors.

4.3. Global Warming Potential (GWP)

Figure show the impact of specifying homegrown, wood fibre-rich products to achieve low GWP components in homes. V1a, the benchmark version that features imported wood fibre-rich products, the $GWP_{(A1\text{-}A4)}$ is 10,142 kgCO_2-eq, when combining the carbon sequestration this figure becomes -4,315 kgCO_2-eq, meaning this interaction is effectively locking-up 4,315 kg of carbon dioxide.

However, if the imported wood fibre-rich products in V1a are substituted for similar products manufactured in Scotland (V1b), the resultant GWP is 9,236 kgCO_2-eq. This figure represents an 8.9% reduction attributed to less transportation needed, and when considering the sequestration, the result is -4,517 kgCO_2-eq.

When evaluating the impact of specifying homegrown, wood fibre-rich products for V1b, the analysis reveals that the impact of selecting homegrown wood fibre products contributed the most significant benefit when calculating the GWP. Whilst Figure illustrates the GWP without accounting for carbon sequestration, Figure 10 provides the complete picture, allowing a comparison of the sequestered values.

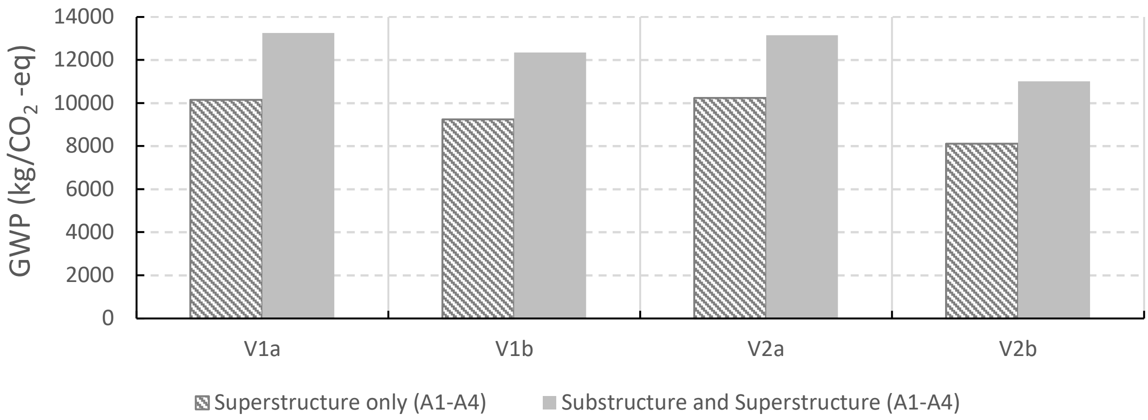

Figure 9: GWP excluding carbon sequestration. Source: Figure created by authors.

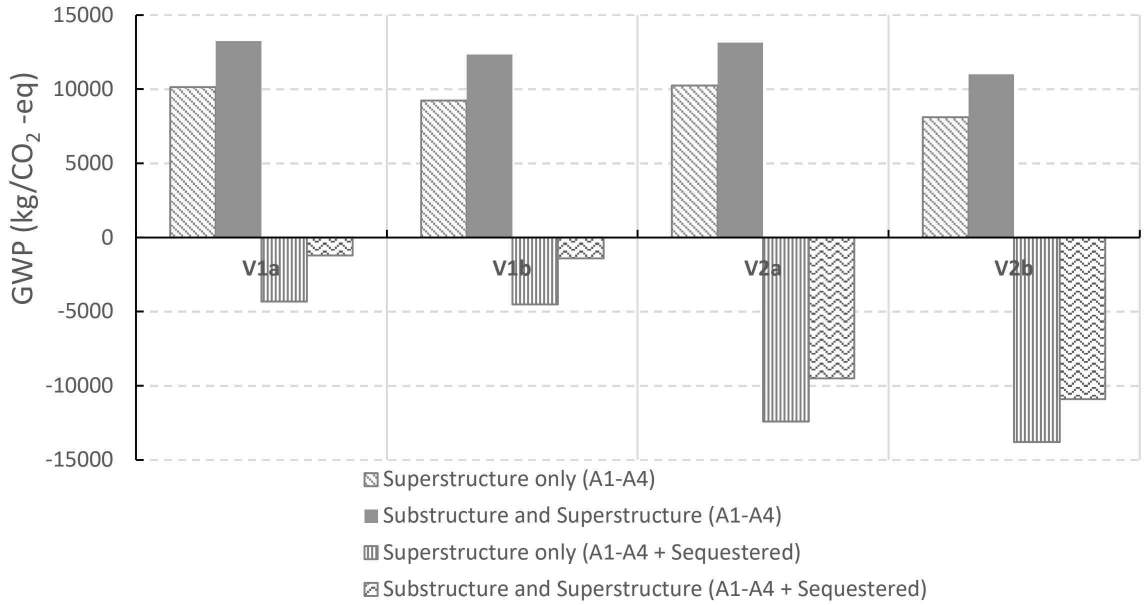

Figure 10. GWP impact of homegrown, wood fibre-rich designs including carbon sequestration. Source: Figure created by authors.

When considering iteration V2a, featuring imported wood fibre-rich materials, the overall GWP is 10,238 kgCO_2-eq. In this iteration, the analysis shows that substituting the traditional block and render finish for timber cladding, provides the greatest overall saving (31% reduction in GWP when considering the carbon sequestration) when compared to V1a/V1b. Other significant savings can be achieved by substituting the plasterboard for internal wood lining, (26.8% reduction in GWP compared to V1a/V1b,) however, due to fire regulations this option is not recommended.

Iteration V2b, the wood fibre-rich house utilising, where possible, homegrown wood fibre-rich products, provides the most significant GWP savings in this study. In comparing iterations V2a and V2b, significant savings can be found in selecting homegrown wood fibre-rich products (providing an 11.2% saving when compared to the imported alternative). The GWP of all products selected for this study is provided in Table 3.

5. Conclusions and Discussion

This study has investigated the environmental impact of selecting homegrown, wood fibre-rich products in the design and construction of a standard 3-bedroom, semi-detached house built to meet the Bronze Standard, as set out in the Scottish Building Standards.

The study has found that in selecting the most advanced version of the homegrown, wood fibre-rich build-up (V2b), the total carbon sequestration for the superstructure increases from -4,315 kg/CO_2eq to -13,802 kg/CO_2eq. This represents a 220% reduction in Global Warming Potential (GWP) when compared to the benchmark build-up featuring imported wood fibre-rich products (V1a).

As such, this study has demonstrated that digital tools can be optimised to minimise environmental impact in the selection of construction details and materials, without compromising performance. However, influencing building professionals in the UK to adopt the use of natural materials such as wood fibre insulation is a significant challenge, particularly if the policy has not imposed targets or specific minimal adoption requirements of bio-based building materials in projects. An example of policy intervention can be found in France, where a regulation introduced in 2020 stipulated a minimum proportion of bio-based materials, leading to a 13% growth in the market for such products (Rabbat *et al.*, 2022). One of the challenges is that building professionals in the UK are preoccupied with achieving a very low U-value of building structures to meet stringent operational energy and carbon levels. While the implementation of high-performing insulation achieves this, switching to lower-performing natural fibres requires increasing the thickness to achieve similar U-values, forcing the re-design of building components. Although lower GWP of wood fibre materials is an important factor, the improvement of the thermal conductivity requires testing and innovation to be competitive in the UK market and change perceptions among the industry.

To reap further environmental benefits from the use of homegrown wood fibre-rich products, it is suggested that the construction industry in Scotland make efforts to expand upon the range of products that are currently manufactured domestically. This process would include further investigation into the capability and availability of natural fibres such as waste sisal, jute, hemp and those using animal bi-products (such as sheep's wool or textile waste). At present, such products are at their manufacturing infancy, and mostly used for high-end, bespoke new-build homes and retrofit projects.

Concerning some of the limitations and challenges of wood fibre-rich products such as wood fibre insulation, the success of the adoption into mainstream construction practices depends on the supply chain for homegrown softwood and hardwood to be processed into fibres and manufactured into insulation which will impact the overall cost of the product. Needed are specific markets, such as the new-build and retrofit of buildings, with enough assured supply of products to justify investment by existing or new companies into manufacturing such products. Legislation and a push for specific dwelling embodied carbon targets by the government would support this drive into specific markets, which drive costs down and increase availability to purchase such products, instead of relying on imports.

Furthermore, increased efforts are required to develop frameworks for mass home building to adopt natural insulation products and increase the specification of wood-fibre-rich structures. This requires support from the government to set up new manufacturing plants to process wood-fibre products and to enhance research on the blending of varying fibre types in line with supply chains and seasonal raw material availability. Similar approaches from other countries to impose legislation and create a wider awareness of the co-benefits of wood fibre products in buildings will increase demand and create confidence in the construction industry to invest and modify their building specifications.

However, given the substantial capital costs involved in assembling new manufacturing plants, or reconfiguring existing plants, any such decisions must be underpinned by robust market research. In this regard, the following lines of enquiry would form the basis for future research within this field:

- Develop further design iterations to evaluate the environmental impact (GWP) of meeting more stringent standards (i.e. Silver, Gold and Passivhaus).
- Evaluate potential demand for homegrown, wood fibre-rich products (as an alternative to standard products), including the identification of barriers.
- Assess manufacturing capability and full economic analysis.
- Perform a detailed sensitivity analysis examining the impact of variations in transportation modes on environmental impact (GWP).

Although this study focused on the thermal and environmental attributes of the construction materials, evaluation of the structural characteristics (mean density, ρmean) of each product is critical to ensure the integrity of the building. As such, the research team intends to further investigate the load-bearing implications of selecting wood fibre-rich products, the findings of which will be reported upon in a subsequent publication.

Another line of inquiry is to further understand the performance of wood fibre-rich products concerning fire safety. As confirmed by many experts, natural fibre insulation is a flammable material and will inevitably burn during a fire, however, one advantage is that it will do so more slowly and far more predictably compared to other materials. This allows for a safer and more timely escape route in case of a fire. A key concern is that wood fibre-rich materials can still contribute to the fuel of a fire, but one advantage is that it will release less toxic smoke compared to synthetic products that can severely harm occupants.

Whilst the impact of this study has clear implications in Scotland, it is intended that the methodology adopted is both replicable and scalable in other locations where building regulations, availability of materials and climatic variations are different. Such studies would further enhance our collective understanding of the benefits of sourcing local, wood fibre-rich products in the provision of housing.

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