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Life cycle carbon and cost assessment comparing milled and whole timber truss systems and insulation options for affordable housing

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ABSTRACT

Increasing demand for housing is one of the biggest challenges facing the world. Affordable housing is a key priority of the UK government in addressing this challenge, which calls for innovative construction methods to address the issue of fuel poverty at an affordable cost. Timber-based modern methods of construction are one of the key solutions to resolve the existing housing crisis while managing climate change. Therefore, this paper presents a case study of "Integra House", which is a proof of concept of a novel truss technology. The case study is an affordable housing prototype that performs well in both life cycle carbon and cost. The proposed construction uses a novel timber truss technology which makes up the floor, walls and roof of the house, thereby reducing on-site operations and waste while providing a low-carbon low-cost design. The prototype underwent design optimisation and evaluation of options; workshop-based production and performance evaluation of elemental prototypes; production and performance evaluation of a full-scale dwelling prototype; and comparison of capital and life cycle costs and environmental impacts. Further, it underwent a simulation-based optimisation to maximize its performance in cost and carbon by replacing milled timber trusses with whole timber trusses and Rockwool insulation with wood wool insulation. The optimised design option (whole timber) has an EC of 261kgCO_2per m^2 and costs £682 per m^2 (excludes substructure, services and fitout) and its operational carbon is 7.9 kgCO_2 per m^2/annum and costs £3.30 per m^2/annum to operate. Life cycle costs and carbon comparison of the two design prototypes concluded that the whole timber design outperformed the milled timber design in both cost and carbon aspects, by 23% and 30% respectively due to being extremely inexpensive and requiring minimal processing compared to the milled timber option.

1. Introduction

The increasing demand for housing coupled with a limited supply is posing a massive challenge to the UK housing market. A briefing paper published by the House of Commons reported that 240,000 to 340,000 homes need to be built each year up to 2031 of which 145,000 must be affordable homes to meet the existing demand in England [33]. The same is true for Scotland, which reportedly requires at least 12,000 affordable homes each year [26]. Affordable housing is a global phenomenon with over 300 million urban households living in substandard housing around the world or are overwhelmed by housing costs [20]. A more recent report analysing affordability ratings for 92 markets in 8 nations found that 36 housing markets are severely unaffordable which includes Hong Kong and some cities in Australia, New Zealand, Canada, the United States of America, Ireland, and Singapore [37]. Further, Wetzstein [34] adds that affordable housing outplays other serious housing-related shortcomings including health, energy efficiency and climate change.

The problem gets more complex with the sustainability layer added on. The UK construction industry has set itself a target of a 33 % reduction of construction costs and a 50 % reduction of Greenhouse Gas (GHG) emissions in the construction 2025 vision. Similar targets exist in many other countries as well (i.e., Paris Agreement). Carbon and cost are the current yardsticks of construction projects [1,25,32], hence, optimising both is a challenge facing most designers and other construction professionals in achieving these targets. A report by McKinsey Global Institute

Abbreviations: EC, Embodied Carbon; MMC, Modern Methods of Construction; OSM, Off-Site Manufacture; CLT, Cross Laminated Timber; BoQ, Bill of Quantities; ICE, Inventory of Carbon and Energy; OC, Operational Carbon; BCIS, Building Cost Information Services.

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[20] on the global affordable housing crisis found that reducing construction costs through value engineering and increasing operational and maintenance efficiency along with other external factors can reduce housing costs by 20–50 %. This is validated by Davies's [9] work which reports that Modern Methods of Construction (MMC) can help tackle the housing crisis at a sustainable cost if designed thoughtfully and considered early in the design stage.

This paper, therefore, presents a proof of concept of a sustainable affordable housing typology named 'Integra House 1′ with a novel milled timber truss technology which made up the floor, wall and roof of the house. Later, the design went through simulation-based optimisation by substituting milled timber trusses with whole timber trusses and Rockwool insulation with wood-wool insulation, generating the design of a second prototype called 'Integra House 2′. This paper evaluates both design prototypes concerning their life cycle costs and carbon performance which are not often compared together in the literature, yet important parameters in evaluating sustainable designs. Finally, the paper addresses the following Research Questions (RQs):

RQ1: Between Integra House 1 and Integra House 2, which design prototype has lower life cycle carbon?

RQ2: Between Integra House 1 and Integra House 2, which housing prototype has lower life cycle cost?

2. Theory

O'Neill and Organ [23] argue that literature on British prefabricated low-rise housing can be traced back to the twelfth century (i.e., cruck frame) and became prevalent during the Industrial Revolution and the twentieth century, with further development in the form of MMCs in the twenty-first century. Kempton and Syms [18] (2009, p.37) define MMC as "building systems that are either manufactured and joined away from the site (off-site manufacture (OSM) or a series of components that are manufactured off-site and brought together on-site for assembly". Examples include Cross Laminated Timber (CLT), modular construction, off-site manufacturing, design for manufacture and assembly. Past studies [5,17,21] indicate that MMC perform well in terms of embodied energy, hence reducing embodied carbon emissions. In addition, improved quality and speedy construction of MMC also make this construction preferable to conventional construction.

Fig. 1 presents embodied carbon figures of different types of frames/external wall construction per 1 m^2 of the external wall that has a u-value of 0.3 W/m^2K [5]. Accordingly, the least carbon-intensive option is to be timber cladding on a timber frame followed by a render system on a timber frame, masonry on a timber frame and masonry cavity wall. The most carbon-intensive option is curtain walling. This suggests that the use of high amounts of processed materials increases the carbon impact of the building. Further, a study by Monahan and Powell [21] reported that the MMC timber frame with larch cladding outperformed its equivalent MMC timber frame with brick cladding and conventional masonry cavity wall (u value 0.18 W/m^2K) and was proven to achieve a 34 % reduction in embodied carbon. Similarly, Iddon and Firth [17] demonstrated that a 24 % reduction in embodied carbon is possible through building fabric changes moving from traditional construction methods to MMCs. A similar study conducted in China by Li et al. [19] reaffirms that replacing high-carbon materials with low-carbon materials (such as straw bales) can reduce embodied carbon by 39.54 % in rural houses. This compelling evidence in the literature suggests that MMC for housing is an efficient way forward towards reaching carbon reduction targets while meeting the housing demand.

The total annual Global Warming Potential (GWP) from the whole UK housing sector amounts to 132 million tonnes of CO_2e which over the 50-year lifetime amounts to nearly 6.6 billion tonnes of CO_2e. This is 11 times higher than the 2012 total UK emissions of CO_2e [7] with use stage contributing the most to the overall emissions from buildings. Therefore, Cuéllar-Franca and Azapagic [7] argue that improvement opportunities in the housing sector predominantly lie in the use stage. Furthermore, Zhu et al. [35] found that the embodied carbon of residential buildings is approximately 1.5–2.2 times that of non-residential buildings and the annual embodied carbon is roughly 50 % of the total carbon emissions of the Chinese building sector. Accordingly, paying attention to residential embodied carbon over its life cycle is crucial in controlling emissions from the building sector. A literature survey on buildings' life cycle energy encompassing 60 cases from nine countries reported that despite embodied energy of solar

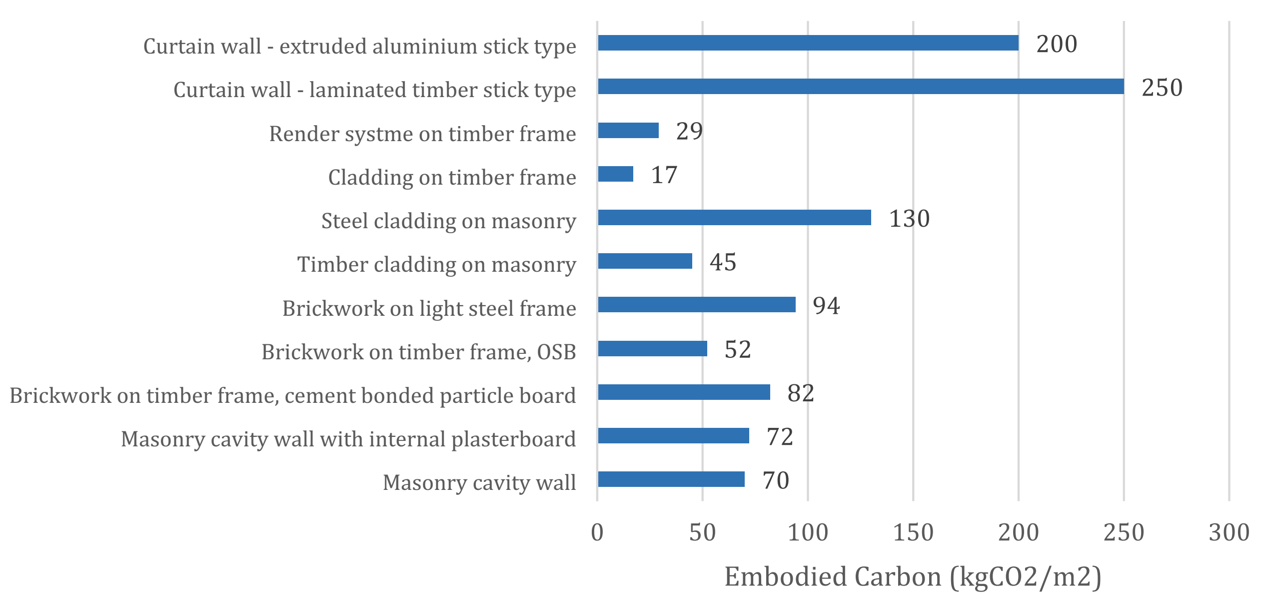

Fig. 1. Embodied carbon values of various external wall constructions in domestic buildings. Source: [5]

houses being doubled compared to conventional houses, solar houses have proven to be more energy efficient as these buildings reduce the 'use stage' energy demand. On the other hand, a passive house is found to be more energy efficient than solar houses and the embodied energy of a passive house is only slightly higher than a conventional building [29]. Nonetheless, embodied carbon of passive house designs can be reduced by opting for a full timber option as demonstrated in the study of Monahan and Powell [21] due to timber being a virgin material with very low embodied carbon.

In 2019, 22 % of timber grown in the UK was used as woodfuel/ biomass [10], this represents 2.6 million tonnes, and this amount increases year on year. The burning of biomass not only releases the embodied carbon of those trees back into the atmosphere but also creates significant amounts of particulate matter that is known to be harmful to human health, particularly in urban environments. By creating timber products from these trees and sequestering the carbon dioxide, a significant reduction in greenhouse gases can be achieved for decades to come. Bukauskas et al. [2] have shown the possibilities of using whole timber in construction. The creation of structures using small roundwood timber is also nothing new. Burton et al. [6] demonstrated that several different types of structures could be constructed in this way. The variety of structures includes post and beam structures, gridshell and pre-tensioned domes. Many believe that MMC is the way forward for the industry to resolve the existing housing crisis and tackle climate change [9,22].

In summary, an abundance of evidence from the literature favour whole timber constructions over conventional construction to reduce carbon emissions from the housing industry to meet the housing demand. One has to tap into the 'use stage' carbon reduction opportunities to achieve the highest possible emission reduction. Buildings with Passihavus standards arguably render the highest 'use stage' or operational carbon savings while their embodied carbon is in-par or slightly higher than a conventional building. This implies that the choice based on life cycle carbon performance alone is undisputed, but sometimes the decision-making becomes an exercise of a trade-off between cost and carbon when life cycle cost is introduced. Apparently, there is a dearth of studies that investigate both life cycle carbon and cost which are considered the dual currency of construction projects. Much of the existing literature focuses on comparisons of timber construction against concrete and steel [8,12,13,16,27,30]. It is also difficult to find studies that have compared the life cycle carbon of one form of timber (MMC) with another form. Therefore, the case study presented in this paper fills that gap by investigating both the life cycle carbon and cost of two similar, but different passive house prototypes that uses two forms of timber for a novel truss technology, a new addition to the MMC family. Both prototypes combine the energy and carbon benefits of timber (as a material), MMC, and passive design principles, and outperform traditional construction methods. The design options presented in the paper also provide an innovative solution to the rural affordable housing issue facing the UK which is both cost and carbon efficient.

3. Material and methods

3.1. Research approach

The case study approach was chosen to test the proposed design typology for affordable housing as it helps to study a problem wholly and in-depth (Yin, 2009). Moreover, the case study approach is widely used by scholars to test design prototypes and study the carbon impact of different house typologies (see for example, [7,21].

3.2. Description of the case study – Integra House

The pilot case study (Integra House 1) is situated in Tyrie, which is located approximately 6.8 km southwest of Fraserburgh. The form and proportions of the proposed house respect the fine tradition of Scottish vernacular architecture. It responds to local conditions, whilst demonstrating key characteristics of good contemporary architecture. The house is rectangular shaped with a Gross Internal Floor Area (GIFA) of 125 m^2 spread over two (2) floors and comprises three (3) bedrooms. The Integra House construction is based on a new truss type that forms the superstructure and the envelope for the entire house as illustrated in Fig. 2, Fig. 3 and Fig. 4. The truss makes the frame (wall, floor and roof) of the house and is spaced at 600 mm centres. A total of 39 trusses were used to build the house.

The completed prototype underwent research by design; workshop-based research and post-construction evaluation in the following stages:

1. Design optimisation and evaluation of options of prototypes of truss profiles, fabric elements and the complete dwelling;
2. Production and performance evaluation of elemental prototypes at the Built Environment-Smarter Transformation Scotland (BE-ST) facilities based at Hamilton International Technology Park, 3 Watt Pl, Blantyre, Glasgow. Construction Scotland Innovation Centre (CSIC), Glasgow;
3. Production and performance evaluation of a full-scale dwelling prototype in rural Fraserburgh;
4. Comparison of capital and life cycle costs and environmental impacts of the prototype with existing models of affordable low-cost housing; and,
5. Experiments on a concept of heat distribution from a wood-burning stove located in the lounge to the unheated bedrooms.

The Integra House is a very low-energy home that reduces the heating requirements compared to the traditional timber kit houses due to its design of 450 mm thick walls comprising of 400 mm thick truss and insulation to achieve a low u-value (see, Fig. 3). The external walls and roof are cladded with 45 X 45 mm Scottish larch timber. The chosen materials change in colour and texture, ageing gracefully in harmony with changes in the seasons. The living spaces have large, glazed surfaces with external decking towards the south which will enjoy plenty of natural light and views (see, Fig. 4). The house was built to Passivhaus standards and therefore eliminated the need for a dedicated heating system. It relies on a backup heating system like Radiators and a wood-burning stove in the main room. Heating is transferred from the living room to the bedrooms using innovative convection and pressure changes.

To further optimise the design of Integra House 1, Integra House 2 was modelled with whole round timber trusses and the insulation of Integra House 1 was replaced with wood wool (loose) insulation (see, Fig. 5) which is comparatively cheaper and embodies very little carbon (around 0.49kgCO2/kg of wood wool) compared to conventional insulation. The truss is made of forest thinnings which are far cheaper than wholesale roundwood. So, using these timbers for construction (rather than burning them as biomass) would be competitive compared to the imported milled timber grades currently used. To determine the size of whole timbers to use in the design of the whole timber truss, a simple geometric engineering substitution was made by assessing the area and second moment of area of round timber as the strength of a structural element is determined by its geometry and two engineering prop-

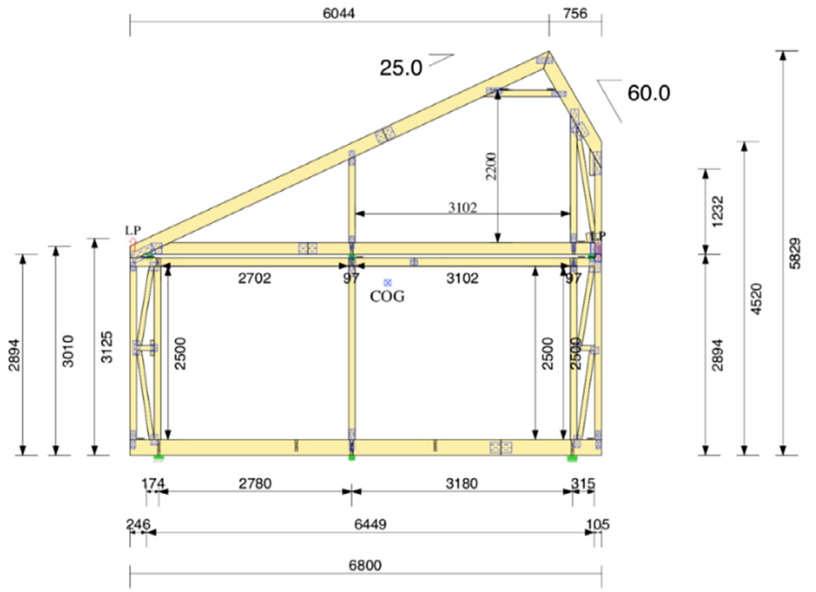

Fig. 2. Integra House 1 Truss Design.

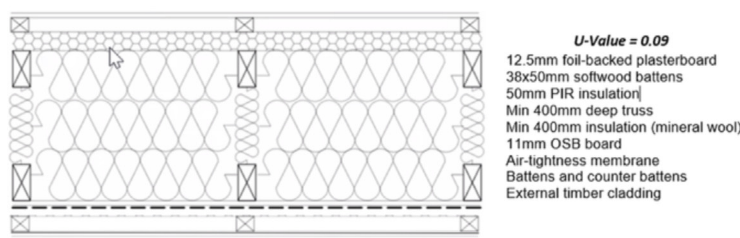

Fig. 3. Integra House Wall Build-Up.

Fig. 4. Integra House 1 Construction Process.

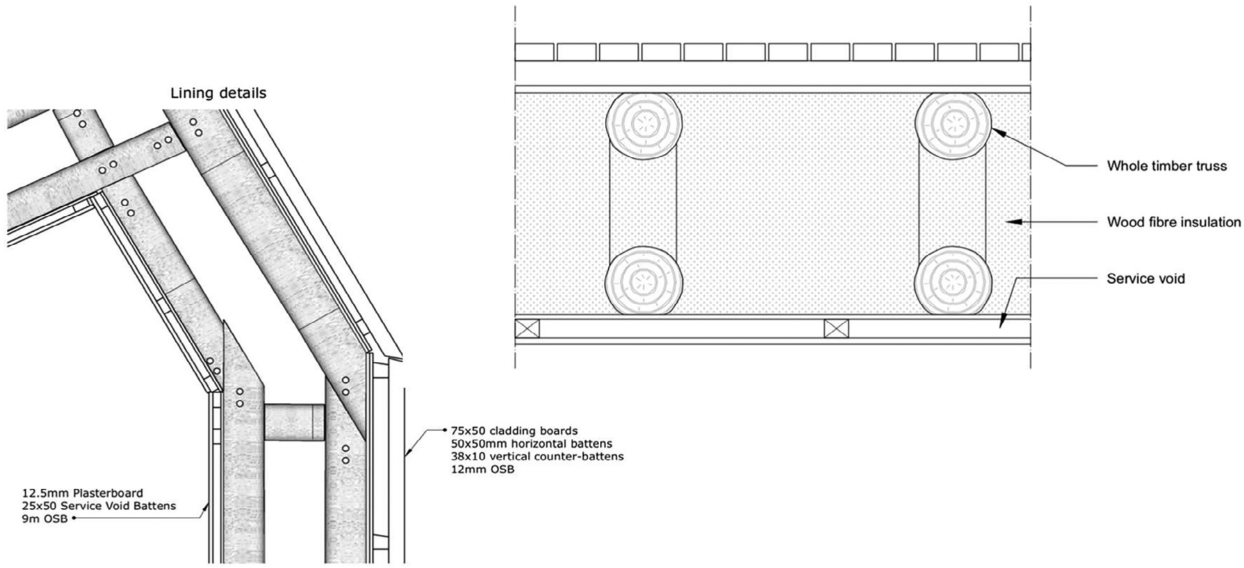

Fig. 5. Integra House 2 Wall Details.

Table 1
Substitution table for round timber weight calculation.

TR-26 timber size		Percentage weight increase where round timbers are stronger than rectangular timbers																				
mm	mm	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180
38	97	n/a	n/a	173%	192%	213%	235%	258%	282%	307%	333%	360%	388%	418%	448%	479%	512%	545%	580%	616%	653%	690%
38	75	176%	199%	223%	249%	276%	304%	333%	364%	397%	431%	466%	502%	540%	579%	620%	662%	705%	750%	796%	844%	893%
47	72	149%	168%	188%	209%	232%	256%	281%	307%	334%	363%	392%	423%	455%	488%	522%	558%	594%	632%	671%	711%	752%
47	97	n/a	n/a	n/a	155%	172%	190%	208%	228%	248%	269%	291%	314%	338%	362%	388%	414%	441%	469%	498%	528%	558%
47	122	n/a	n/a	n/a	n/a	n/a	n/a	166%	181%	197%	214%	231%	250%	268%	288%	308%	329%	351%	373%	396%	419%	444%
47	147	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	192%	207%	223%	239%	256%	273%	291%	309%	329%	348%	368%
47	172	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	204%	219%	233%	249%	265%	281%	298%	315%
47	197	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	217%	231%	245%	260%	275%
47	222	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	231%	244%

erties governing its performance including Area and Second Moment of Area. Table 1 shows the diameters of timbers that match or exceed the structural performance of equivalent rectangular sizes. Rectangular sections are more efficient per unit mass when it comes to these properties. Hence, there is an increase in weight when using equivalent round timbers.

3.3. Life cycle assessment

The life cycle assessment of Integra House was carried out following EN 15978. The steps followed in the assessment are shown in Fig. 6.

Accordingly, the purpose of the assessment was to compare the Embodied Carbon (EC) and the cost of Integra House 1 and Integra House 2 to identify the more economical and eco-friendly design solution. The object of the assessment is the case study building "Integra House" - Integra House 1 was built of milled timber trusses and Rockwool insulation whereas Integra House 2 is modelled with whole timber trusses and wood wool (loose) insulation. Structural elements of the two buildings were compared including the ground floor, frame, upper floors, roof, external walls, internal partitions and windows and doors.

The Bill of Quantities (BOQ) of Integra House 1 was used as a baseline to estimate the likely embodied carbon and cost of Integra House 2. Milled timber trusses were replaced with whole timber trusses and all insulations were replaced with wood wool (loose) to make Integra House 2 a whole timber solution. Key EC databases including Inventory of Carbon and Energy (ICE, v2.0, v3.0) [15,36], the UK Building Blackbook [11] and other online sources were used to calculate the embodied carbon and cost of Integra House 1 and 2. Transport EC was calculated using the EC coefficients obtained from the guide published by The Institution of Structural Engineers [24] which were based on published greenhouse gas reporting conversion factors.

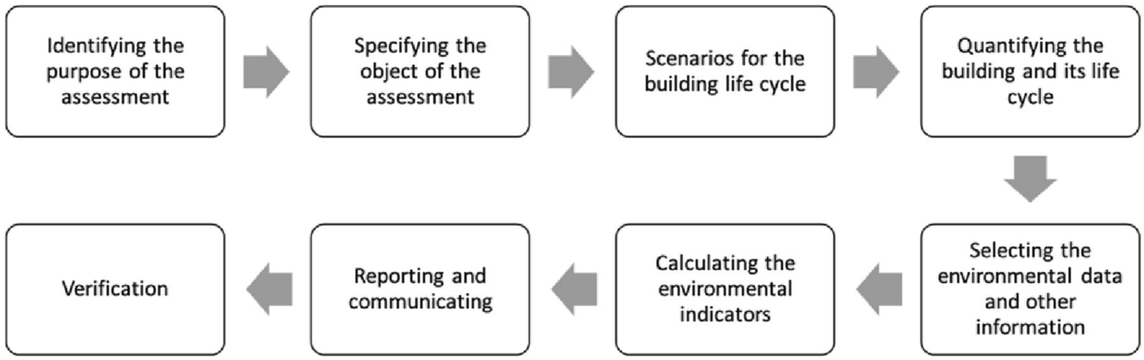

Fig. 6. Process steps for the assessment of the environmental performance of buildings, adapted from Fig. 3 in EN 15978, Source: BRE [5].

The cost and EC of an item/material are calculated as follows:

$$CCorEC_{m/i} = Q_{m/i} \times CCForECF_{m/i}$$

Where,$CCorEC_{m/i}$-Capital Cost (CC) or EC of a material or an item$Q_{m/i}$-Quantity of the respective material (usually in kg) or item (m, m2, m3, nr etc.)$CCForECF_{m/i}$–CC or EC factor of the respective material (kgCO2/kg of material) or item (kgCO2/unit of the item).

Then, the items/materials were grouped into elements as per the New Rule of Measurements (NRM1) element classification which is the current elemental standard adopted in the UK construction industry [28]. Elemental cost per Gross Internal Floor Area (GIFA) and elemental embodied carbon per GIFA were then calculated to normalise the values for comparison purposes. The equation used to calculate the elemental unit costs/carbon is as follows:

$$CCorECperGIFA_n = \frac{CCorEC_n}{\mathrm{GIFA}}$$

Where,$CCorECperGIFA_n$–CC or EC per GIFA of element 'n'$CCorEC_n$-Total CC or EC of element 'n'GIFA - Gross internal floor area of the building.

All costs were adjusted to 2020 3Q and Scotland by obtaining indices from BCIS [4,3]. Annual operational energy for space heating and lighting was simulated using the EDSL Tas software package. Hourly dynamic thermal simulations for the Integra Houses 1 and 2 were simulated based on the specification of construction elements, as-built drawings, site location, and orientation and the resultant U-values shown in Table 2. It also included the specification of a weather conditions file for Aberdeen Dyce – the location of the nearest weather station. The surrounding context was specified as rural terrain with a flat profile and a ground solar reflectance of 0.2(0–1). A standard calendar with 8 public holidays (NCM standard calendar) was specified with 15 pre-conditioning days for the energy calculations.

Table 2
Elemental U-values of Integra Houses 1 and 2.

Element	U-Values (W/m^2.°C)	
	Integra House 1	Integra House 2
Ground Floor	0.109	0.095
Door and Window Frames	1.001	1.001
Upper Floor	0.323	0.317
External Walls	0.090	0.077
Roof	0.111	0.149
External Windows & Door panes	1.001	1.001
Roof window	1.200	1.200
Internal Partitions	0.355	0.347
Internal Doors	1.001	1.001

4. Results and discussions

4.1. Integra House 1 vs Integra House 2

4.1.1. Product stage

Table 3 presents a comparison between EC and cost figures of Integra House 1 and Integra House 2, i.e., milled timber vs whole timber option. The design of Integra House 2 has made a reduction possible in all the elements studied (except for windows and doors which were identical) making the whole timber option more attractive than Integra House 1. This is a 55 % reduction in EC and a 28 % reduction in cost compared to Integra House 1. However, it should be noted that the embodied carbon of trusses is higher for the whole timber option compared to the milled timber option due to the increase in weight of the whole timber trusses by almost 100 % to achieve the same structural performance. This was due to the whole timber being younger thinnings, which are expected to be weaker in strength than the mature trees that are used for milled timber. The reduction in EC was mainly achieved by substituting insulation with wood wool insulation. On the contrary, the cost is minimal for the whole timber option as the selected type of timber is not normally used for structural purposes, hence, the cost of procuring whole timber appears to be very low, resulting in a significant reduction of cost for the whole timber option.

The EC and cost profile of the elements are presented in Fig. 7. External walls can be identified as an EC hotspot, and the External Walls of Integra House 2 are responsible for nearly-two-thirds of the total EC. This is mainly due to trusses being included in the external wall element and the EC of whole timber trusses accounts for 65 % of the external wall EC. Yet, the EC of Integra House 2 walls is 82kgCO_2e/m^2 of external wall area which is 35 % lower than Integra House 1. The second most carbon-intensive element is the Roof followed by Ground Floor. Similarly, External Walls and Roof are to be the most cost-significant elements in both cases as well. This is mainly attributed to the weight of materials in these elements resulting in high carbon and costs compared to other elements.

Transport EC and cost will be the same for both Integra House 1 and 2 for a given site for all elements except for the trusses and is reported to be very low compared to the total EC (as low as 2 %, see Monahan and Powell [21]). The timber for Integra House 1 was imported from Sweden and taken to Perth from Montrose for production and delivered to the site in Fraserburgh. On the other hand, the whole timber trusses can be sourced from forests within 50 miles (80 km) radius of the site. Accordingly, the transport EC for the trusses is presented in Table 4. The figures are insignificant compared to their total EC and replacing imported milled timber trusses with locally sourced whole timber trusses would mean 76 % savings in the transport EC.

Table 3
EC and cost profile comparison between Integra House 1 and 2 (A1-A3).

	EC per GIFA ($kgCO_2e/m^2$)		CC per GIFA (£/m^2)	
	Integra 1	Integra 2	Integra 1	Integra 2
Ground Floor	130	26	113	74
External Walls (Frame incl.)	228	167	386	233
Upper Floor	13	10	32	28
Roof + Rainwater good	195	48	302	241
Internal Partitions	10	7	24	21
Windows and Doors	3	3	86	86
Total	**580**	**261**	**942**	**682**

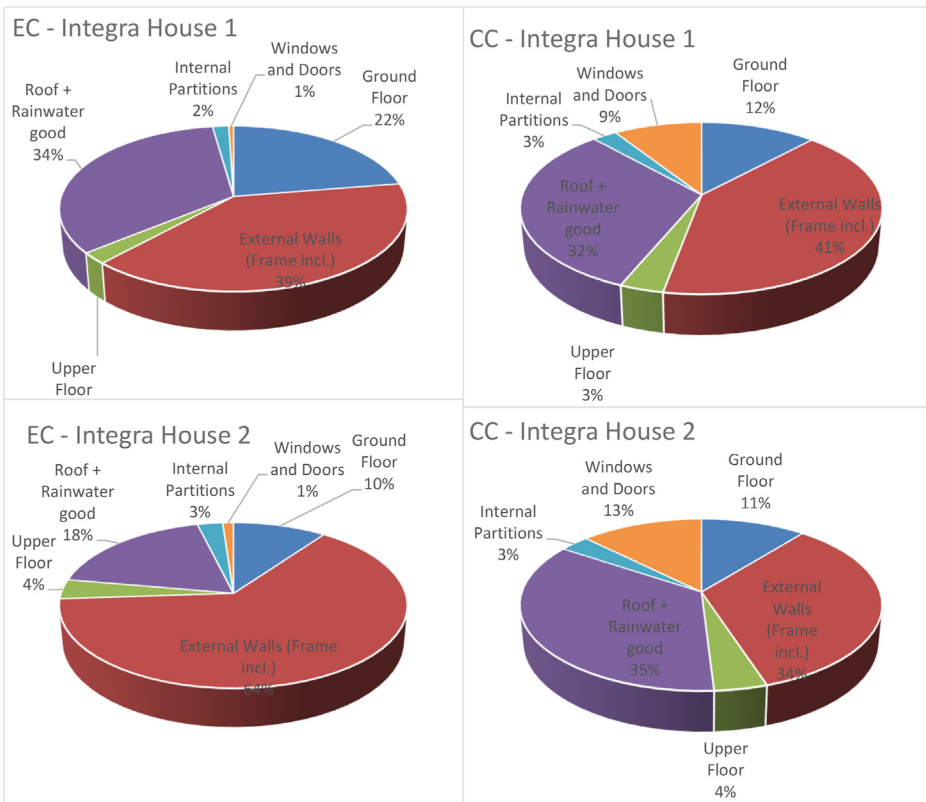

Fig. 7. EC and cost profile of Integra House 1 and 2.

Table 4
Transport EC (A4).

	Distance (km)	EC Coefficient ($gCO_2e/kg/km$)	Integra House 1 ($kgCO_2e$)	Integra House 2 ($kgCO_2e$)
Sea	2640	0.01614	8.522	
Road	265	0.10650	5.645	
	80	0.10650		3.408
Total			14.167	3.408

4.1.2. Construction stage (A5)

With regards to the construction EC and cost, the truss erection operation of Integra House 2 can be completed within a day by two labourers similar to Integra House 1 truss erection, while all other operations will be the same except for the insulation installation. The difference being Integra House 2 relies on wood wool blowing operation which requires power while the conventional insulation installation does not require additional power. This, however, is insignificant compared to the savings achieved in the cradle-to-gate stage.

4.1.3. Use stage (B1-B6)

EC and costs during the use stage will be the same for repairs, maintenance, and replacements due to the same components (apart from trusses and insulation which are sealed and do not require repair, maintenance, or replacement during the life of the house); Operational Carbon (OC) and costs of water usage will also be the same if the two houses were to be used by the same occupants.

Fig. 8 presents the operational carbon of Integra Houses 1 and 2. OC of Integra House 1 was estimated to be 7.8 $kgCO_2e/m^2$ GIFA/an-

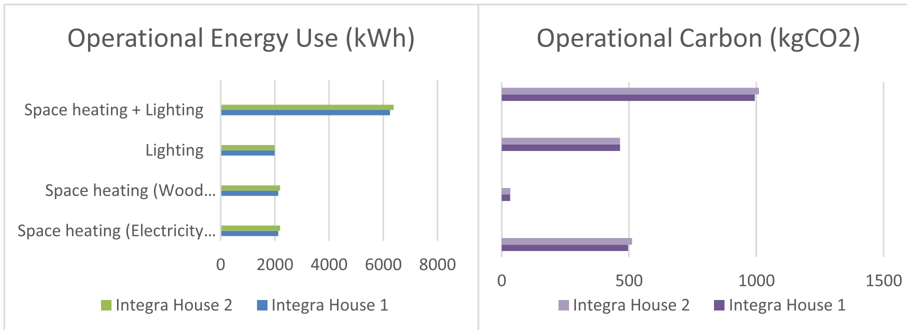

Fig. 8. Annual operational energy (KWh) and operational emissions (kg CO2e) for Integra Houses 1 & 2. *Conversion factors: KWh to kg CO_2e = 0.23314 for electricity and 0.01545 for wood pellets/chips* [31].

num while Integra House 2 was slightly higher at 7.9 $kgCO_2e/m^2$ GIFA/annum.

4.1.4. End of life stage (C1-C4)

EC and costs of demolition of trusses and other components are to be the same for Integra House 1 and 2. However, in terms of waste processing and disposal, EC and costs for wood wool insulation in Integra House 2 will be lower compared to the synthetic insulation in Integra House 1, as it can be decomposed locally in a compost pit or compost bags. The insulation used in Integra House 1 will have to be disposed of properly for which fees for transportation and disposal will be incurred.

Table 5
End-of-life options for Integra House 1 and 2.

	Integra House 1	Integra House 2
Re-use	Milled timber trusses can be re-used in construction or other purposes	Whole timber trusses can be re-used in construction or other purposes
Recycling		Wood wool can be upcycled into timber products such as chipboard and wood fibreboard
Recovery		Whole timber truss can be used for energy recovery

4.1.5. Benefits and loads beyond the system boundary (D)

Benefits beyond the system boundary include reuse, recovery and recycling potential. Some timber products can be reused or recycled into a new material or product. The possible end-of-life options available for Integra House 1 and Integra House 2 are presented in Table 5.

4.2. Integra House vs Conventional and other MMCs

Table 6 presents a comparison of the study findings with the literature findings of three studies including Monahan and Powell [21], Hacker et al. [14] and Iddon and Firth [17]. Monahan and Powell [21] studied a 45 m^2, 3-bedroom semi-detached house while Hacker et al. [14] studied a 65 $m^{2,}$ 2-bedroom semi-detached house. Both case studies have a similar layout. Iddon and Firth [17] analysed a 166 m^2, 4-bedroom detached house similar to Integra House. Yet, Integra House has a unique form and structure (i.e., integrated truss) that is different from the other three studies. It is also important to note that the u-value of the Integra House walls is lower than the reported studies because Integra House walls are designed to Passivhaus standards.

Monahan and Powell's [21] case study had a system boundary of cradle-to-site which included emissions associated with transport, waste, disposal and construction and used several data

Table 6
Comparison of study findings with the literature findings.

Study	Frame type	Product Stage EC ($kgCO_2e/m^2$ GIFA)	Operational Carbon ($kgCO_2e/m^2$ GIFA/annum)
Monahan and Powell [21] (3 bedrooms, semi-detached, 45 m^2, excl. internal finishes and fittings, wall u-value 0.18 W/m^2K)	Timber frame timber cladding (273 mm thick walls)	332	Not given
	Timber frame brick cladding (319 mm thick walls)	535	
	Masonry (327 mm thick walls)	612	
Iddon and Firth [17] (4 bedrooms, detached, 166 m^2)	Traditional masonry (312.5 mm thick walls, U-Value 0.29 W/m^2K)	297	17.24
	Heavyweight construction (300 mm thick walls, U-Value 0.35 W/m^2K)	226	19.32
	Timber frame (385 mm thick walls, U-Value 0.15 W/m^2K)	337	17.46
	Structural Insulated Panels (SIP) (350 mm thick walls, U-Value 0.17 W/m^2K)	319	15.86
Hacker et al. [14] (2 bedrooms, semi-detached, 65 m^2, two-storey, wall u-value 0.27 W/m2 K)	Timber frame with brickwork cladding (lightweight)	493	Not given
	Mediumweight concrete block with brickwork cladding (medium weight)	512	
Integra House (3 bedrooms, detached, 125 m^2, excl. foundations, internal finishes and fittings, 450 mm thick walls)	Milled timber + conventional insulation (u-value 0.09 W/m^2K)	580	7.8
	Whole timber + wood wool insulation (u-value 0.07 W/m^2K)	261	7.9

Table 7
Life cycle cost and carbon summary.

	Carbon (kgCO2e)			Cost (£)	
	Integra House 1	Integra House 2		Integra House 1	Integra House 2
Embodied (A1-A3)	72,500	32,625	**Capital**	117,750	85,250
Operational (B6)	58,500	59,250	**Operational**	24,300	24,675
Life Cycle Carbon	131,000	91,875	**Life Cycle Cost**	142,050	109,925

sources such as published Government carbon emission factors, ICE, ecoinvent and U.S. Life-Cycle Inventory. Hacker et al.'s [14] EC values primarily came from the Institution of Structural Engineers' publication, but the system boundary is not explicitly stated. Iddon and Firth [17] used the ICE database and adopted a cradle-to-gate system boundary. Based on the analysis of the scope of these studies, Integra House is expected to mimic Iddon and Firth's [17] study findings, but the values reported by Iddon and Firth [17] appear to be very low. This may be due to Iddon and Firth [17] including only key materials in the analysis. Similarly, Monahan and Powell [21] included only key materials in their analysis. It can also be noted that the EC figures of Hacker et al. [14] are slightly lower than Monahan and Powell [21] because of the use of varied data sources and the scope of analysis (i.e., elements covered and wastage allowance). These differences (i.e., different system boundaries, data sources, scope and specification of elements) make a comparative analysis of findings almost impossible. Nevertheless, Integra House 2 outperforms all other designs including Integra House 1 in product stage EC.

The operational carbon of Integra House 1 was estimated to be 7.8kgCO$_2$e/m^2 GIFA/annum while Integra House 2 was slightly higher at 7.9 kgCO$_2$e/m^2 GIFA/annum. Accordingly, over a 60-year life cycle, Integra House 2 will have a total emission of 59,250 kgCO$_2$e which is 1 % higher than Integra House 1. Although, this is much lower than conventional buildings.

According to the Building Cost Information Services (BCIS), the average cost of building a traditional two-storeyed detached house is calculated to be £1,078 per m^{2}ranging between £407 per m^2 and £1,997 per m^2(superstructure only) based on 85 projects (BCIS, 2020a). This is almost comparable to the cost of Integra House 1, although Integra House 1 is 13 % less costly than standard traditional construction. On the other hand, the cost of Integra House 2 is 37% lower than the traditional house construction due to the use of forest thinnings which are not normally used for structural purposes, hence, cheaper.

Further, the 2016 report of the National House Building Foundation reports that the operational cost of a 4-bedroom detached modern housing with a GIFA of 114 m^2 costs around £1040/100 m^2/annum (BCIS, 2020b) whereas the operational cost of Integra House 1 is estimated to be £324/100 m2/annum which is 69 % lower than a conventional building. The operational cost of Integra House 2 is estimated to be £329/100 m^2/annum, which is slightly higher than Integra House 1, yet the life cycle cost of Integra House 2 is 23 % lower than Integra House 1 over a 60-year life cycle.

Table 7 presents a summary of the life cycle cost and carbon figures of Integra House 1 and 2. Integra House 2 has 55 % and 28 % lower embodied carbon and capital cost respectively compared to Integra House 1. However, considering a 60-year lifecycle, Integra House 1 performs better in operational carbon than Integra House 2, but Integra House 2 is estimated to achieve an overall reduction of 30 % life cycle carbon compared to Integra House 1.

5. Conclusions

This paper presented a case study of "Integra House", which is a proof of concept of a novel truss technology. The truss technology was aimed at reducing life cycle cost and carbon through reduced operations and installation time on site, speedy construction (reducing wet trade) and reduced on-site waste (through prefabricated elements and just-in-time delivery). The design of the truss was optimised by eliminating structural components for openings at the gable ends, and integrating the construction system for walls, roof and floor. Integra House 1 used milled timber and Rockwool insulation to form the building fabric whereas the design was later optimised by opting for whole timber trusses and woodwool insulation, creating a prototype 'Integra House 2'.

The life cycle cost and carbon analysis highlighted that Integra House 2 outperformed Integra House 1 in both embodied carbon and capital cost by 55 % and 28 %, respectively. Such a significant reduction in EC was made viable by substituting Rockwool insulation with wood wool which embodies very low carbon due to it being a natural material and its circularity. Similarly, a significant cost reduction was possible due to opting for forest thinning which is not normally used for structural construction. Integra House 2 has more benefits beyond the system boundary including reuse, recycling and recovery potential compared to Integra House 1 making it a preferable option in the context of the circular economy. With regards to the operational carbon, Integra Houses 1 and 2 were almost similar, and both houses outperformed other traditional methods of constructions. Considering a 60-year lifecycle, Integra House 1 outperformed Integra House 2 in operational carbon, although, Integra House 2 is estimated to be saving 30 % life cycle carbon compared to Integra House 1 over a 60-year life cycle.

Integra House 1 was found to be 13 % less costly than a standard traditional construction while Integra House 2 costs 37 % less than a traditional house. In-use or operational energy cost of Integra House 1 is found to be 69 % lower than a conventional building due to heavily insulated building envelope which is to Passivhaus standards. The operational cost of Integra House 1 is 1 % lower than Integra House 2, however, the lifecycle cost of Integra House 2 is 23 % lower than Integra House 1. Therefore, the case study findings reveal that Integra House 2 outperforms Integra House 1 in both life cycle carbon and cost, making it a more efficient design option in terms of both life cycle cost and carbon.

The novelty of the work lies in the proof of concept of a new timber truss technology coupled with life cycle cost and carbon analysis of two design solutions. Similar studies reported in the literature failed to address the cost aspect of low-carbon designs and mostly compared the mainstream constructions. Cost is one of the key yardsticks used by construction clients to aid decision making and low carbon design without cost benefit would not entice clients. Therefore, this paper proves that low-carbon designs that are of Passivhaus standards are possible at a lower cost closer to conventional designs, demystifying the myth that low-carbon designs are expensive. It further highlights the importance of appraising design options holistically rather than focusing on either embodied or operational carbon/costs alone. Looking at only one component can sometimes be misleading and lead to decisions that are skewed and not necessarily the right decision.

Despite explicitly demonstrating the potential economic and environmental benefits of the proposed Integra House prototypes, Integra Houses were also designed to address the issues around social sustainability. The design will address fuel poverty by reducing the energy demand of the building and hence, reducing energy bills. The lower construction cost of Integra Houe 2 means that the house is affordable. This can be achieved by locally sourcing whole timber which is normally used in low-value applications. Therefore, this investigation is a first step towards creating higher value for forest thinnings used in construction as our industry search suggests that 22 % of forest thinnings are used in low-value applications.

The paper presents further research opportunities around laser scanning during the selection of forest thinnings and exploring the possibilities of bringing whole timber to the mass market.

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Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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