Life cycle assessment of Integra House: a case study of modern methods of construction using truss technology.

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Life Cycle Assessment of Integra House: A Case Study of Modern Methods of Construction using Truss Technology

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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 constructions to address the issue of fuel poverty at an affordable cost. Timber based modern methods of constructions are believed to be a key way forward for the construction industry to resolve the existing housing crisis while managing the 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 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. Life cycle cost 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.

Keywords: Embodied Carbon, Truss, Milled Timber, Whole Timber, Cost.

1. Introduction

The ever-increasing demand for housing coupled with a limited supply is posing a massive challenge to the UK housing market. A briefing paper published by 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 (Wilson and Barton, 2018). The same is true for Scotland, reportedly requiring at least 12,000 affordable homes each year (Powell et al., 2015). The problem gets bigger and complex with the sustainability layer added on. The UK construction industry has set itself a target of 33% reduction of construction costs and 50% reduction of Greenhouse Gas (GHG) emissions in the construction 2025 vision. Carbon and cost being the current yardsticks of construction projects (Ashworth & Perera, 2015; Perera & Victoria, 2017; Victoria et al., 2017), optimising both is a challenge facing most designers and other construction professionals in achieving these targets. However, Modern Methods of Construction (MMC) can help tackle the housing crisis (Davies, 2018) at a sustainable cost if designed thoughtfully.

This paper, therefore, presents a proof of concept of a sustainable affordable housing typology named 'Integra House 1' that had the following design objectives:

- reduced operations and installation time on site
- speedy construction
- reduced on-site waste

- optimised design by eliminating lintels, freeing the gable ends and integrated construction system
- Minimised life cycle carbon and cost

A novel milled timber truss technology, that made up the floor, wall and roof of the house was tested in 'Integra House 1' project to achieve the stated design objectives. Later, the design went through simulation-based optimisation by substituting milled timber trusses with whole timber trusses and synthetics insulation with wood-wool insulation, generating the design of a second prototype called 'Integra House 2'. This paper evaluates both design prototypes in relation to their life cycle cost and carbon performances 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 is better performing in life cycle carbon?

RQ2: Between Integra House 1 and Integra House 2, which housing prototype is better performing in life cycle cost?

2. Theory

O'Neill and Organ (2016) 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 (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 (BRE, 2008; Monahan & Powell, 2011; and Iddon& Firth,2013) 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 makes this construction more preferable to conventional construction.

Table 1presents embodied carbon figures of different types of frames/external wall construction per 1m^2 of external wall that has a u-value of 0.3 W/m^{2}K (BRE, 2008). Accordingly, the least carbon intensive option is to be timber cladding on masonry followed by masonry on 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 (2011)reported that 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^{2}K) and was proven to achieve 34% reduction in embodied carbon. Similarly, Iddon and Firth (2013) demonstrated that 24% reduction in embodied carbon is possible through building fabric changes moving from traditional construction methods to MMCs. Literature findings suggest that MMC for housing is an efficient way forward towards reaching national carbon reduction targets while meeting the housing demand.

Table 1: Embodied carbon values of various external wall constructions in domestic buildings (source: BRE (2008))

Frame Type	Specification	$kgCO_2e/m^2$
Masonry cavity wall	Brickwork outer leaf, insulation, dense solid blockwork inner leaf, cement mortar, plaster, paint	70
	Brickwork outer leaf, insulation, dense solid blockwork inner leaf, cement mortar, plasterboard on battens, paint	72
Brickwork on framed construction	Brickwork, cement mortar, cement-bonded particle board, timber frame with insulation, vapour control layer, plasterboard on battens, paint	82
	Brickwork, cement mortar, OSB/3 sheathing, timber frame with insulation, vapour control layer, plasterboard on battens, paint	52
	Brickwork, cement mortar, cement-bonded particle board sheathing, insulation, light steel frame, vapour control layer, plasterboard on battens, paint	94
Cladding on Masonry	Canadian Western Red Cedar cladding on timber battens, insulation, aircrete blockwork, plasterboard, paint	45
	Coated steel composite profiled panel with pentane blown PUR/PIR insulation and steel liner on steel support, breather membrane, aircrete blockwork with cement mortar, plasterboard, paint	130
Curtain wall	Laminated timber stick type curtain wall: 2 transoms per floor, laminated sealed glass unit, coated aluminium spandrel panel with pentane blown PUR/PIR insulation, medium dense concrete solid blockwork, plasterboard on dabs, paint	250
	Extruded aluminium stick type curtain wall: 1 transom per floor, laminated sealed glass unit, coated aluminium spandrel panel with pentane blown PUR/PIR insulation	200

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 (Cuéllar-Franca and Azapagic, 2012) with use stage contributing the most to the overall emissions from buildings. Therefore, Cuéllar-Franca and Azapagic (2012) argue that improvement opportunities in the housing sector predominantly lie in use stage. A literature survey on buildings' life cycle energy encompassing 60 cases from nine countries reported that despite embodied energy of solar houses being doubled compared to conventional houses, solar houses 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 to be only slightly higher than a conventional building (Sartori and Hestnes, 2007). Nonetheless, embodied carbon of passive house designs can be reduced by opting for full timber option as demonstrated in the study of Monahan and Powell (2011) due to timber being a virgin material with very low embodied carbon.

In 2019, 22% of timber grown in the UK was used as wood-fuel/biomass (Forest Research, 2020), 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 realised for decades to come. Bukauskas et al. (2019) 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. (2010) demonstrated that several different types of structure could be constructed in this way. The variety of structures included post and beam structures, grid-shell and pre-tensioned domes. Further, many believe that MMC is the way forward for the industry to resolve the existing housing crisis and tackle the climate change(Davies, 2018; Nadim and Goulding, 2010).

In summary, an abundance of evidence from literature favour whole timber constructions over conventional construction to reduce carbon emissions from the housing industry to meet the housing demand. It is clear that one has to tap into the 'use stage' carbon reduction opportunities to achieve the highest possible emission reduction. Buildings with passive house standards arguably renders the highest 'use stage' or operational carbon savings while their embodied carbon being 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 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 as the dual currency of construction projects. Therefore, the case study presented in this paper fills that gap by investigating both life cycle carbon and cost of two similar, but different passive house prototypes that use a novel truss technology, a new addition to the MMC family. Both protypes combine the energy and carbon benefits of timber as a material, MMC, and passive design principles.

3. Material and Methods

3.1. Research Approach

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, case study approach is widely used by scholars to test design prototypes and study different house typologies (see for example, Monahan and Powell, 2011; Cuellar-Franca and Azapagic, 2012).

3.2. Description of the Case Study – Integra House

The pilot case study (Integra House 1) is situated in Tyrie, which is located approximately 6.8km south west 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 125m^2spread over two (2) floors and comprises of 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 Figure 1. The truss makes the frame (wall, floor and roof) of the house and spaced at 600mm centres. A total of 39 trusses were used to build the house.

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 450mm thick walls comprising of 400mm thick truss and insulation to achieve a low u-value (see, Figure 2). The house is cladded externally with Scottish larch and the roof finish to be 50 x 50mm Scottish larch cladding. 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 natural light and views (see, Figure 3). Brief elemental specification of Integra House is presented in Table 2.

In the effort of further optimising the design of Integra House 1, Integra House 2 was modelled with whole round timber trusses and all the insulation of Integra House 1 were replaced with wood wool (loose) insulation (see, Figure 4) 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 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 area and second moment of area of round timbers.

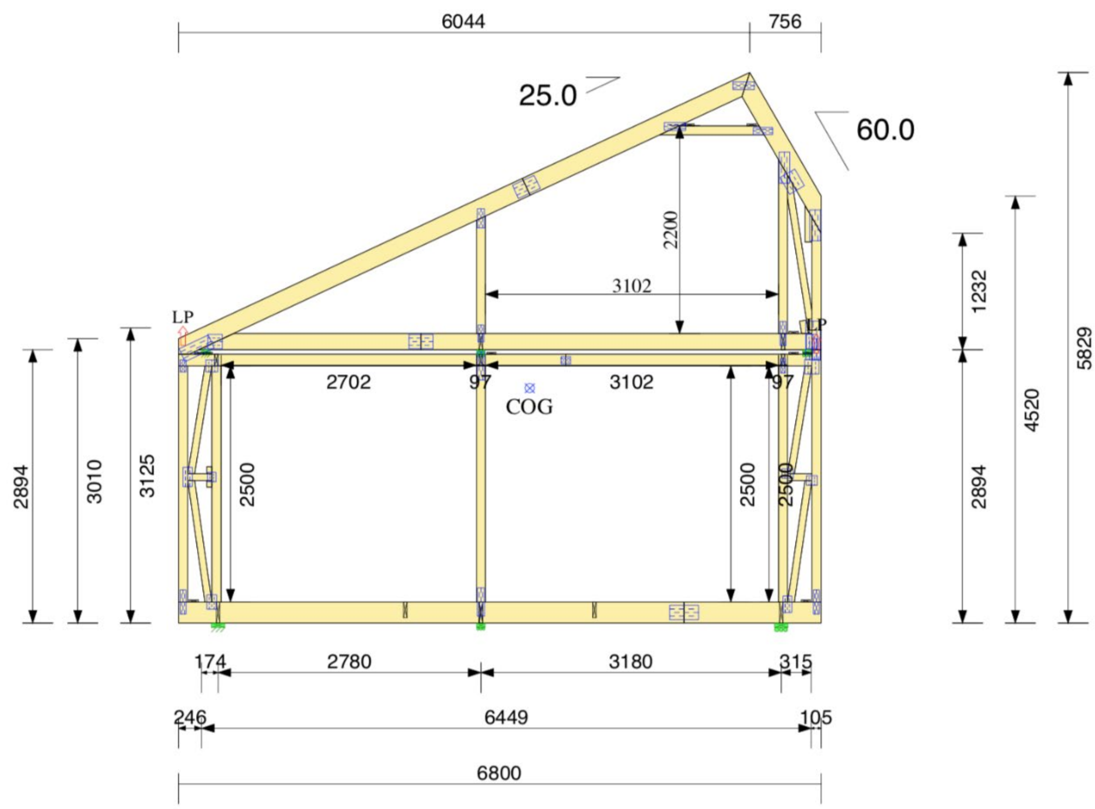

Figure 1: Integra House 1 Truss Design

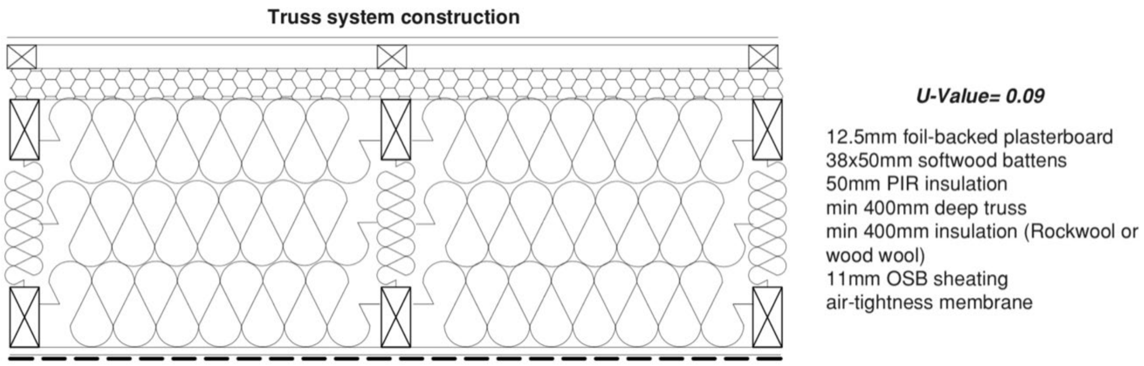

Figure 2: Integra House Wall Build-Up

Figure 3: Integra House 1

Table 2: Elemental specification of Integra House 1

Element	Specification
Substructure	Strip foundation and softwood ground floor forming part of the truss; 190mm (100mm layer + 90mm layer) rigid PIR insulation tightly fitted between truss bottom chords; 22mm moisture resistant P5 t&g chipboard flooring glued to truss chords; exposed soffits at perimeter lined with 11mm OSB3 to support Wraptite membrane lapped and sealed to underfloor polythene; soffit finished with 9mm WBP sheathing plywood;
Frame	Timber truss, prefabricated all-house trusses, generally at 600mm centres
Upper Floors	Timber floor with 22mm moisture resistant chipboard flooring insulated with 90mm thick acoustic wool insulation; 2 layers 12.5mm plain taper-edged plasterboard.
External Walls	Fully filled timber cavity wall with Siberian larch cladding; 400mm Rockwool slabs between trusses; 50mm continuous layer rigid PIR insulation to inside face of trusses; 38 x 50mm

	treated softwood cavity straps to form service cavity; 12.5mm thick foil-backed vapour check plasterboard.
Roof	Timber roof truss and corrugated steel sheet roofing; Siberian larch cladding; 190mm (100mm layer + 90mm layer) rigid PIR insulation tightly fitted between truss top chords; 12.5mm thick foil-backed vapour check plasterboard.
External Windows and Doors	Nordan external windows and doors
Internal Partitions	45 x 95mm C16 softwood stud framing generally at 600mm centres; 90mm thick acoustic wool insulation between studs at all partitions; 12.5mm plain taper-edged plasterboard to both sides.
Internal Doors	Painted flush doors

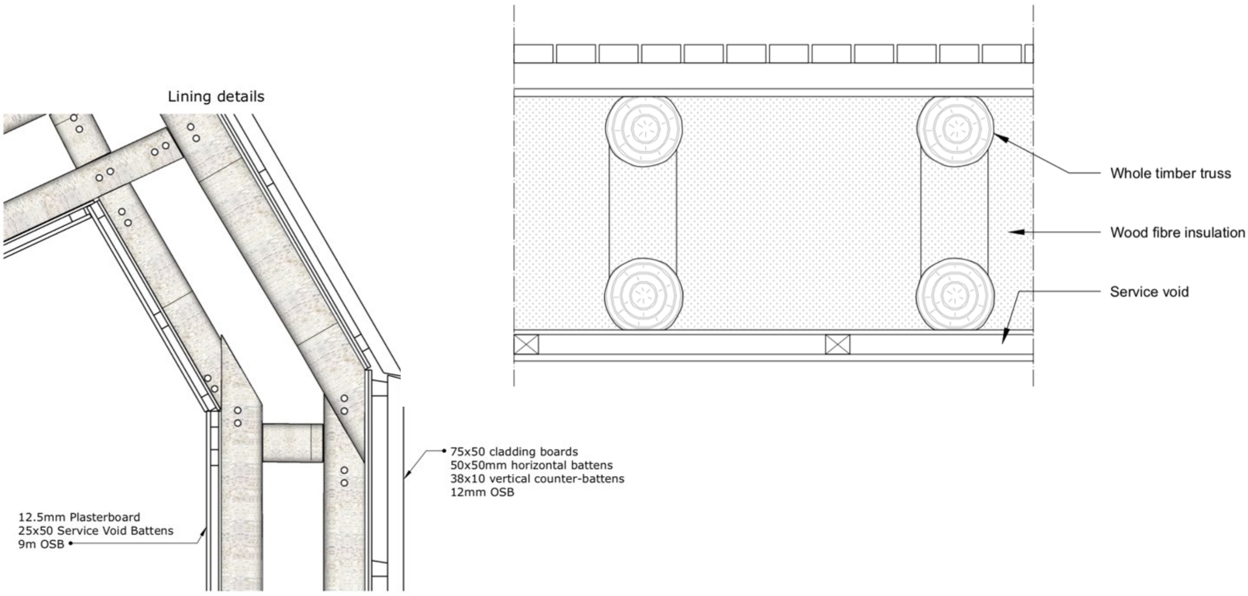

Figure 4: Integra House 2 Wall Details

3.3. Life cycle assessment

Life cycle assessment of Integra House was carried out in accordance with EN 15978. Steps followed in the assessment is shown in Figure 5.

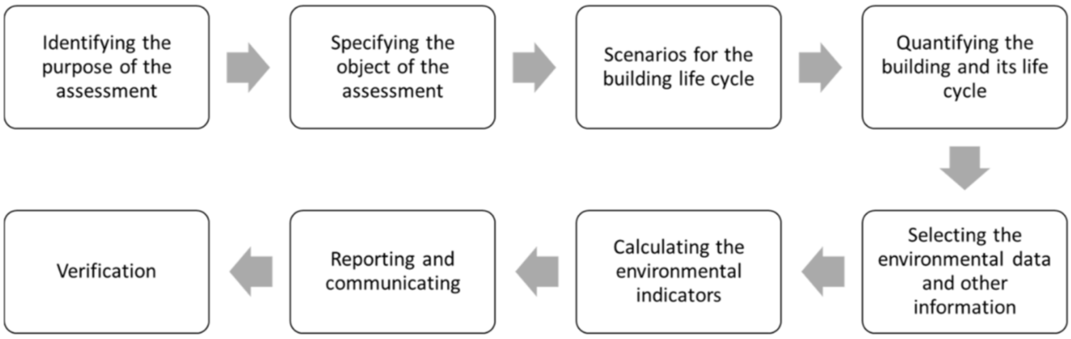

Figure 5: Process steps for the assessment of the environmental performance of buildings, adapted from Figure 3 in EN 15978

Source: BRE (2018)

Accordingly, the purpose of the assessment was to compare Embodied Carbon (EC) and 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 conventional 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 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. The thicknesses as insulation were kept similar in both houses. Key EC databases including Inventory of Carbon and Energy (ICE, v2.0, v3.0) (Hammond & Jones, 2011; 2019), the UK Building Blackbook (Franklin & Andrews, 2011) and other online sources were used to calculate the embodied carbon and cost of Integra House 1 and 2 (Note: All embodied carbon values exclude carbon sequestration as it is a complex phenomenon to account for in the calculations and the sequestered carbon is released into the environment when burnt).

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

$$CC/EC_{m/i} = Q_{m/i} \times CCF/ECF_{m/i}$$

Where,

$CC/EC_{m/i}$	-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.)
$CCF/ECF_{m/i}$	-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 in accordance with New Rule of Measurements (NRM1) element classification which is the current elemental standard adopted in the UK construction industry (RICS, 2012). Elemental cost per Gross Internal Floor Area (GIFA) and elemental carbon per GIFA were then calculated to normalise the values for comparison purposes. The equation used to calculate the elemental unit cost/carbon is as follows:

$$CC/EC\ per\ GIFA_n = \frac{CC/EC_n}{\text{GIFA}}$$

Where,

$CC/EC\ per\ GIFA_n$ - CC or EC per GFA of element 'n'

CC/EC_n - Total CC/EC of element 'n'

GIFA - Gross internal floor area of the building

All costs were updated to 2020 3Q and Scotland by obtaining indices from BCIS (2020).

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 in Table 2 and resultant U-values in Table 3, the as built drawings, site location, and orientation. It also included 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, and 15 pre-conditioning days for the energy calculations.

Table 3: Elemental U-values of Integra Houses 1 and 2

Element	**U-Values** ($W/m^2.^oC$)	
	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 whole timber option more attractive than Integra House 1. This is a 55% reduction in EC and 28% reduction in cost compared to Integra House 1. However, it should be noted that the embodied carbon of trusses is higher for whole timber option compared to milled timber option due to the increase in weight of the whole timber trusses by almost 100% to achieve the same structural performance, perhaps due to the whole timber being from younger thinnings, which are expected to be weaker in strength than the mature trees that are used for milled timber. In fact, the reduction in EC was mainly achieved by substituting insulation with wood wool insulation. In the contrary, 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.

Table 4: EC and cost profile comparison between Integra House 1 and 2

	EC per GIFA (kgCO$_2$e/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**

The EC and cost profile of the elements are presented in Figure 6. External walls can be clearly identified as an EC hotspot, 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 account for 65% of the external wall EC. Yet, the EC of Integra House 2 walls is 82kgCO$_2$e/m^2 of external wall area which is 35% lower than Integra House 1.

Transport EC and cost will be the same for both Integra House 1 and 2 for a given site and is reported to be very low compared to the total EC (as low as 2%, see Monahan and Powell (2011)).

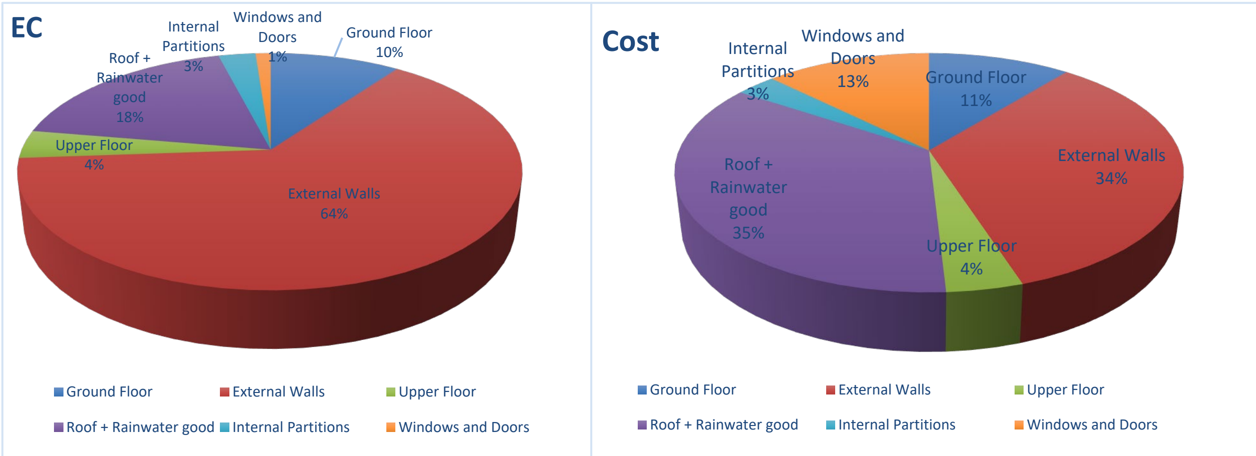

Figure 6: EC and cost profiles of Integra House 2

4.1.2. Construction Stage

With regards to the construction EC and cost, 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 exact 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

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

Table 5 presents the operational carbon of Integra House 1 and 2. Integra House 1 was estimated to be 7.8kgCO_2e/m^2 GIFA/annum while Integra House 2 was slightly higher at 7.9 kgCO_2e/m^2 GIFA/annum. Considering a 60-year lifecycle, Integra House 1 will emit 130,925 kgCO_2e which is 30% higher than Integra House 2.

Table 5: Annual operational energy (KWh) and operational emissions (kg CO_2e) for Integra Houses 1 & 2

		Integra House 1		Integra House 2	
		KWh	kg CO_2e	KWh	kg CO_2e
Space heating (Electricity – 50% of heating load)	Whole house	2129.5	496.45	2196	511.86
	Per m^2	16.7	3.9	17.2	4.01
Space heating (Wood stove – 50% of heating load)	Whole house	2129.5	32.9	2196	33.9
	Per m^2	16.7	0.26	17.2	0.27

Lighting	Whole house	1993	464.6	1993	464.6
	Per m^2	15.6	3.64	15.6	3.64
Space heating + Lighting	Whole house	6252	994	6385	1010.4
	Per m^2	49	7.79	50	7.92

Conversion factors: KWh to kg CO_2e = 0.23314 for electricity and 0.01545 for wood pellets/chips (UK Govt., 2020)

4.1.4. End of Life Stage

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. Insulation used in Integra House 1 will have to be disposed properly for which fees for transportation and disposal will be incurred.

4.1.5. Benefits and loads beyond the system boundary

Benefits beyond system boundary includes reuse, recovery and recycling potential. Some timber products can be reused or recycled into a new material or product. When reuse/recycle is not possible, timber can still be used to recover energy through direct combustion or through conversion to gaseous or liquid fuel before burning. while clean wood or untreated wood can be burned in private stoves and power stations, contaminated wood such as treated wood, painted wood, or chipboards containing adhesives (e.g. formaldehyde glue), can only be used for energy generation in special stations equipped with appropriate combustion facilities (Ramage et al., 2017). The ambition for Integra House 2 is to eliminate contamination of the timber through treatment, painting, or use unclean adhesives to optimise end-of-life options. The possible end-of-life options available for Integra House 1 and Integra House 2 are:

Table 3: 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 fibre board
Recovery		Whole timber truss can be used for energy recovery

4.2. Integra House vs. conventional and other MMCs

Table 5 presents a comparison of the study findings and literature findings. Accordingly, Integra House EC values are almost comparable to the findings of Monahan and Powell (2011) and Hacker et al. (2008) while the values reported by Iddon and Firth (2013) appear to be very low. This may be due to Iddon and Firth (2013) including only key materials in the analysis. It can also be noted that EC figures of Hacker et al. (2008) are slightly lower than Monahan and Powell (2011) owing to the fact that these studies used different data sources and the scope of analysis is not identical (i.e. elements covered and wastage allowance). These reasons make parallel comparison of findings almost impossible. Nevertheless, Integra House findings are compared to Monahan and Powell (2011) which is the closest match with regards to the study design and the scope of analysis.

MMC (EC of timber frame with timber cladding) proposed by Monahan and Powell (2011) is 43% lower than Integra House 1, yet Integra House 2 outperforms Monahan and Powell's (2011) MMC by 21% (although, it should be noted that Integra House ECs exclude foundations while Monahan and Powell's (2011) study includes foundation which will have an impact on the figures).Further, timber frame with brick cladding is shown to have a better EC performance compared to Integra House 1 but Integra House 1 outperforms the traditional masonry wall construction. It is important to note, however, the wall thicknesses and u-values are significantly different between Monahan and Powell (2011) and Integra Houses which will have a huge impact on the total emissions of the building.

Table 4: 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/annuum)**
Monahan and Powell (2011) (3 bedrooms, semi-detached, 45 m^2, excl. internal finishes and fittings, wall u-value 0.18 W/m^2K)	Timber frame timber cladding (273mm thick walls)	332	Not given
	Timber frame brick cladding (319mm thick walls)	535	
	Masonry (327mm thick walls)	612	
Iddon and Firth (2013) (4 bedrooms, detached, 166 m^2)	Traditional masonry (312.5mm thick walls, U-Value 0.29 W/m^2K)	297	17.24

	Heavy weight construction (300mm thick walls, U-Value 0.35 W/m^2K)	226	19.32
	Timber frame (385mm thick walls, U-Value 0.15 W/m^2K)	337	17.46
	Structural Insulated Panels (SIP) (350mm thick walls, U-Value 0.17 W/m^2K)	319	15.86
Hacker et al. (2008) (2 bedrooms, semi-detached, $65m^2$, 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, $125m^2$, excl. foundations, internal finishes and fittings, 450mm 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

Operational carbon of Integra House 1 was estimated to be 7.8kgCO_2e/m^2 GIFA/annum while Integra House 2 was slightly higher at 7.9 kgCO_2e/m^2 GIFA/annum. Accordingly, over a 60-year life cycle, Integra House 2 will have a total emission of 59,661 kgCO_2e which is 1% higher than Integra House 1. Although, this is much lower than conventional buildings. It is important to note that this does not include the emissions from burning of wood pellets/chips in the heating woodstove.

According to the Building Cost Information Services (BCIS), average cost of building a traditional two storeyed detached house is calculated to be £1,078 per m^2ranging 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 House1, although Integra House 1 is 13% less costly than an average conventional construction. On the other hand, Integra House 2 outperforms traditional house construction by 37% in cost due to the use of forest thinnings which are not normally used for structural purposes resulting in very low cost.

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

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)
- reduced on-site waste (prefabricated elements, just-in-time delivery)

The design of the truss was optimised by eliminating lintels, freeing the gable ends and integrating the system for walls, roof and floor. Integra House 1 used milled timber and rockwool/PIR insulation to form the façade whereas the design was later optimised by opting for whole timber trusses and woodwool insulation, creating a prototype 'Integra House 2'.

Table 5: Life Cycle Cost and Carbon Summary

	Carbon			**Cost**	
	Integra House 1	**Integra House 2**		**Integra House 1**	**Integra House 2**
Embodied	72,500	32,625	**Capital**	117,750	85,250
Operational	58,425	59,400	**Operational**	24,300	24,675
Life Cycle Carbon	130,925	92,025	**Life Cycle Cost**	142,050	109,925

Table 5 presents a summary of life cycle cost and carbon figures of Integra House 1 and 2. The LCA and LCC analyses highlighted that Integra House 2 outperformed Integra House 1 in both embodied carbon and capital cost by 55% and 28%. Such a significant reduction in EC was made viable through substituting rockwool insulation with wood wool which embodies very low carbon due to it being a natural material and its reuse potential. Similarly, a significant reduction in cost was possible due to opting for forest thinning which are not normally used for structural construction. In addition, Integra House 2 has more benefits beyond the system boundary including reuse, recycle and recovery potential compared to Integra House 1 making it a more preferrable option in the context of circular economy. With regards to the operational carbon, Integra Houses 1 and 2 were almost similar, and both houses outperformed other traditional constructions by large figures. Considering a 60-year lifecycle, Integra House 1 outperformed Integra House 2 by 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 an average conventional 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 thicker walls and near passivhaus standard façade. 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.

This paper further highlights the importance of appraising design options holistically rather than focusing on either embodied or operational carbon/cost alone as looking at only one component can sometimes be misleading and lead to decisions that are skewed and not necessarily the right decision.

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