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A Novel Application of Sustainable Material Sourcing and Building Performance Monitoring: Case Study Based Approach

Dr. Boris Ceranic[1*], Jaideep Singh Rajpurohit [1], Prof. Derek Latham [2]

[1] *University of Derby, Markeaton Street, Derby DE22 3AW, UK*

[2] *Hieron's Wood, Vicarage Lane, Little Eaton, Derby DE21 5EA, UK*

* Tel: +44 1332 593136; E-Mail: b.ceranic@derby.ac.uk

Abstract: In this research, a novel use of building materials and their impact on the building performance and its climatic adaptability is explored, based on a complex real word case study of a unique low energy sustainable building project. In particular, an innovative use of sycamore and its suitability as a structural and constructional timber has been investigated and reported, considering that is deemed not appropriate for structural applications by current standards. A research method of in-situ longitudinal study has been adopted, concentrating on the performance monitoring and assessment of its structural performance and conditions in which it might deteriorate. On the system level, the climatic adaptability of the building as a whole has been analysed via dynamic performance simulation and compared to the in-situ measurements. This was important in order to develop a holistic building performance monitoring strategy, but in particular, to understand the impact of building microclimate on the sycamore frame and hempcrete components of the external load-bearing wall. So far research has concluded that sycamore can be used as structural and constructional material in building design, but due attention has to be paid to construction detailing and provision of a breathable, low humidity environment with an effective resistance to decay and insect attack. This includes measures that ensure a low equilibrium moisture content conditions, effective ventilation provision and appropriate service class uses.

Keywords: sustainable development, materials, building performance monitoring.

1. Introduction

As defined by Ceranic (2013), "sustainable design analysis (SDA) could be referred to as rapid and quantifiable feedback on diverse sustainable alternatives and 'what if' questions posed by a design team and client during the early stages of the project". Its key purpose is to increase benefits of the project in terms of environment and cost, by making relevant design choices in the initial phase of the project, on the basis of timely feedback on different aspects such as building materials, construction specifications, energy consumption and generation, CO_2 emissions, water use and harvesting, waste and pollution management. Of course there are other facets which are inherently linked and therefore considered, such as: functional (constructional, operational), human (safety and security, comfort health and wellbeing), socio-cultural (context, sense of place, aesthetics) and economical (profits, environmental cost impact, life cycle costing etc. (Ceranic et al, 2016).

Importance of integration of sustainable design analysis (SDA) within a design process facilitated by building information modelling (BIM) is self-evident, in particular at early stages of design. SDA should be seamlessly integrated with the building design process itself, evolving concurrently rather than being treated as an "afterthought" or something that is undertaken when the design is complete. In doing so it should broadly follow two key stages; conceptualisation and calculation.

Conceptualisation stage conceives potential solutions. It challenges, interrogates and solves problems, trying to depict wider creative and rational constructs, their macro scale, context and the directional choices. On the other hand the purpose of calculation stage, being more analytical in its nature, is to quantify those qualitative directional choices from the conceptualisation stage and compare them with different sustainable design scenarios and alternatives. There are multiple building performance simulation products available on the market that are capable of undertaking these calculations.

The next stage, as shown in Fig.1, would then naturally be integration with smart built environments (SBE), sufficiently 'smart' to intelligently control building energy consumption, whilst providing a comfort and support for their users (Zhang et al. 2015). This integration is further reinforced and validated via building performance monitoring, real time data feedback, system optimisation and finally, technological solution for intelligent behaviour that minimises building energy consumption.

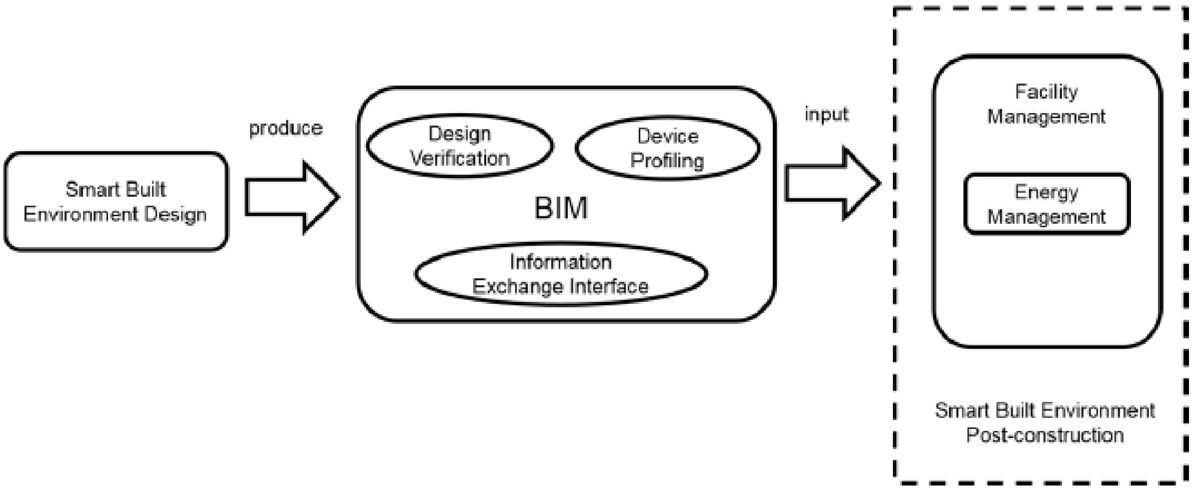


Figure 1: Concept of BIM and SBE integration

The Figure 2 describes structure of SDA and BIM integration within smart built environment (SBE) adopted in this research, from its conceptualisation to calculation stage, where SBE refers to environments with smart objects, such as sensors and actuators that communicate with the BIM and

SDA within an integrated system. A prototype of this system has been developed and published by the authors (Ceranic et al. 2018).

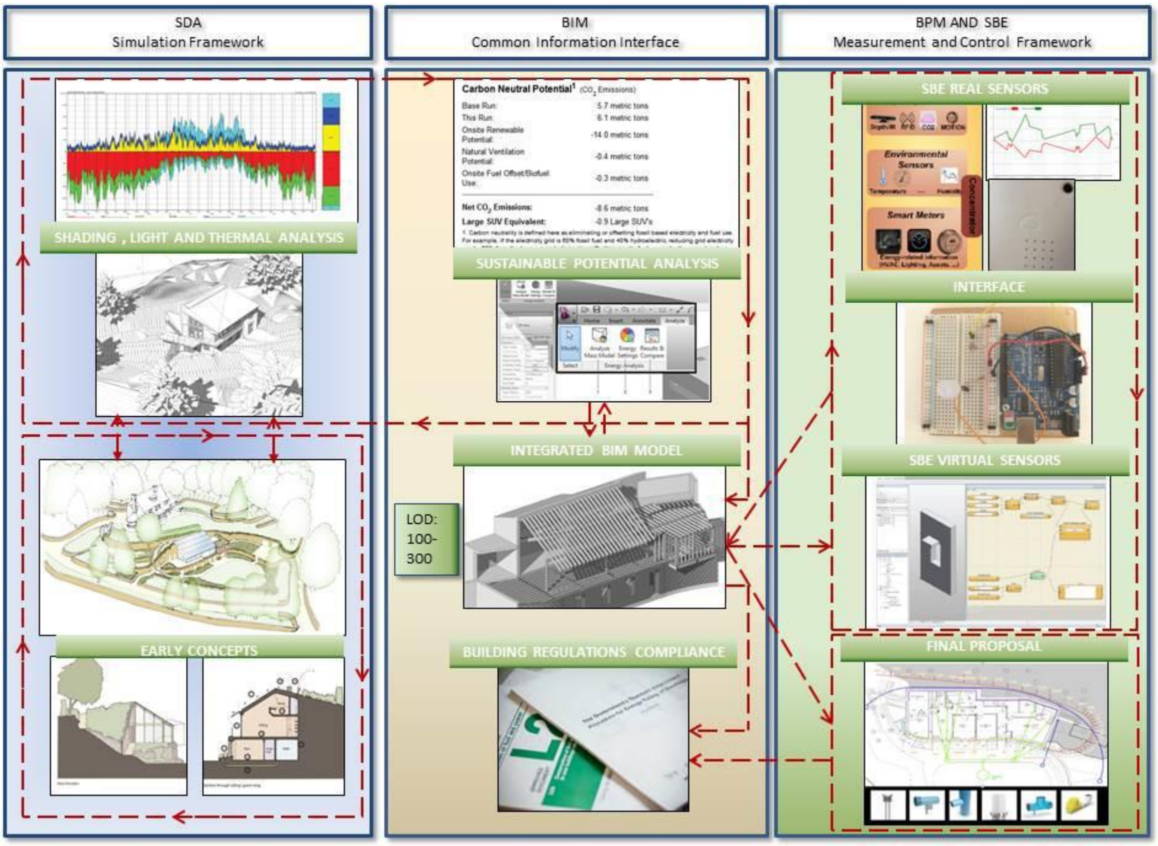


Figure 2: BIM SDA SBE Integration Research Approach

2. Research Methodology

The fundamental reason for choosing a case study approach in this research is to establish and analyse performance monitoring through the prism of a complex real word project, including a detailed assessment of its novel aspects. Case study approach helps in studying the topic from multiple perspectives i.e. analysing its intricacies and differences between theoretical simulations and in situ real life building performance.

Simons (2009) explains the reason behind choice of a case study as a valid research method, stating that a case study analyses all the complexities and uniqueness of a particular project from multiple angles, in real life context. It is research based, inclusive of different methods and is evidence-led. The primary purpose is to generate in depth understanding of a specific topic.

According to Yin (2009), “the holistic design approach is beneficial when the theory pertinent to the case study itself is of a holistic nature or where no logical sub-units can be identified. However, he further asserts the importance of access to the real world data stating that otherwise the case study may be an overly abstract, with a lack of suitably clear measures or data.”

Hence, this research investigates potential of a novel and sustainable structural material, within a holistic context of the single case study building performance and in conjunction with other materials and integrated passive design strategies. It is reinforced and triangulated via building simulation analysis, longitudinal in-situ building performance measurements and laboratory experimentation. This enables a detailed assessment of its novel aspects, including structural performance, within the framework of overall sustainable design and its integration with building performance monitoring.

3. Case Study - Energy Plus House, Hieron's Wood, UK

3.1. Case Study

Heiron's Wood is an experimental 4-bedroom dwelling that is situated in the vicinity of an original 1920's arts and crafts period style house. It location is on the edge of Little Eaton in Derbyshire and it is sited is on the former stone quarry (see Fig 3a,b). The design concept was to construct a building with a minimum visual impact and carbon imprint on the site respecting its physical, historical and visual context, assisted by a careful selection of sustainable materials (see Fig 5a,b). The project represents a unique opportunity to undertake long term research in three key areas; monitoring of building performance with regard to 1/ energy consumption/embodied carbons/health and wellbeing; 2/ innovative use of materials and technology; and 3/ detail design and construction.

Figure 3. (a) Aerial View - Site Location; (b) Site build progress

The building is designed as an "upside down" concept, with sleeping accommodation on the lower ground floor and living accommodation on the upper ground floor, emphasising the "fabric first" principle of design. It is consisted of (see Fig 4a,b):

- Lower ground floor comprising of an ensuite master bedroom, two-guest room and a study with utility and garden store, with external excess.
- The upper ground floor has an open living/ dining/ kitchen, larder, WC and an entrance hall.

- The mezzanine level comprises of an open study balcony, looking down to the living and dining area.

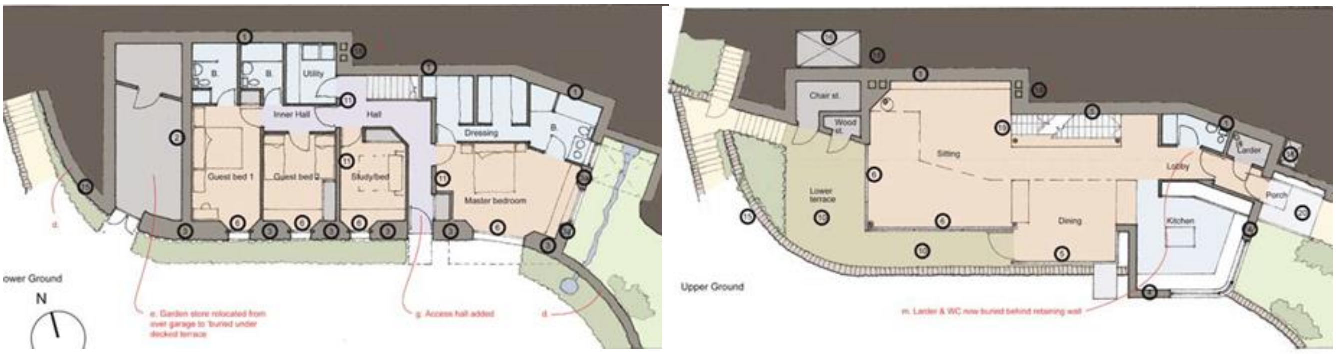


Figure 4. (a) Lower ground floor; (b) Upper ground floor

It benefits from highly insulated but breathable wall construction. Both of primary wall materials, i.e. stone for drystone walling and sycamore for timber frame are sourced from the former stone quarry situated within the site, providing not only very sustainable material sourcing but enabling the house to blend within its immediate surroundings (see Fig 5a).

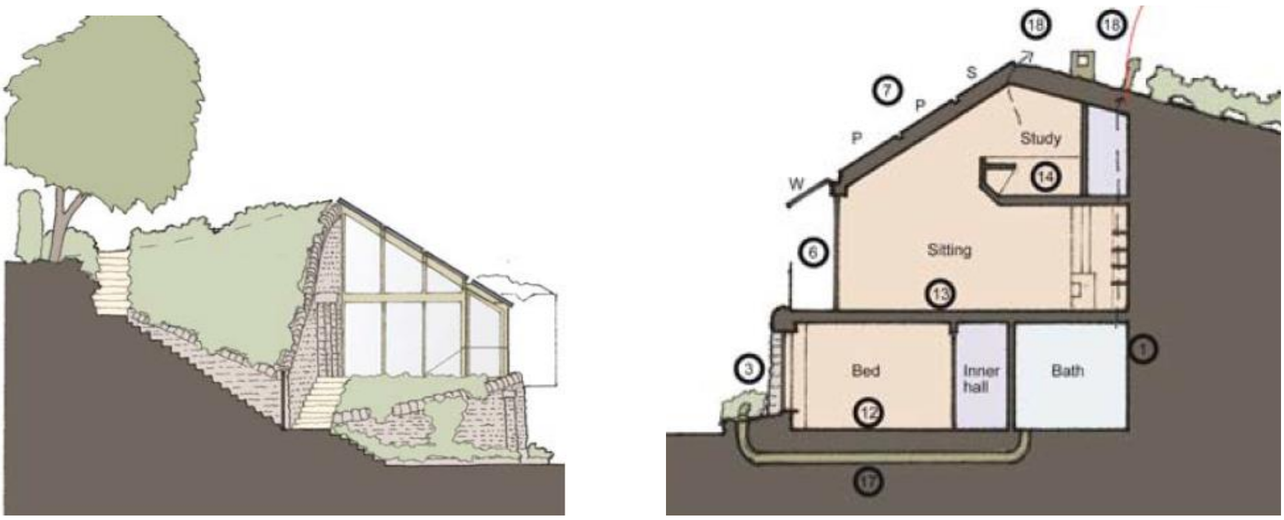


Figure 5. (a) West Elevation; (b) Section with south facing roof and the earth tube

The building capitalises on the PV energy generation through its southern orientation (see Fig: 5b). Its design exploits a number of low energy technologies alongside passive energy saving measures, such as zoning, solar gains, natural light, solar shading, high thermal mass, earth embankment on the northern side, passive stack, natural ventilation and earth tube as a passive earth to air heat exchange device (see Fig. 5b). As estimated by the initial energy design simulations, the building produces more energy from the renewables than it consumes, making it defacto an “energy plus” house. Fig 6 and 7 below show completed project at the stage of the site handover to the client.

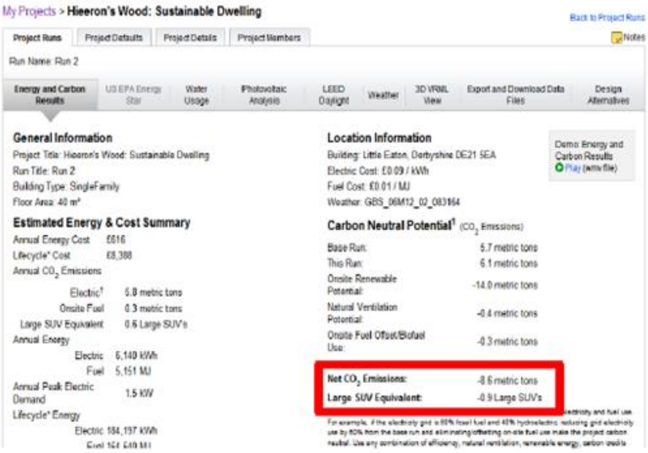
Figure 6 (a) View from mezzanine level; (b) Sycamore Flitch Beam Fix.

Figure 7: (a) South elevation; (b) South west view from the living room

4. Results and Discussion

4.1 Whole Building Simulation and Performance Monitoring

A building energy model was generated at feasibility stage based on initial concept to provide an early analysis and understanding of building's energy efficiency. A building energy consumption and costs, including water usage, renewables and carbon neutrality potential were estimated (see Fig 8a), followed by finalising building construction specification, mechanical services, thermal zones and enclosures. As the next stage of analysis, a total of 11 scenarios of heating demand were analysed based on calculations performed for air to water aroTHERM 8kW heat pump (©Vaillant), as a main source of heating and hot water provision in the building. These 11 scenarios are listed in the Table 1 below, demonstrating that if heat pump flow temperature is kept at 35°and energy efficient lighting and appliances are specified throughout the property, then given its constant predicted PV generation, the scenarios 5,6,7,8,9 and 10 become both "energy positive" and "carbon negative".



Scenario	1	2	3	4	5
Heating demand [kWh/annum]	13389.0	13389.0	12103.0	12103.0	11778.0
Solar gains [kWh/annum]	0.0				
Internal gains [kWh/annum]	0.0	500.0	500.0	500.0	1500.0
Flow temperature [°C]	40.0	40.0	35.0	35.0	35.0
Electricity for heating [kWh/annum]	3648.2	3512.0	2967.5	2967.5	2628.6
DHW demand [kWh/annum]	2585.0	2585.0	2010.0	2010.0	2010.0
Electricity for DHW [kWh/annum]	982.9	982.9	764.3	764.3	764.3
Electricity applicances & misc [kWh/annum]	3300.0	3050.0	2800.0	2550.0	2300.0
PV power generation [kWh/annum]	6092.7	6092.7	6092.7	6092.7	6092.7
Overall [kWh/annum]	1838.4	1452.1	439.0	189.0	-399.8
CO2 emissions [kg/annum]	964.4	761.8	230.3	99.2	-209.8

Scenario	6	7	8	9	10
Heating demand [kWh/annum]	11778.0	9266.0	9266.0	8451.0	8451.0
Solar gains [kWh/annum]					
Internal gains [kWh/annum]	1500.0	1500.0	3000.0	3000.0	3000.0
Flow temperature [°C]	35.0	35.0	35.0	35.0	35.0
Electricity for heating [kWh/annum]	2628.6	1986.2	1602.6	1394.1	1394.1
DHW demand [kWh/annum]	2010.0	2010.0	2010.0	1800.0	1800.0
Electricity for DHW [kWh/annum]	764.3	764.3	764.3	684.4	684.4
Electricity applicances & misc [kWh/annum]	2050.0	1800.0	1700.0	1600.0	1500.0
PV power generation [kWh/annum]	6092.7	6092.7	6092.7	6092.7	6092.7
Overall [kWh/annum]	-649.8	-1542.3	-2025.9	-2414.2	-2514.2
CO2 emissions [kg/annum]	-340.9	-809.1	-1062.8	-1266.5	-1319.0

Figure. 8. (a) Carbon Neutral Potential Analysis, b) Table 1 Energy Consumption, PV Generation and CO_2 emissions estimates (Scenarios 1 - 11)

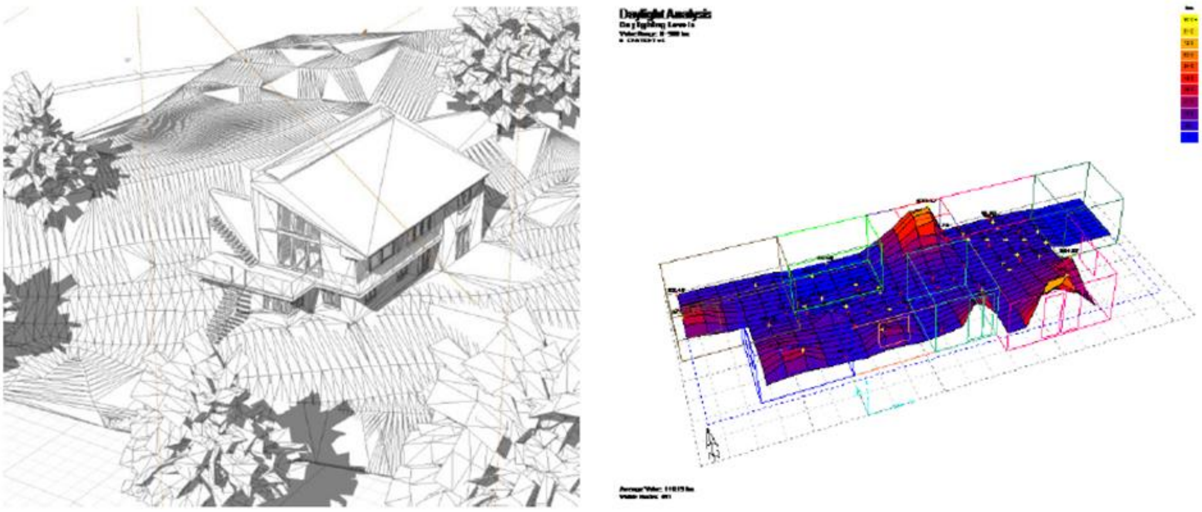


Figure. 9. (a) Solar Analysis Example, Summer Solstice 21st June, 16:00pm ; (b) Daylight Lux Levels

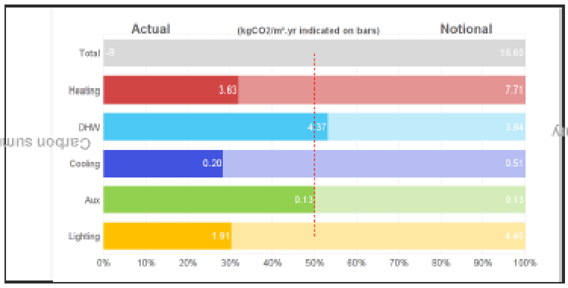
In the final stage of analysis, a whole building thermal simulation has been performed using IES© <VE> software that is UK Part L building regulations compliant and known for its accuracy and reliability. A thermal templates for zones, services and occupancy patterns were defined, in order to generate final thermal performance calculations. These included hourly temperature profiles, heating and cooling loads, solar and light level analysis (see Fig 9a,b), passive gains and losses and incident solar radiation, (Schlueter, 2009). The thermal zones were than redesigned according to these results to produce more optimal results; these factors were size, shape and position of apertures, including protection against excessive solar gains in the summer and a choice of materials and U-values, hence finalizing the design for building control approval and commencement of the works on the site.

The Figure 10 below shows the actual and notional energy summary from the Approved Document L: Conservation of fuel and power building regulations report. The actual building emission rate was estimated at 10.25 kg.CO_2/m^2.yr which is significantly under the target emission rate i.e. 16.6 kg. kg.CO_2/m^2.yr. Furthermore, this notional carbon output calculation does not consider the carbon emissions "offset" due to the use of PV renewable energy which amounts to -17.7 kg.CO_2/m^2.yr, thus making the building defacto "carbon negative" to the value of -7.52 kg.CO_2/m^2.yr.

Part L2 (2013) England results

BER:	-7.52 kg.CO_2/m^2.yr	Pass
TER:	16.6 kg.CO_2/m^2.yr	

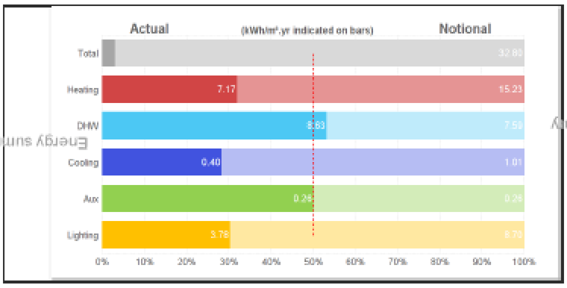
Carbon summary (kgCO_2/m^2.yr)



kgCO_2/m^2.yr	Actual	Notional
Heating	3.63	7.71
DHW	4.37	3.84
Cooling	0.20	0.51
Aux	0.13	0.13
Lighting	1.91	4.40
Renewables	(-17.77)	(0.00)
Total	-7.52	16.60

Results represent total CO_2 output. BER rating includes applicable adjustment factors.

Energy summary (kWh/m^2.yr)



kWh/m^2.yr	Actual	Notional
Heating	7.17	15.23
DHW	8.63	7.59
Cooling	0.40	1.01
Aux	0.26	0.26
Lighting	3.78	8.70
Renewables	(-19.23)	(0.00)
Total	1.02	32.80

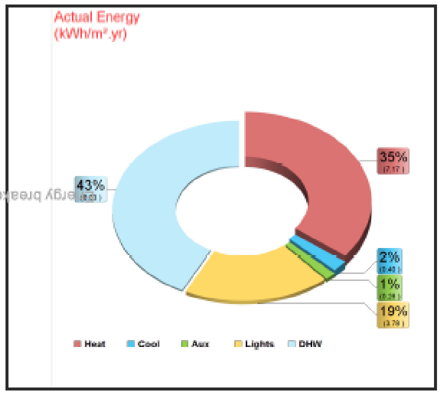
Being the residential property, in terms of energy consumption the majority of demand is attributed to the heating (35%), hot water (43%) and lighting (19%), totaling 97% of the overall consumption, as shown in Fig. 11a (note that the appliances consumption is excluded when producing the rating). The building primary energy demand is estimated to be 20.24 kWh/m^2, assuming the operational flow temperature of the heat pump of 40°C. If lower flow temperature of 35°C is used the building consumption drops to 18.21 kWh/m^2/yr, and given that 19.23 kWh/m^2 /yr is estimated to be produced from the renewable sources, building net energy consumption becomes -1.26 kWh/m^2/yr, making it defacto an "energy positive" proposal.

Actual building - energy breakdown (kWh/m^2.yr)

Conditioned area: 347 m^2

kWh/m^2.yr	Heat	Cool	Aux	Lights	DHW	Renew - ables	Equip*
Jan	1.38	0.00	0.02	0.39	0.73	-0.37	0.70
Feb	1.04	0.00	0.02	0.33	0.65	-0.59	0.63
Mar	0.91	0.00	0.02	0.33	0.73	-1.22	0.70
Apr	0.76	0.00	0.02	0.28	0.73	-1.86	0.68
May	0.27	0.02	0.02	0.26	0.74	-2.96	0.70
Jun	0.05	0.06	0.02	0.24	0.71	-3.35	0.68
Jul	0.01	0.19	0.02	0.25	0.73	-3.40	0.70
Aug	0.01	0.11	0.02	0.27	0.73	-2.50	0.70
Sep	0.09	0.01	0.02	0.30	0.72	-1.47	0.68
Oct	0.46	0.00	0.02	0.37	0.71	-0.76	0.70
Nov	1.02	0.00	0.02	0.36	0.69	-0.43	0.67
Dec	1.19	0.00	0.02	0.39	0.77	-0.31	0.70
Total	7.17	0.40	0.26	3.78	8.63	-19.23	8.21

*-Equipment excluded when producing rating



Actual building - carbon breakdown ($kgCO_2/m^2.yr$)

Conditioned area: 347 m^2

$kgCO_2/m^2$ .yr	Heat	Cool	Aux	Lights	DHW	Renew-ables	Equip*
Jan	0.70	0.00	0.01	0.20	0.37	-0.34	0.35
Feb	0.53	0.00	0.01	0.17	0.33	-0.55	0.32
Mar	0.46	0.00	0.01	0.17	0.37	-1.13	0.35
Apr	0.39	0.00	0.01	0.14	0.37	-1.72	0.34
May	0.13	0.01	0.01	0.13	0.37	-2.73	0.35
Jun	0.02	0.03	0.01	0.12	0.36	-3.09	0.34
Jul	0.01	0.10	0.01	0.13	0.37	-3.15	0.35
Aug	0.01	0.06	0.01	0.14	0.37	-2.31	0.35
Sep	0.04	0.00	0.01	0.15	0.36	-1.36	0.34
Oct	0.23	0.00	0.01	0.19	0.36	-0.70	0.35
Nov	0.52	0.00	0.01	0.18	0.35	-0.40	0.34
Dec	0.60	0.00	0.01	0.20	0.39	-0.28	0.35
Total	**3.63**	**0.20**	**0.13**	**1.91**	**4.37**	**-17.77**	**4.16**

*-Equipment excluded when producing rating

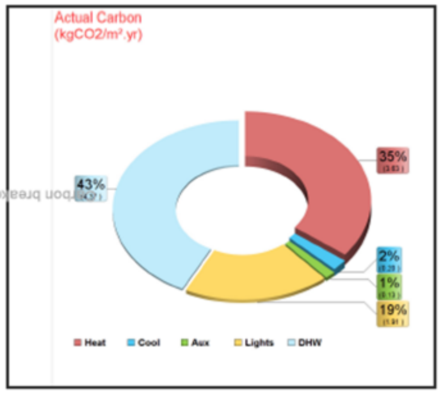


Figure 11: a.) Estimated energy consumption b.) Estimated carbon emissions

4.2 Building Performance Monitoring

A long term building performance monitoring strategy (at least five years) of the Hierons Wood development is proposed (see Fig 12). It is consisted of building performance monitoring on the whole system level and on the building component level from the systematic analysis of the sycamore structural frame and its hempcrete surrounding with regard to moisture content, temperature, relative humidity and rot resistance.

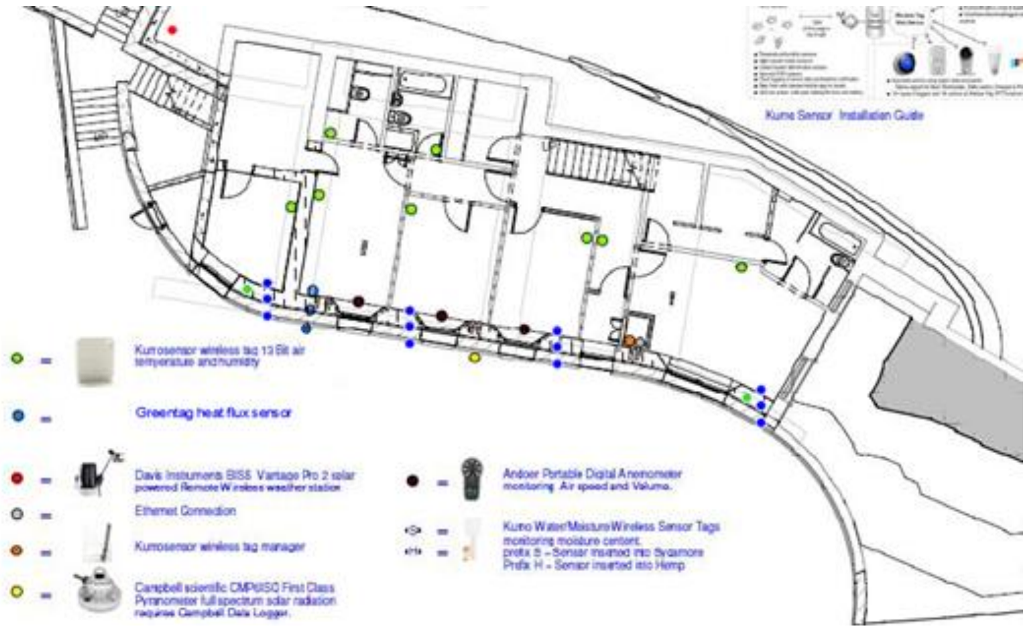


Figure 12: Building Performance Monitoring Strategy – Lower Ground Floor

4.3 Materials Performance Testing and Monitoring

It is important to note that sycamore in Hierons Wood project was structurally used in the service classes 1 and 2 (see Fig 13a), where it was maintained at less than 20% moisture content and thus unlikely to perish due to being attacked by wood decaying fungi or sapstain (TRADA, 2010). The likelihood of sycamore perishability is the main concern of this research given that the BS EN 350-1 (1994) classifies sycamore as class 5 i.e. non-durable and perishable in less than five years (see Fig 13b). However, BS EN 350 experimentation is based on approximate life of 50x50mm stakes driven into the ground and as such conducted in conditions much more severe than is likely to occur in modern building such as Hierons Wood. Thus, the strategy of using structural sycamore only in service classes 1 and 2 was reinforced with high quality construction detailing and quality workmanship as the first line of defence and the use of non-toxic preservatives as the second line of defence,

Service Class	Examples of use in building	Typical upper moisture content in service
1	Warm roofs Intermediate floors Timber-frame walls, internal and party walls	12%
2	Cold roofs Ground floors Timber-frame walls, external walls External uses protected from direct wetting	20%
3	External uses, fully exposed	>20%

BS EN 350 Durability classes		BRE classes	
Class	Description	Description	Approx life of 50x50mm stakes in ground
1	Very durable	Very durable	More than 25 years
2	Durable	Durable	15 - 25 years
3	Moderately durable	Moderately durable	10 - 15 years
4	Slightly durable	Non durable	5 - 10 years
5	Not durable	Perishable	Less than 5 years

Figure 13 a) Service Classes and Moisture Content b) BS EN 350 Durability classes

Although the hardwoods are in practice visually graded (BS EN 1912:2012), after consultation with TRADA it was decided to test its mechanical structural properties in addition, as per BS EN 408 (2010); namely its local modulus of elasticity, bending and compression strength, as well as recording the density and moisture content of each sample specimens.

Table IV. Compression Test Results

Sample 50x50x300 (mm)	Density (kg/m³)	Moisture Content (%)	Compression strength II to grain (N/mm²)
1	566.8	14%	33.1
2	572.3	14%	37.3
3	582.8	14%	38.6
4	585.9	14%	41.3
5	591.2	14%	42.1
6	587.4	14%	39.9
7	580.3	14%	38.8
8	577.4	14%	37.9
9	590.2	14%	41.3
10	578.6	14%	38.4
Avg	**581.3**	**14%**	**38.9**
SD	7.8	0.00	2.6

Figure 14: Compressive strength test

The preliminary outcomes were equivalent to the published data (see Fig. 14,15), e.g. TRADA reports sycamore bending strength to be 99 N/mm^2, modulus of elasticity 9400 N/mm^2, density 630 kg/m^3 and compression parallel to grain 48 N/mm^2 (TRADA, 2013). Noting that the sycamore was sourced locally from the site, its performance is comparable to other hardwoods, confirming that the sycamore can be used for structural purposes as long as it is not left exposed to the conditions with increased humidity (i.e. MC >20%) for a prolonged periods of time.

Table V. Bending Strength Test Results

Sample 50x50x1000 (mm)	Density (kg/m^3)	Moisture Content (%)	Local Modulus of Elasticity (N/mm^2)	Bending Strength ll to grain (N/mm^2)
1	566.8	14%	9785	123.7
2	582.8	14%	9677	96.9
3	571.2	14%	9406	96.7
4	575.6	14%	9529	108.6
5	583.9	14%	9590	91.5
6	575.2	14%	9350	92.6
7	578.3	14%	9370	93.7
8	585.5	14%	9610	97.5
9	579.1	14%	9512	98.6
10	580.2	14%	9570	99.2
Avg	**577.9**	**14%**	**9540**	**99.9**
SD	5.8	0	137.8	9.6

Figure 15. Bending strength test

Hygrothermal tests are also been conducted in order to evaluate the building envelope performance and its impact on the sycamore frame, including monitoring of hempcrete temperature, relative humidity and envelope hygrothermal performance. This is measured in accordance with standards specified in ISO 9869 (2014), ASTM C1046 (2013), recording heat flux and dynamic changes of U-values, as the hempcrete that surrounds sycamore goes through its weather dependent periods of wetting and drying and thus change in its moisture content (Ceranic et al, 2016). To demonstrate those results, a building envelope performance monitoring of the guest bedroom south facing wall are presented below, covering 3 weeks of typical heating period from 20/02/18- 12/03/18 (see Fig. 16).

The indoor air temperature is maintained around 20°C to 22°C with the heating system, whilst the outdoor air temperature during this period varies between -5°C and 12°C. The indoor relative humidity varies between 27% to 40%, whereas outdoor relative humidity varies between 50% to 95%. As shown in the Figure 16 below, the overall average U-value for the analysed time is around 0.16 W/m^{2}K. The variation in the U-value is dependent on the changes in relative humidity, particularly indoor, worsening when the hempcrete is in the wetter state and improving when it is in a comparatively dryer state.

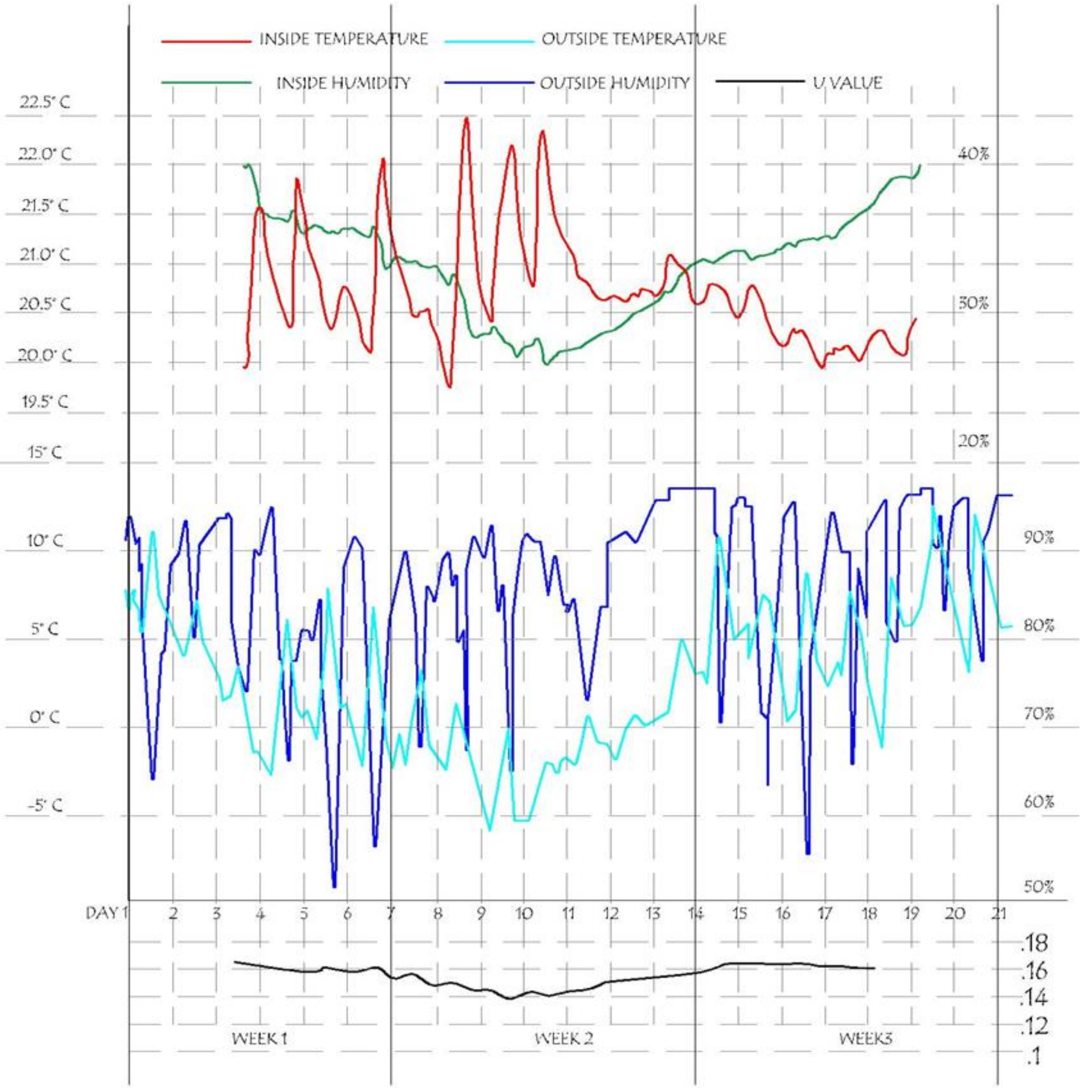


Figure 16: Monitoring results of the guest bedroom south facing wall (20/02/18- 11/03/18)

One of the important building performance monitoring test conducted was using DmP microprobe (©Sibtec Scientific), measuring the rate of decay of sycamore (see Fig. 17 a).

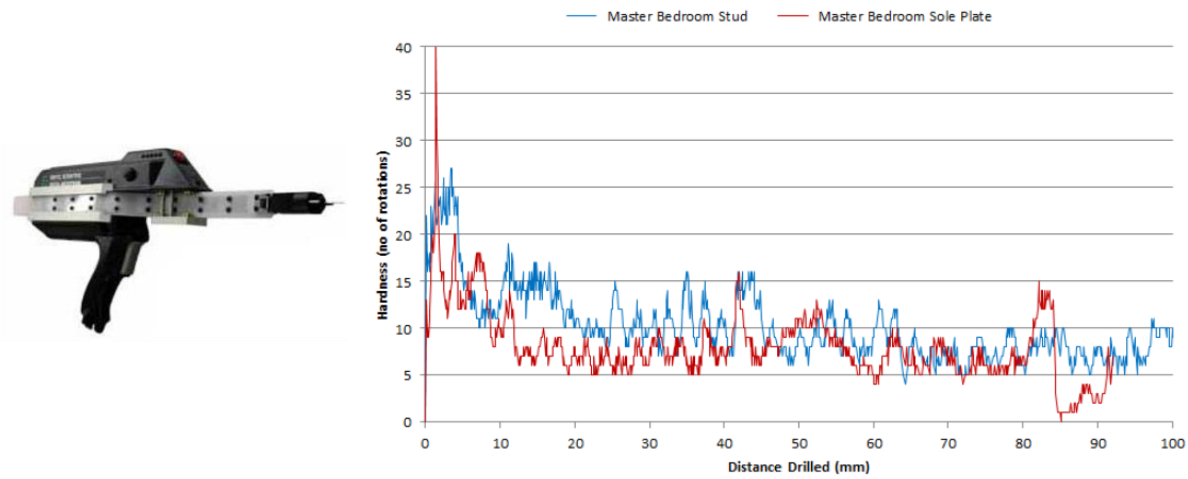


Figure 17. (a) Digital Microprobe, (b) Master Bedroom Stud and Sole Plate Hardness

The Fig 17b shows the master bedroom stud and sole plate hardness, measured in the number of rotations required by DmP rotating probe to penetrate every 0.1mm. Whilst there are no abrupt decreases in the penetration resistance between the stud and sole plate, the latter has some *soft* wood between 10 and 30mm depth, with a potential cavity discovered between 80 and 90 mm. This, as well as other junctions are monitored on a regular basis.

5. Conclusions

The building used in this research has evolved from a unique design concept, including a distinctive approach to sustainable design and site conditions context, with design and build undertaken by a dedicated team of practitioners and researches. This makes it bespoke, but it does not undermine the importance of this project serving a useful learning precedent and providing valuable lessons of "one off" innovative design case study. Following are the key conclusions:

- The mechanical properties of sycamore used within the project have been tested in accordance with British standards and proven to be comparable to the published data, albeit on a small sample of solid wood specimens from within the site boundaries.

- It is essential to keep sycamore maintained at a moisture content of less than 20%, thus making it significantly less likely to be susceptible to a substantial fungal decay.

- The breathability of walls has to be protected to ensure an inhibited moisture movement and thus prevent sycamore being exposed to prolonged periods of high humidity within its immediate surroundings.

- Evidence of potential rate of decay and local issues with the moisture content and hardness of timber can still be encountered, in particular in weak areas on the junctions between the studs and base plate. It is important that their moisture content and hardness be measured regularly.

- As any other timber, it is important to dry the sycamore prior to installation in order to keep its moisture content as close as possible to its in-service condition. (MC=14% for this case study).

- Location of the sycamore within the building seems to be one of the factors in sycamore's behaviour with respect to its moisture content. There is a variation of moisture content ranging from 7% to 21% observed over last 18 months, with the moisture content of sycamore situated within the external wall being on the higher side compared to the sycamore inside.

- The assignment of visual grades and species in the BS EN 1912:2012 lists a German Standard DIN 4074 Teil 5 which gives grading rules for Acer Pseudoplanatus, ordinarily referred to in the UK as sycamore.

- With increasing moisture content, water molecules fill the gaps between cell walls resulting in their expansion which tends to soften the cell walls. It makes the bonding weaker and wood more fragile (Sonderegger et al. 2013).

- Being a natural material, the results of its testing and analysis invariably vary from site to site, and hence due to a relatively small sample sourced and tested from the same location it cannot be considered to be statistically relevant for applications on other sites. This however is to be expected and it does not undermine the importance of the Hieron's Wood project as a precedent.

As a final conclusion, research has indicated that sycamore could indeed be used for structural and constructional applications, as long as due care is taken to its intended service class uses, quality of construction detailing in relation to the resistance to decay and insect attack, moisture content control and effective ventilation provision.

Potential Conflicts of Interest

"The authors declare no conflict of interest."

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