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Eco-minimalism and GAIA Architects:

Analysis of a building of high ecological value.

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Index

Abstract 4

Howard Liddell 6

Chapter 1 8

1. The origins of eco-minimalism 8
   1.1 The Granada House – A house for the future 9
2. What is eco-minimalism? 12
   2.1 The eco-minimalist approach 13
      2.1.1 A holistic approach 13
      2.1.2 Eco-minimalism as a virtue 14
      2.1.3 The stakeholders 14
3. Environmental aspects of eco-minimalism 17
   3.1 Eco-blings 18
   3.2 Eco-minimalism 19
4. Economic aspects of eco-minimalism 22
5. Human well-being 24
6. Research and learning 25

Chapter 2 27

1. Dunning 27
2. Tressour Woods 33
3. Glencoe Visitor Centre 38
4. David Douglas Pavilion 47
5. Glentress Visitor Centre 54
6. Acharacle Primary School 61

Chapter 3 70
1. Introduction 70
  1.1 Acknowledgment of previous study 71
  1.2 History of the project 72
2. Structure 75
  2.1 Foundations 75
  2.2 Load-Bearing Structure 76
    2.2.1 Brettstapel, what is it? 77
    2.2.2 The use of Brettstapel in Plummerswood 78
    2.2.3 Fire protection 80
  2.3 Roof 82
  2.4 Metalwork 84
3. Insulation 85
  3.1 Issues with the insulation 87
4. Cladding 90
5. Floors 92
6. Wall finishes 94
7. Furniture 96
8. Ventilation and heating strategies 97
  8.1 Ventilation 97
  8.2 Hygroscopic materials 99
  8.3 Heating 100
  8.4 Solar Gains 102
9. Energy Consumption 104
10. Embodied Energy and Embodied Carbons 106
  10.1 Databases 107
  10.2 Bill of quantities 108
  10.3 Weight calculation 109
  10.4 Embodied Energy and Carbon calculation with ÖKOBAUDAT 110
  10.5 Embodied Energy and Carbons calculation with ICE 112
  10.6 EE and EC of Brettstapel 114

10.7 Comparison with other case studies 117

Conclusion 123

Abstract

GAIA Architects has been pioneering ecological design in Scotland since the early 1990s. Their philosophy, named eco-minimalism by their chief architect Howard Liddell, rejects the greenwashing of contemporary sustainable architecture in favour of simpler, more effective solutions. Through detailed scientific assessments of their projects, they were able to design buildings that aim to solve today's most pressing issues of sustainable construction with the use of extremely low-technologies rather than the high-technologies commonly associated with 'green' architecture.

The first part of this thesis provides a description of the main aspects of eco-minimalism, useful to understand GAIA's design choices and project outcomes. The second section outlines a selection of their most important and exemplificative projects, illustrating both the evolution and the recurrent sustainable features of their work. Further, the third part of this thesis focuses on a case study on the Passivhaus-certified dwelling called Plummerswood. The analysis provides an evaluation of its embodied energy and carbons and highlights its high environmental qualities achieved with the use of Brettstapel panels for its load-bearing structure. This study, while showing the high ecological qualities of Plummerswood, underlines a lack of research on the embodied energy and carbons of the Brettstapel construction system and the need for additional studies on the matter.

Howard Liddell

Fig. 1 Howard Liddell
Source: The Architect's Journal

Howard Liddell was an English-born architect who pioneered sustainable architecture and ecological development with a passive approach and the UK.

He was born in 1945 in Yorkshire and grew up in Newcastle-upon-Tyne and later in Edinburgh. He graduated at the Edinburgh School of Architecture (Harwood, 2013). In 1971 he started lecturing at the Hull School of Architecture, where he eventually became director of the research department. From 1971 up until his death he also became a guest professor at the University of Oslo, where he held a summer post-graduate course for international students in Building Ecology (Butters, 2013). In 1984 he also participated to the creation of the Green Association of Idealistic Architects (GAIA Architects), a name inspired by the GAIA hypothesis conceived in 1979 by James Lovelock (Halliday, 2015b).

Between 1974 and 1979 he chaired the Architecture and Ecology Group of the Royal Institute of British Architecture (RIBA) (Harwood, 2013). In 1991 he was also one of the founders, the first chairman and a strong promoter of the Scottish Ecological Design Association (SEDA), a membership organization with the aim to promote and implement ecological design in buildings and services across Scotland (Harwood, 2013; SEDA, n.d.). He founded GAIA Planning in 1994 with Drew Mackie and GAIA International in 1990. GAIA International is meant to be a network of architects, researchers and academics who focus on ecological architecture and sustainable design. Its mission is to create a balance and integration of the built environment with ecosystems to create a sustainable way of life for all species on the planet (Halliday, 2015a).

Back in Edinburgh, after the Norwegian experience, in 1996 he merged GAIA Architects and Planning into GAIA Scotland, which was the architecture division of the newly founded GAIA Architects. The research division of the Group was GAIA Research, headed by Prof. Sandy Halliday, Liddell's wife, whose specialization is the development of sustainable design strategies and technologies for buildings. The two practices worked both together with and independently from GAIA Norway and GAIA International, creating a business model that revolves around continuous improvement generated through research, design, evaluation, dissemination, training and exchange of knowledge (GAIA Architects, n.d. e).

GAIA received numerous prestigious awards such as the UK House of the Year Award in 1992 for his Tressour Wood project, the UN World Habitat award for the Fairfield Housing project in Perth and the Sustainability Award for the Glencoe Visitor Centre in 2003 (Butters, 2013), and many others. In 2013, Liddell received an OBE (Order of the British Empire) for his contribution to ecological design in architecture, but he died at 67 years old, just days before its appointment at Buckingham Palace (Hartman, 2013). After Liddell's death, GAIA Architects ceased its activities, while Sandy Halliday continued the work of GAIA Research (GAIA Architects, n.d. e).

Howard Liddell's influence on ecological design is not simply connected to his projects, he is also known for his theoretical contribution to sustainable design through his literary work, mostly expressed in his book *Eco-minimalism. The Antidote to Eco-bling*, which is the starting point of this dissertation. The first edition of the book was published in 2008, and a second, revisited one was eventually released in 2013, shortly before his passing.

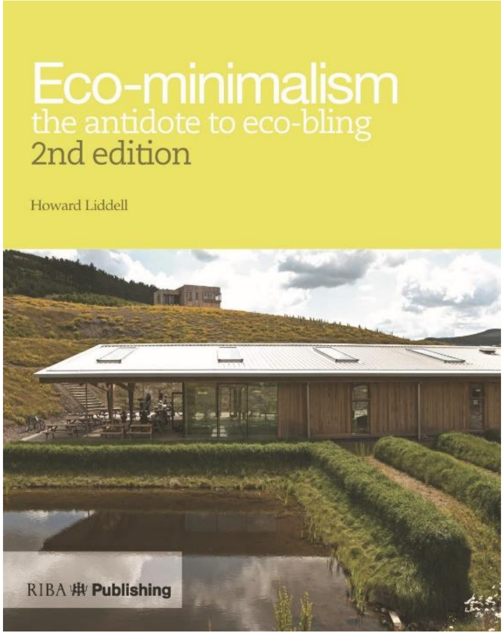


Fig. 2 Book cover
Source: Routledge

Chapter 1

1. The origins of eco-minimalism

Since the industrial revolution and well into the first decades following the Second World War, the general perception was that the Earth was an infinite reservoir of resources for humans to rely on and use in perpetuity (Halliday, 2018). This mentality was very relevant to the construction world, as, the availability of new construction materials, technologies and perceived infinite resources provided the industrialized countries with a great number of buildings that heavily relied on energy to be liveable (Penna, 2013). Demands for change in the energy supply by early environmental activists who were trying in the 1970s to raise attention on the effects of human activities on the planet were usually seen as unnecessary alarmism. The search for sustainable technologies and ways of living were considered “wasteful, expensive and obstruction to innovation” (Halliday, 2018, p. 16). New technologies and new kinds of housing and living were left to the initiative of single individuals, mostly associated with alternative subcultures.

Nevertheless, discussions about sustainability had already initiated in the late sixties and early seventies, when Liddell was studying and starting to practice, these debates certainly affected his views on the topic, as Sandy Halliday said during the first Howard Liddell memorial lecture at SEDA in 2015*. In the late sixties the Club of Rome speculated that the 34% growth in food production between 1951 and 1961 was unsustainable, and that “limits of growth” should be enforced to slow the rate down before the point of no return was reached (Halliday, 2015b). In 1972 the effects of pollution were even more clear and at the UN Conference on the Human Environment in Stockholm a debate was held over what would happen if the then-current model of development of Western countries was to be replicated all over the world (Halliday, 2015b). The governments of developing nations were more concerned about economic growth and poverty issues rather than environmental ones. This conference resulted in the release of the book O*nly One Earth* by Barbara Ward and René Dubos, a seminal book for early environmentalists, that started collecting data about the ecological footprint of human activities and the notion of circular economy that influenced Howard Liddell (Halliday, 2015b).

The first major cultural shift towards different sources of energy came the following year with the international crisis caused by the Yom Kippur War in 1973, which resulted in a devastating economical and energetic crisis for the next decade (Penna, 2013). Driven by the necessity of not relying solely on the oil from the Middle East and by an increasing awareness on environmental issues, Western countries were stimulated in searching ‘alternative’ sources of energy, as well as reflecting on the limited resources of the planet (Penna, 2013). In this context, renewable energy resources started being considered as possible alternatives to fossil fuels. In the following years, many Western countries put in place new laws with the purpose of increasing the energy efficiency of buildings. In this context, some early activists, researchers and architects started to focus on ways to induce society to shift to renewable resources, resulting in occasional utopian solutions as well as scientific advancements and new ‘green’ technological solutions (Penna, 2013).

1.1 The Granada House – A house for the future

During these years Howard Liddell was senior lecturer at the Hull School of Architecture and later its director of research (Butters, 2013). In 1976, after participating as a volunteer and consultant to a reality TV programme called *A House for the future* (Liddell, 2013), he got the cue for what he would later name eco-minimalism.

Fig. 3 A House For The Future

The show was focused on energy technology. The Grants family, together with the help of architect Don Wilson and some volunteers, not only had to convert ‘hands-on’ an old barn into a house, but they also had to change their lifestyle in a sustainable way. As it was a TV programme, the retrofitting and renovation of the barn had to be visually appealing to the public, and many technological solutions were adopted in order to make the dwelling energetically self-sufficient and supposedly ‘green’ (Liddell, 2013). Each of the thirteen episodes dealt with a specific technology such as:

- Very high insulation levels provided by an inner layer of glass fibre and an outer one of expanded polystyrene in the external walls, Styrofoam panels on the ground floor and fibre glass in the roof;
- Airtight skin and a mechanical ventilation system for heat recovery from the kitchen;
- A 42 m^2 solar roof installed on the south-west facing slope with a 45° pitch connected to two tanks with a 2,500 litres capacity;
- A passive greenhouse (conservatory) on the south-west façade to deliver heat into the first and ground floors through flaps in the bedroom windows and openings in the doors;
- A 12 m^2 insulated rock layer underneath the conservatory floor to store the heat.
- A heat pump
- A wind turbine in close proximity
- Energy saving fittings
- Low embodied energy materials
- Vegetable garden for increased food self-sufficiency

(McLaughlin, 1977; Trueman & Murgatroyd, 1977)

After the show, the Grants were asked to record some parameters of interest. In particular, they recorded twice a day the temperatures of different place of the house and kept a log of weather conditions, while other parameters were measured by experts through specific instruments. The results were discussed two years later in a follow-up documentary, where it was reported that the thermal energy gains in the dwelling were:

- 42% from domestic electricity
- 29% from solid fuel
- 21% from solar gains
- only 1,5% through the massive roof. (Trueman & Murgatroyd, 1977)

This showed that the investment in the solar roof was not worth by the economical point of view, as it would not provide any savings. Other failures were the wind mill, which broke within the first year and had to be replaced, while other technologies did not prove as efficient as expected (Liddell, 2013).

On the other hand, it was proved that the high level of insulation of the building together with the air tightness and the heat recovery from the kitchen alone, were very effective, since they more than halved the energy demand of the Granada house (22,000 kWh), compared to a similar contemporary average building (55,000 kWh). In his book *Eco-minimalism. The Antidote to Eco-bling*, Liddell states that the insulation and the airtightness of the envelope alone were responsible for all the savings of energy in the building, while the whole house could be effectively heated by passive gains from the users, the electrical fixtures and especially by the heat recovered from the kitchen. Everything else was superfluous and redundant (Liddell, 2013).

Nevertheless, the technologies employed in the construction of this house and of many others in the following decades were almost inseparably connected to the idea of the ‘sustainable’ and ‘green’ home. This might be one of the reasons why sustainable architecture has often been associated with expensive technologies not always living up to their promises, and the idea of the perfect green house made architects make many mistakes in the years to come.

These observations regarding the Granada house experience were the base of Lidell’s following work in the following decades.

2. What is eco-minimalism?

Despite containing the word minimalism, eco-minimalism is not an architectural "style, or set of new clichés" (Grant, 2007, p.32), but rather an approach to design. On one hand, eco-minimalism rejects the greenwashing of contemporary architecture in favour of simpler, sometimes traditional, more effective solutions (Liddell, 2013). On the other hand, it debunks the common misconception that sustainable architecture has to be expensive or the product of a counter-culture (Liddell, 2013). The concept of eco-minimalism was extensively explained by Liddell in his 2008 book *Eco-minimalism. The Antidote to Eco-bling* (a second edition was issued in 2013), but the idea was first presented in 2002 to the Scottish "green" architects in an article co-written with water and energy consultant Nick Grant. They blamed the "technical fixes" (Liddell & Grant, 2002) of contemporary green architecture that are often expensive "one-size-fits-all" (Liddell & Grant, 2002) elements added to the buildings to easily address individual negative symptoms of modern buildings in a visible way, rather than tackling the design problems that create the problems in the first place (Atkins & Halliday, 2016). Attractive green products and technologies, which Liddell dubs *Eco-blings* or *Eco-cliché*, are added to the project to upgrade it to a perceived satisfactory level of sustainability, often with the risk of poor outcomes or even with the abandonment of the technologies once the project becomes too expensive, leaving the problems unsolved. Such projects also usually do not take in consideration the ecological impact that they have on the larger scale, i.e. not only on the environment, but also on the communities and the economy. Green architects and the general public usually tend to focus only on one issue to solve, which is usually the energy used for the carbon emissions, overlooking the whole picture and undermining the possibility of designing a truly sustainable building (Halliday, 2015b).

Although Liddell provides some eco-minimalist alternatives to the eco-clichés, eco-minimalism itself does not provide a readymade answer to the issues of all buildings: it is rather a case by case approach to sustainable design that can be learnt and taught. That is why Liddell and Grant refer to eco-minimalism as a virtue driven by a cycle of researching, learning and decision-making (Halliday, 2015b) led by practical wisdom (Knights, Littlewood, Firth, 2011).

In the next sections, the key aspects of eco-minimalism will be treated more in detail.

2.1 The eco-minimalist approach

2.1.1 A holistic approach

"The most ubiquitous sustainability clichés of all is probably the one about solutions being 'holistic'. It is also probably the most ignored".

Howard Liddell, Nick Grant (Liddell & Grant, 2002).

The main characteristic of Liddell's approach to design is to think of the building holistically and to make things as simple and sustainable as possible. In this respect, Liddell was inspired by the work of Sir Patrick Geddes (1854-1932) (Halliday, 2015b), a Scottish biologist, sociologist and urban planner who popularized the idea of 'think globally, act locally' (Butters, 2013). Geddes' idea was that the health of the planet had to be considered in its entirety and that, in order to achieve it, people had to take actions in their own communities and cities (Halliday, 2015b). According to him, society, economy and environment were intrinsically interconnected and a truly sustainable development had to affect positively all of them. Howard Liddell adopted and revisited this idea in his work, creating the concept of the 'three-legged economic stool' (Halliday, 2015b), where the Folk-Place-Work constitutes the legs, i.e. the three pillars of sustainable development. If one leg "does not work, the whole system is destined to fall down" (Halliday, 2015b).

For example, a development or a new project should be as minimally impactful on the environment as possible. Minimizing the pollutants and energy consumption means also creating a healthier indoor and outdoor environment without VOCs or other pollutants. Reducing the toxicity of the closed environments promotes well-being of the occupants and their productivity (Atkins & Halliday, 2016). This has an economic and social input on the community, since it creates a healthier environment and reduces the medication costs. Thermal mass, good levels of insulation and airtightness and natural ventilation produce savings in construction, running and maintenance costs, while reducing the impact on the environment. "The affordability both in the output and input of a project is what makes the politicians and stakeholders get on board with the project" (Halliday, 2015b).

2.1.2 Eco-minimalism as a virtue

Paul Knights et al. (2011) argue that Eco-minimalism is an approach that has to be learned. Architects, professionals and clients have to be trained in true sustainability and environmental impact in order to obtain an eco-minimalist project. Paul Knights et al. (2011) also argue that eco-minimalism can be seen as a virtue that has to be understood and practiced by all the people involved in the project of a building (Knights et al., 2011).

From this perspective, Liddell and Grant say that the only way to achieve this virtue is through a trade-off of scientific knowledge and common sense (Knights et al., 2011). Scientific assessment and analyse before, during and after the completion of a building are key aspects in order to evaluate each case and to have the correct knowledge to guide the decision-making process of current and future projects. Nevertheless, scientific knowledge alone is not enough, as it can lead to eco-blings. Therefore, critical thinking and common sense are required to find the “optimal solution” (Knights et al., 2011, p. 346) that meets all the various sustainability goals, especially when the decision-making process makes it difficult to reach different sustainability goals or to decide for the optimal solution between “competing designs and proposals” (Knights et al., 2011, p. 351).

2.1.3 The stakeholders

The understanding of what is really sustainable is not a prerogative of the designer. An eco-minimalist project cannot in fact be successful if its sustainability values are not shared by every actor involved. Although the intentions of the stakeholders can be genuine, their understanding of what is truly sustainable might not be on point. A “Sustainability champion” (Atkins & Halliday, 2016, p. 28) is a helpful figure to educate and address sustainability issues in the design and building process. The Sustainability Champion can be a member of the project team, like the architect, or an external consultant (Atkins & Halliday, 2016).

In the following paragraphs, the role of the different stakeholders will be briefly discussed, as presented by Nick Grant et al. in their 2011 article *Eco-Minimalism as a Virtue* in the *Environmental Ethics* journal.

The architects/designers

They have to find the design for a specific building that best includes sustainability values. The architect "would have awareness of a wide range of materials, fittings and construction techniques" (Knights et al., 2011, p. 346), but they also have to be able to assess the environmental impact of the construction. They have to trade off sustainability goals with construction and operational costs, prioritizing human wellbeing (Knights et al., 2011). Further, they have to avoid eco-cliché technology if it is superfluous to the building specifications (Knights et al., 2011). Lastly, they have to consider the lifespan and sustainable decommissioning of the building (Knights et al., 2011).

The builders

They have to carefully execute the construction following the design. In order to do that, they have to be "aware of the principles of eco-minimalism" (Knights et al., 2011, p. 347), so that the detailing can be executed according to them and later adjustments of construction mistakes can be avoided (Atkins & Halliday, 2016). They have to be skilled/instructed on the characteristics of construction materials that might not be common in conventional buildings (Atkins & Halliday, 2016; Knights et al., 2011). They have to "minimise" and "dispose of the waste that arises in a sustainable way" (Knights et al., 2011, p. 347).

The clients

They have to be instructed on sustainability (Atkins & Halliday, 2016) and they have to give "importance" to the "environmental impact" of the building and its costs during the building process and its whole lifetime (Knights et al., 2011, p. 347). They should not be excessively attracted by eco-cliché technologies, but rather be driven by the goals of sustainability (Knights et al., 2011).

The users

They should “use the building in the way it was designed to be used” (Knights et al., 2011, p. 347), and possibly aim to improve its performance (Knights et al., 2011). This means operating the building in a way that takes in consideration its impact on the environment, its operational costs and the wellbeing of the users (Knights et al., 2011). A “user guide” (Atkins & Halliday, 2016, p. 156) written in easy language can be useful to explain the functioning of the building, “why its services have been installed, what they are supposed to do, when they are meant to be used and how to tell when they are not working properly” (Atkins & Halliday, 2016 p. 156).

The de-commissioners

They have to plan and execute the demolition of the building balancing “the environmental impact, cost and human wellbeing” (Knights et al., 2011, p. 347). They have to maximize recycling construction materials, while disposing of hazardous materials in the appropriate way (Knights et al., 2011).

3. Environmental aspects of eco-minimalism

"An eco-minimalist design must be judged on how successfully it minimises environmental impacts and maximises human benefits – not by how minimal it is"

Nick Grant (Paul Knights et al., 2011, p. 248)

The aim of eco-minimalism is to reach environmental goals through minimal technology, i.e. using as little devices as possible while preferring a thorough detailing of the building envelope. Eco-minimalist architects have to take in consideration not only the performance of the finished building, but also consider the origin and properties of the raw materials that are used in the construction, the methods used to produce components, and how the whole process can be made more sustainable. The model of development that should be pursued is that of a circular economy, or a "cyclic approach, whereby we know where we seek to resolve the cycles without environmental damage" (Liddell, 2013, p. 10). Extracting, processing raw materials and producing high-technology devices is "energy and material intensive and creates significant environmental damage" (Zynk & Geyer, 2017, p. 2), therefore reducing, repairing, reusing and recycling the materials before disposing of them have to be the relevant goals.

Controlling the envelope and its physics instead of embracing over-engineered solutions is essential for a cyclic approach to design, where waste and pollution are minimized. In order to do so, GAIA Architects have developed a system of subdivision of building parts into four areas representing the natural elements (Liddell, 2013).

These elements are:

1. Fire, or all the parts that imply the energetic aspect of a building, such as electricity and heating;
2. Air, or what revolves around gases, ventilation;
3. Earth, or the materials, everything that is solid;
4. Water, including water and moisture management (Liddell, 2013).

Liddell used this subdivision in his *Eco-minimalism* book to describe the technologies/approaches to design Eco blings (or Eco-clichés): those eco-technologies that he deems as "inappropriate, unnecessary and ostentatious" (Knights et al., 2011, p. 339). Liddell goes as far as defining them "sexy" (Grant & Liddell, 2002, para.6) i.e. attractive and visible technologies that are meant to be perceived as green and clean (Liddell, 2013). These clichés should be avoided when possible in favour of the eco-minimalist approach, which means scrupulous detailing of the building features in order to minimize its impact on the environment.

In the following, a few eco-bling examples from Liddell's book will be briefly explained, followed by some examples of Eco-minimalism.

3.1 Eco-blings

Many of the technologies that Liddell deemed as eco-blings are exactly those which are commonly associated with green architecture. Photovoltaic and solar panels are perhaps the most popular ones.

Photovoltaic panels require maintenance and resources, they are expensive, have a very long payback period (especially in northern lands/territories, such as UK) despite producers promising a life-span of approximately 25 years. (Liddell, 2013; Kurtz, 2016). Electric energy "is bound to be more expensive than [the resources] that it exploits for its creation" and "solar-energy supply is no different: like any basic fuel, it is only as cheap as the cost of exploiting it for an end use" (Liddell, 2013, p. 15). This means that producing electrical energy is still too expensive when the installation costs are taken in consideration. Thermal solar collectors also have a long payback-period (12-15 years at UK latitude), although modern ones can outlive that, still requiring constant maintenance and repairs (Liddell, 2013). Paradoxically, the better the quality, the longer is the payback period, because, Liddell claims, "there is insufficient difference in energy efficiency between a simple home-made collector" and a high-quality panel (H. Liddell, *Eco-minimalism*, 2013, p. 21). On the other hand, self-built and recycled collectors can be very cost-effective, but the panels will work best only during sunny days, making them an inefficient technology in countries like the UK and during winter time (Liddell, 2013).

Wind farms can be effective, but small single-family wind turbines are not. Their cost-effectiveness, efficiency, and carbon footprint are not sustainable compared to larger plants, and their effectiveness is very location-specific.

Mechanical ventilation requires constant energy and is not very effective in dealing with indoor moisture inside a building (Liddell, 2013).

Heat pumps are usually not very efficient in northern Europe. In the UK for example, to get one unit of electrical energy, you need 3 units of gas energy, which is also the same as the average output of a heat pump (Liddell, 2013). This makes the heat pump a technological redundancy and leads to a lot of technical complication and costs to get the same results (Liddell, 2013). For Liddell, condensing boilers also are ineffective, as cheap options are mostly available on the market and they usually fail after a couple of years, making them equal to conventional non-condensing boilers. For Liddell, having a condensing boiler becomes merely a mean to "tick the box" exercise of sustainability despite no real environmental or cost benefits (H. Liddell, 2013, p. 23).

Conservatories are considered good as they provide free solar gains, potential heat storage and shelter from winds. Nevertheless, these positive benefits become marginal if the conservatory is also provided with a heating system, creating a huge thermic dispersion to the outdoors (Liddell, 2013). Modern green roofs require extra structural support and petrol-based damp-proofing membranes, and their longevity has not been proven (Liddell, 2013).

Grey water recycling requires secondary plumbing systems alongside the one for clean water. The expense might be excessive if water supply is not an issue in the site (Liddell, 2013). Reed beds make no "environmental sense" (H. Liddell, *Eco-minimalism* 2013, p. 47) in an urban context where land is not abundant and a connection to sewerage infrastructure is available. Moreover, most of reed beds are usually mono-cultures and are not able to purify water from all the pollutants (H. Liddell, 2013).

It is also worth noting that many of these fittings have high embodied energy, carbon and water to. Most of these technologies can quickly become obsolete or have a short life span and are difficult or impossible to recycle or reuse, making them not suitable for the model of a circular economy.

3.2 Eco-minimalism

Eco-minimalist design can be related to the 'fabric first' approach: the climatic response of a building can be controlled through a careful detailing of the "landscape, building orientation, form and structure" (Halliday & Atkins*, 2016,* p. 90) avoiding the need for active systems the first place. It all comes down to "reducing the demand, before increasing the supply" (Liddell, 2010e. 0:09), as Liddle says.

Analysing Liddell's projects with GAIA, it is clear that some of the main elements of the eco-minimalist approach are super-insulation and airtightness, which are also two important specifications of the Passivhaus standards. A good detailing of super-insulated external walls allows the fabric to keep almost all of the heat gains inside the building. This way, heat losses through conduction are minimised and the need for active heating system is drastically reduced.

Nevertheless, the benefits of super-insulation cannot be achieved without high levels of air tightness (Liddell, 2013). Ventilation is essential to the building in order to maintain a healthy and enjoyable indoor air quality, but this has to be achieved in a controlled fashion and by completely avoiding air infiltration. The Passivhaus standards require a Mechanical Ventilation Heat Recovery system in order to get the certification, but Liddell argues that is not necessary and that it is more environmentally friendly to use other approaches such as the "Active House" standard or hybrid ventilation systems (H. Liddell, *Eco-minimalism,* 2013, p. 77). The Active House is an approach that was invented in Norway, that focus on passive technologies, healthy indoor air and daylight (Active House Alliance, 2020). This approach, is based on natural ventilation and the design of the building has to obviate the need for fans. When mechanical ventilation is necessary, heat loss can be avoided with hybrid systems (Liddell*,* 2013) such as a heat exchanger that "provides a good payback in invested energy" while introducing "other advantages, such as humidity control and excellent air quality" (N. Grant, 2007, p. 33).

GAIA has also researched and used dynamic insulation in some projects of large indoor sport halls, where ventilation is ensured by a constant and controlled air-flow that is drawn through the building insulation thanks to a pressure difference. This system also allows to passively recover the heat lost by conduction by exchanging it with the air coming through the insulation. Untreated timber, hemp and lime, unfired clay are examples of hygroscopic, moisture-transfusive materials that dramatically reduce ventilation requirements inside a building.

Passive solar gains are another important element of the approach. Passive solar design requires mechanical systems and virtually no maintenance. A correct orientation of the building and its windows is essential to allow solar gains and use the greenhouse effect, and heat-retaining materials allow to store energy for free (Liddell, 2013). The heat of the occupants and of the electric fixtures and equipment are also an important part of the gains of a super-insulated building and have to be taken in consideration. Heat losses in winter through the windows can be reduced through shutters and curtains, while overheating in summer can be easily avoided with external solar shades (Liddell*,* 2013). Trees and bushes also have a significant impact on the energy efficiency of a building throughout the year. In winter they can shelter a building from cold winds resulting in less heat loss, while in summer they can provide shade and let air go over or through rooms (Liddell, 2013).

Materials should be untreated, especially wood, to maximize health benefits and air quality (Liddell, 2013). Local and second-hand materials should be used if healthy, and new buildings should be designed in order to facilitate the maintenance and disassembly of their components so that they can be reused in new projects (Liddell, 2013). Materials with a low embodied energy such as solid timber, earth or straw bale should be preferred. Solid timber usage in construction has a big impact on carbon sequestration, and GAIA has produced a lot of research on the use of Scottish and British low-grade timber for load bearing structures (GAIA Architects, 2000.). Scottish timber is usually too weak, but modern methods like *Brettstapel* make it suitable for load-bearing applications. The usage of heartwood affects the durability of the material (Liddell, 2013).

> *"[Wood] is pure eco-minimalism: contributing to good value for money, healthy indoor-climate credentials and a perfect strategy for carbon storage – and all is invisible to the untutored eye."* Howard Liddell, *Eco-minimalism*, 2013, p. 93

Other eco-minimalist choices regard water conservation using low energy fittings, low/dual flushes, waterless fittings in order to reduce the demand and treatment of water (Liddell, 2013). Attention to water conservation and efficient wastewater treatment measures are usually cheaper and more sustainable than technical fixes like rainwater harvesting (Halliday & Atkins, 2016). The fact that buildings can be easily connected to the grid for power supply (as in most cases) avoids the cost of purchasing and replacing the power generators and their maintenance. Most of the buildings cannot produce all the energy they need on site, and most of the time it can be more effective to use appropriate technologies or to buy electricity from suppliers who rely on a low-carbon grid supply network (Liddell, 2013).

4. Economic aspects of eco-minimalism

"Too often there is a fear that a sustainable approach delivers a hair shirt for the cost of a silk one. Sustainable projects should be neither more expensive nor more complicated than less benign alternatives."

S. Halliday, R. Atkins, *RIBA Plan of Work 2013 Guide - Sustainability*, p. 38

Another important goal of eco-minimalism is the economic aspect of sustainability. Green architecture is often perceived as being more expensive than conventional architecture. According to Liddell, this misconception derives from the fact that sustainable architecture is usually linked to eco-clichés, that indeed tend to be more expensive in terms of installation and maintenance (Liddell, 2013). In contrast, he argued that well researched green design can lead to buildings costing less than conventional ones. Eco-minimalist design simplifications such as minimising services, optimising layouts, superinsulation and airtightness can be cost-neutral at delivery and give economic and functional benefits (Halliday & Atkins, 2016). Even when they lead to more expensive buildings, the extra expense is almost irrelevant compared to the economic benefits in use (Liddell, 2013). For instance, gypsum plaster is quicker and cheaper to apply compared to a clay alternative, and the building contractor is likely more experienced on it. Nevertheless, clay plaster moderates moisture in indoor areas. Removing it would require the size of the mechanical ventilation system to be increased, resulting in more heat loss and requiring more radiators and a larger boiler, adding expenses both during the construction and the life of the building (Liddell, 2013).

Since eco-minimalism is a holistic approach and requires the sustainability goals to be taken in consideration from the start of the design process, the risks of failing are less likely. In fact, the risks are derived from an additive approach to sustainable architecture that can be easily avoided. Technical fixes can, in fact, be easily subtracted from a building, and this often happens when there are cuts of budget that undermines the sustainability assets of the whole project (Liddell, 2013). On the other hand, many eco-minimalist choices are inter-dependant and the whole system has to be considered in its entirety to be successful. For example, the installation of super-insulation on a building can provide tangible economic benefits, but it only makes economic sense if the building is also airtight (Liddell, 2013).

In a 2010 lecture Liddell gave an example of how cost effective the eco-minimalist approach can be. He briefly outlined how the environmental and economic performance of a building full of eco-clichés can be improved with an eco-minimalist revision. A single house was fitted with small turbines (£6.000), thermal collectors (£3.000), photovoltaic cells (£12.000) for a total £21.000 with an expected payback of a 100 years in front of an expected lifespan of 20 years. The same building stripped of all the technologies could also have been fitted with 300mm of extra insulation (£5.000) and airtight openings (construction + test £3.000) for a total of £8.000 with a 5 years payback period in front of an expected lifespan of 50 years. According to him then, this option would have been three times more effective at a third of the original cost (Liddell, 2010e).

5. Human well-being

Along with minimising the environmental impact and the monetary costs, another very important aspect that can be deduced from the eco-minimalist approach regards the health of the users of a building. There is a vast amount of materials in the construction world, yet less than 3% have been tested for carcinogenicity or for any effect on the human organism (Liddell, Gilbert, Halliday, 2008; Halliday, 2015). Air pollutants can cause allergies and an overall unpleasant environment, while VOCs like formaldehyde can cause headaches, nausea, dizziness, and can aggravate asthma especially in children (Liddell, Gilbert, Halliday, 2008). Otherwise natural and healthy materials are often chemically treated with toxic preservers to avoid decomposition, which turn them into toxic materials that can have an effect on human health and are impossible to discard without polluting (Halliday, 2015b).

GAIA Research conducted numerous studies on the effects of indoor pollutants on human health, while GAIA architects often precautionarily avoided chemicals in their buildings, prioritising natural and untreated materials at every stage of the construction. The appropriate choice of benign materials and the consequential reduction of off-gassing also impact the economics of the projects, since it can reduce in ventilation requirements (Liddell, Gilbert, Halliday, 2008). A proper ventilation nevertheless needs to be ensured to get rid of any indoor pollutants (Atkins & Halliday, 2016).

Another factor that influences the user's well-being is lighting. “Daylight” is a “vital contribution to people's experience of building” (Atkins & Halliday, 2016, p. 66). Any circumstance resulting in glare or overheating should be eliminated in the design process, in order to create a quality space (Halliday, 2018).

6. Research and learning

Howard Liddell and Sandy Halliday stress the importance of education on sustainability issues and values of all the stakeholders. They developed a cyclic scheme of learning and researching where the eco-minimalist professionals have to evaluate and learn from their experience and mistakes, so that they can disseminate what they learn. A couple of times per year they would retire to discuss and see how they could put their lessons in their business.

Sandy Halliday identifies various instruments that can help in the process:

Research

GAIA's business model has always been focused on scientific research to back the principles of sustainability and eco-minimalism. They have produced numerous studies on different topics. Many of them revolve around the wellbeing of the users, like the *Design for toxic chemical reduction in buildings* (Liddell et al. 2008) and *Energy Efficiency & Indoor Air Quality in Traditional Buildings* (Halliday, 2009). Other examples of research projects regard dynamic insulation, Brettstapel technology and the commercial usage of logs and round poles from northern European forests in architecture.

Post Occupancy Evaluation (PoE)

PoEs is a range of building performance evaluation methodologies that can be implemented as soon as the building starts functioning. These methodologies allow to collect quantitative data such as temperature, relative humidity, CO_2, glare that can be reviewed and used to assess the success of a design strategy and possibly modify it in order to improve its performance. Repeated measures at regular intervals help identifying where performance failures persist and where problems have been solved, and the lessons can then be taught and replicated in future projects (Atkins & Halliday, 2016).

Study tours

They are useful both for the designers and the clients, to learn from previous works by other architects and to set the sustainability aspirations for a project. Visits to manufacturers can also be useful to learn about technologies (Halliday, 2018). GAIA has produced some publications as a result of such tours, such as the *Design & Construction of Sustainable Schools* study in Northern European schools that was influential in the Acharacle School project.

Community consultations

Halliday and Liddell were inspired by the work of the American social worker Sherry Arnstein (1930-1997) and her “ladder of citizen participation” (S. Halliday, 2015b). Different levels of community participation in the design process are very important, especially in buildings with a public usage. Community consultations can provide “guidance to assist project teams to enhance the benefits and mitigate adverse effects” of a project (Halliday, Atkins, 2016, p. 50). Through workshops, citizens can be involved in all the aspects of the project, they can learn about sustainability and they can have hands-on experiences (Halliday, 2018).

Chapter 2

1. Dunning

In 1998 architect Raymond Young and his wife Jean asked GAIA Architects to design and build a tiny house to be used as a study in their own garden in Dunning, Perthshire (Merrick, 2000). The clients' explicit request was to be "as green as possible" (GAIA Architects, n.d. c, par. 1), opening up to the possibility for GAIA to experiment on a very small-scale building with minimum environmental impact. The design process was led by GAIA's architect Chris Morgan (who since 2004 has been running his own practice) and the building works lasted from December 1998 until April 1999 (Locate Architects, n.d. b).

Fig. 4 Exterior
Source: GAIA Architects

Working closely with the clients, GAIA was able to deliver a project in line with the philosophy of Eco-minimalism and that, at the time, was described as "radical […] doing as little as possible" (Merrick, 2000, par. 5). In accordance with the principles of eco-minimalism, the choice of the materials fell almost exclusively on natural or recycled materials sourced from within 20 miles and on simple design choices (Atkins & Stephens, 2017). The main objective was to deliver a cheap, well-heated working environment despite the far from optimal Scottish climate conditions (Atkins & Stephens, 2017). The end result was a 30 m^2 (external perimeter: 7x5m) building with a simple wood load-bearing structure (GAIA Architects, n.d., d).

The one-room study was constructed on concrete foundation pads raised from the ground (Merrick, 2000). A grid of nine untreated larch beams (Fig. 6) was half-buried in these foundation pads to sustain the floor (Merrick, 2000). The floor itself is made of salvaged Douglas fir boards (Atkins & Stephens, 2017). It was necessary to have a raised ground level in order to provide an adequate ventilation under the floor and to protect the structure above from the rising damp (Merrick, 2000).

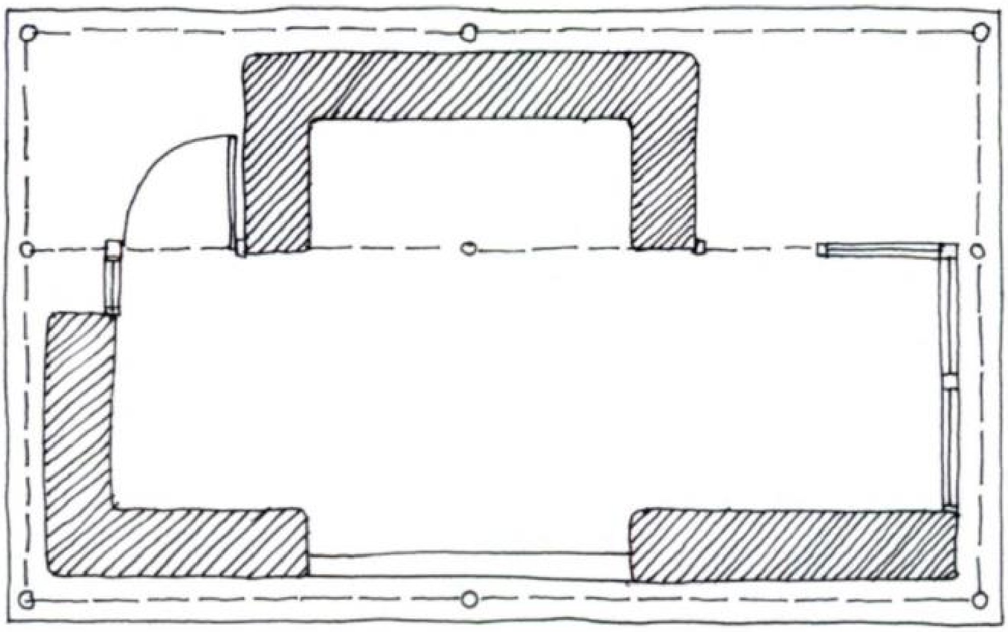


Fig. 5 Plan
Source: Locate Architects

The load-bearing structure consists of eight unbarked wooden poles (fig. 6) with a 20-22 cm (8-9 inches) diameter (GAIA Architects, 2000). This choice was the opportunity to implement the results of a research previously led by GAIA and financed by the European Union as part of the *European Union Periphery Program* (Atkins & Stephens, 2017), a program with the aim to mitigate the social and economic disadvantages due to the peripherality of Northern European communities such as Scotland (GAIA Architects, 2000). The aim of this study, called *Adding Value to Timber in the Northern Periphery*, was to explore the opportunities that derive from small cross section trunks (between 7 and 60 cm) without the need of machinery (GAIA Architects, 2000). In fact, this type of lumber is generally considered not valuable by the construction industry, and is rarely used. Nevertheless, an unbarked trunk is more resistant than a squared machine-made one, as the fibres are not severed (GAIA Architects, 2000). Trunks with a smaller diameter are thus more resistant compared to squared poles with the same section, and their use on a bigger scale would give economic value to a wide range of forests that are otherwise not utilised (Halliday, 2019). This kind of lumber is easily available in northern European forests and, according to research, it is particularly suitable for small dimensions and low-technology buildings as the one described in this section (GAIA Architects, 2000). Moreover, the use of round poles is suitable for buildings with a very low environmental impact in terms of embodied energy and carbons, since the lumber is generally locally sourced and requires minimal machining (Halliday, 2019). The only difficulty that derives from this construction system involves the connections between the poles, as they have non-plane and irregular surfaces (GAIA Architects, 2000). In fact, the joints have to be machined in order to be strong. In the case of Dunning, connection plates made it easier to join the poles to the glulam beams and yacht cables in order to brace the structure (Steen, et al, 2005).

Fig. 6 Construction of the round pole structure
Source: Locate Architects

The wall structures are then infilled with around eighty tightly packed straw-bales (Merrick, 2000). At the time, the Dunning study was only the third building in Scotland to use straw bales in its walls, but it was the first one to be realized on a "breathing base" (Steen, et al, 2005, p. 86). This was created by GAIA Architects with the aim of dissipating the humidity that may accumulate inside the bottom course of straw bales (Merrick, 2000). In fact, laying the bales directly on a concrete base is not beneficial to the longevity of the building as the base of the wall cannot breathe, increasing the risk of rotting. To avoid such risk, the bales have been placed on salvaged wood-wool boards laid on the floorboards, which are also slightly distanced from one another in order to drain humidity (Steen, et al, 2005).

Fig. 7 Rendering of the straw bales
Source: Locate Architects

Both the internal and external surfaces of the walls were covered with lime plaster and limewash (Fig. 7), in order to make the surface of the straw-bales as smooth as possible (Merrick, 2000). This was achieved with a clay-straw mix filling that also allowed to strengthen the structure (Locate Architects, n.d. b). The walls were then finished in two days with a 20 mm lime plaster on both sides and with five coats of limewash (Merrick, 2000).

Fig. 8 Interior and roof structure
Source: Locate Architects

The roof has a curved shape and it is covered with soil coming from the garden itself. It is supported by glulam beams fixed to the eight unbarked poles through recovered stainless steel shipping fixings (fig. 9) (Steen, et al, 2005). At first, they contemplated using unbarked, bent round poles also for the roof structure, an option that was later discarded in favour of the glulam beams manufactured by Charles Dobb (GAIA Architects, n.d., e). Rain water is directed from the gutters down to a drainage gravel area with a rain chain (Steen, et al, 2005). Both the roof and the floor were insulated with sheep's wool from a wool mill in Bradford, 400 km from Dunning. At the time of construction, commercial sheep's wool was 20 times more expensive than rock wool, and the only way to avoid the excessive cost was to purchase untreated raw wool from a mill (Steen, et al, 2005).

Fig. 9 Shipping fixings
Source: GAIA Architects

All the windows and the doors were recovered from other buildings, and a porthole was obtained from the offcut of a gas pipeline, which in the UK has the same diameter as the height of a straw bale, thus allowing to fit it without a lintel (Steen, et al, 2005). Each section of the wall was either entirely of straw or glazed, a choice that simplified and sped up the construction process (Steen, et al, 2005).

All the wood used in this project was not chemically treated. Every element was positioned to ensure adequate ventilation and to prevent mould and water stagnation (Atkins & Stephens, 2017). After completion, they noticed that the straw bales can retain moisture during part of the year, causing stains on the surface of the walls (Merrick, 2000). Nevertheless, the previously described precautions allow the moisture to be passively evacuated, avoiding water stagnation for a long period (Merrick, 2000).

Years after, this building can still be considered a success, both from an environmental and economic point of view. With a total cost of around 16.000£, it requires very little energy for its heating (Merrick, 2000). The study is in fact fitted only with a small electric heater that is used no longer than one hour per day in winter; the heat generated by the occupants and the electric fittings is enough to warm up the indoor space, while the high level of insulation retains the heat (Merrick, 2000). The success of this project can also be attributed to its small scale and to the willingness of the clients to experiment with low-tech solutions with a low environmental impact (Atkins & Stephens, 2017).

2. Tressour Woods

Designed in 1992 by John Brennan from GAIA Architects (Urquhart, 2003) and located in Weem, Perthshire, Tressour Woods has been referred by *The Herald Scotland* as "one of Scotland's greenest houses" (McIntosh, 1993). At that time, a wider ecological sensibility described as 'Ecological Design' was emerging, i.e. an attitude that embraced localism, natural materials and the principles of 'building biology' (Sang et al., 2011). Brennan was inspired by the wooden houses that American architect Charles Moore built in the 1960s (Urquhart, 2003) as well as Scandinavian wooden buildings with high-pitched roofs. The result was an innovative design in terms of health and sustainability that was the forerunner of high-quality sustainable houses in Scotland and that has inspired many other projects (Atkins & Stephens, 2017). The project won the UK House of the year 1993 prize (Liddell & Grant, 2002) and came out on top on a *Daily Telegraph* competition for self-built houses because of "the ecological aspects of the design and the fuel-efficiency and insulation" (McIntosh, 1993).

Fig. 10 Tressour Woods
Source: GAIA Architects

Tressour Woods shows how fundamental it was for GAIA to engage on an educating process with the clients and the builders about what real sustainability and eco-minimalism are. This project was in fact a new experience for everyone involved. The clients, Marjorie and Peter Bourne, were initially looking for something more traditional, "they were not eco-freaks" (McIntosh, 1993), as Howard Liddell said. They had an open mind though, and they were looking for something different when they approached the architecture firm (McIntosh, 1993). On the other hand, GAIA was very willing to experiment with self-building and with natural and healthy materials (McIntosh, 1993). They were able to carry out meaningful conversations with the clients and the contractors in order to overcome creative and planning problems that were emerging, such as the perception of the clients that green buildings were appropriate only for alternative and hippy lifestyles (McIntosh, 1993). Peter Bournes said “it was ignorance more than anything else. We didn’t know that these non-toxic materials existed. But we did want a house that was warm, comfortable and a pleasure to live in. The house feels very comfortable all of the time, the air inside is very fresh” (McIntosh, 1993). Liddell reported “We discussed every one of these things with the Bournes, who were very courageous in deciding to go for it. You need a special sort of client to carry out projects like this one” (McIntosh, 1993).

Large rocks on a steep slope had to be blown up in order to lay the foundations of the house. The foundations consist of concrete pads on which steel column bases are bolted to support the structure of the house (Urquhart, 2003). Wooden columns and beams form the load-bearing structure that, according to Brennan, is similar to that of a steel-framed building (Urquhart, 2003).

The house layout was conceived primarily in section (Fig. 11), and orientation and passive solar gains were the organizing principles that guided the design (Sang et al., 2011). GAIA Architects drew in fact on many of the design typologies of the autonomous building tradition. The goal was to obtain an autonomous house operating independently from any inputs except for those of its immediate environment (Sang et al., 2011).

Fig. 11 Section
Source: Sang et al.

A central stove (Fig. 12) on the open ground floor heats the whole house and divides the living and dining areas (*The Herald Scotland*, 2012). A staircase housed in a glass atrium and two verandas (Fig. 13) increase the solar gains when it is cold, and during the winter season, the open floor plan allows the heat to reach the upper floors through the atrium (The Herald Scotland, 2012). The staircase-atrium also helps the house cool down in summer with the help of a vent placed on its roof, which creates a stack effect (The Herald Scotland, 2012). Thick cellulose insulation (from recycled, shredded newspapers) was used to minimize heat losses (Atkins & Stephens, 2017; McIntosh, 1993). Peter Bournes states that no solar panels were installed on the roof of the house, because "at the time they were considered un-aesthetical and full of toxic chemicals" (Urquhart, 2003).

Fig. 12 Stove
Source: GAIA Architects

The architects used natural and healthy materials. Most of them were locally sourced, which introduced a wider environmental perspective in the design choices and benefitted the local economy (Sang et al., 2011). Natural and non-toxic materials were chosen, mostly European white softwood (Urquhart, 2003), providing a healthy indoor environment (Atkins & Stephens, 2017). For this reason, non-natural chemicals were avoided, either internally or externally (Atkins & Stephens, 2017). Instead, "a mellow lichen-coloured, water-based paint" (Urquhart, 2003) was chosen to protect the wood. No plastic vapour barrier was used in the walls, as it would not have allowed moisture to pass through, increasing the water retention of the wall (McIntosh, 1993). This element makes Tressour Woods one of the very first examples of moisture transfusive constructions in the UK (Urquhart, 2003). The result was a house perceived by its occupants as a ‘wooded’, fresh environment, comfortable to live in all year round (Atkins & Stephens, 2017; McIntosh, 1993).

Fig. 13 Glass façade
Source: GAIA Architects

As far as the costs are concerned, GAIA Architects was also able to debunk the myth that sustainable construction equals high costs. The Bournes already owned the land, yet the construction and materials were very cost effective. They in fact spent 80.000 pounds to build a 160 m^2 house (McIntosh, 1993), and since then, it has been put on sale multiple times reaching 335.000 pounds in 2012 and more recently over 415.000 pounds (Rettie & Co, n.d.).

Over the years, new owners have changed the overall appearance of the house, undermining its eco-minimalistic credentials. Changes in the heating system started two years after the Bournes first moved in, when they decided to install additional electric heaters (Sang et al., 2011). This decision was not taken because of a dissatisfaction with the indoor heat performance of the house, which actually proved to be highly efficient, but because the original wooden stove “lacked the kind of the automation that the owners expected” (Sang et al., 2011, p. 140), making the Bournes unwilling to light the stove early in the morning during the cold season (Sang et al., 2011). Since then, the house changed multiple owners, was used as a second home for a while and needed maintenance work (McLuckie, 2012). This led to major renovations (Fig. 14, 15): the interiors of the house were completely remodelled and the internal and external timber varnished as it can be seen from later listings (McLuckie, 2012). According to architect John Brennan, these changes show that any basic technology, however cost and environmentally effective is, “needs to be mediated and negotiated, not ignored, within the context of the inhabitants’ pattern of living” (Sang et al., 2011, p. 140).

Fig. 14 The house today
Source: rettie.co.uk

Fig. 15 The interiors after the renovation
Source: rettie.co.uk

3. Glencoe Visitor Centre

Fig. 16 Glencoe Visitor Centre
Source GAIA Architects

In 1995 GAIA started designing the new Glencoe Visitor Centre on a caravan park situated on the site of the MacDonald Clan Massacre, an area that today belongs to the National Trust of Scotland, who is also the client and operator of the centre (Sassi, 2006). The budget was 2 million pounds (Liddell et al., 2008). The appointed architect for the project was Chris Morgan, who drew the plan, the tender drawings, and was also responsible for the building construction on site (Locate Architects, n.d. a). The new complex had to provide a café, a kitchen, a shop, toilets, an interpretation centre and educational spaces for the public as well as administrative spaces, storage and staff accommodation (Davies, et al., 2002). The centre also had to replace the older outdated complex located in another area in the heart of the National Park that was deemed not easy to access by the expected 200,000 tourists per year (Locate Architects, n.d. a). The operations of demolition were performed by Telford Construction under the directions of GAIA Architects, who was also asked to direct the recycling of the old visitor centre, and to re-naturalize the area (Telford-Construction, n.d). During the demolition and construction phases, the work area was strictly delimitated in order to prevent storage, traffic and building activity from damaging the surrounding plants and wildlife (Network21, 2005). The construction activities started in in 2000 and were completed in 2002 (Sassi, 2006).

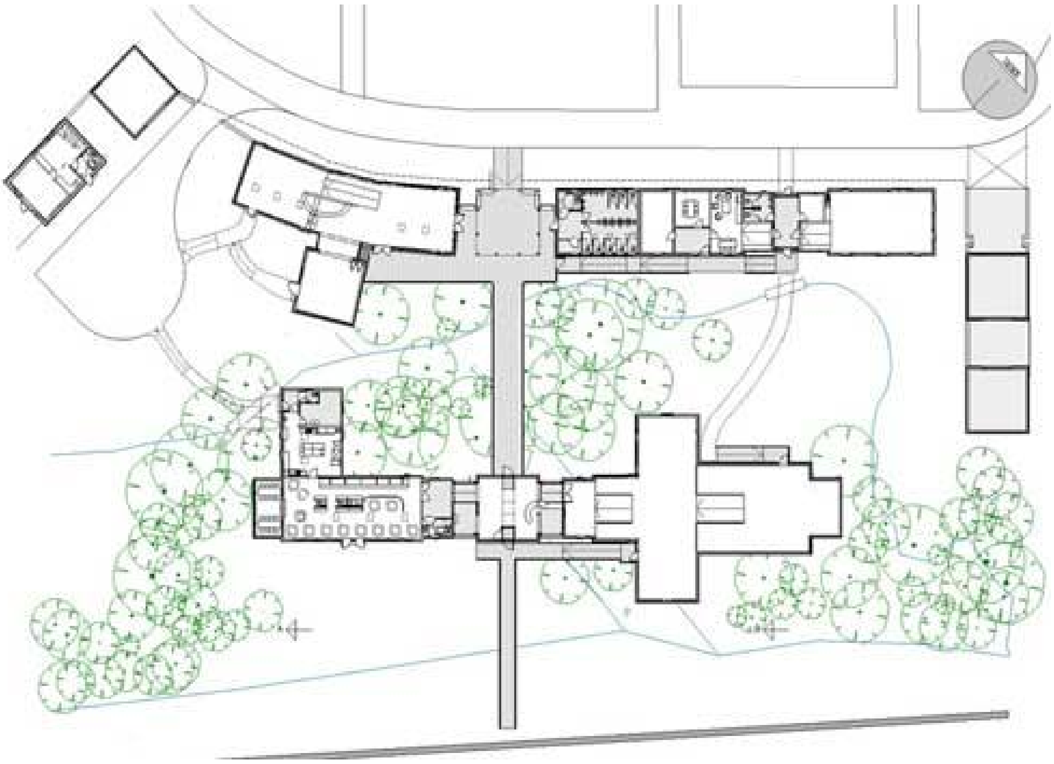


Fig. 17 Plan
Source: GAIA Architects

The aims of the project were to minimise its environmental impact as much as possible, as well as to be sensitive to the local landscape by conjugating modern green solutions with a regional design. The result was a group of small buildings connected by a raised wooden walkway, a design that on one hand reminds of the traditional clachan village type (Fig. 16, 17), whilst on the other hand being obviously contemporary in its detailing (GAIA Architects, n.d. b). The material choice draws both from the Scottish (stone) and the Scandinavian (wood) traditions (Liddell, 2010c). GAIA paid a great amount of attention to energy consumption in all the life phases of the buildings, the usage of natural materials and a radical approach to the indoor climate. This cutting-edge approach granted GAIA numerous prizes like the International Sustainability Award in 2003 by The Royal Institution of Chartered Surveyors, the Dynamic Places Award in 2002, the Green Tourism Award in 2002 and the Association Sustainability Award by the Edinburgh Architectural Association in 2002. (GAIA Architects, n.d., a).

According to Paola Sassi (2006), flexibility is one of the defining characteristics of the complex, both in its usage and in its structure. Flexibility in fact allows to maximise the durability of the centre and to minimise the costs of changes and repairs. Each layer of the structure is as independent as possible, making it easy to disassemble, modify and recycle each component and allowing to save money and material (Sassi, 2006). In order to allow the layers to be accessed, most of the fixings were screwed or bolted and were preferably left exposed (Sassi, 2006). These decisions proved successful, considering that, the complex has undergone several changes over the years (Sassi, 2006).

Fig. 18 Salvaged slates

Fig. 19 Wooden roof

The vast majority of the materials is natural and sourced locally, supporting the local economy and saving carbon emissions deriving from transportation. The slates of the roof come from the Ballachulish quarries, about a mile and a half from the complex (Fig.18) (Liddell, 2010d). This kind of slates has been part of the local architecture since the 17h century (Ballachulish Community Council, n.d.). They blend perfectly with the local tradition, but they do not come directly from the quarry itself, as it has been closed for almost half a century (Liddell, 2010d). They were in fact salvaged from a nearby building when it was demolished. This material is nowadays not produced locally anymore and has to be imported. Liddell takes this as an example to underline the importance of not discarding perfectly usable building materials coming from a demolition (Liddell, 2010d). However, the repurposed slates were not enough for covering the whole roof surface, which led the architects' team to use another local material: larch timber (Fig. 19) (Liddell, 2010d). Wood has not been traditionally used for roofing in Scotland, but it has for centuries in Norway, a country whose climate is similar to the Scottish one (Liddell, 2010d). According to Liddell (2010d) larch trees are renewable on a 30-years cycle and their wood is expected to last 50 years with the correct maintenance, a durability that does not exceed the one of the slates. The wood roofing was placed on a waterproofing layer and it was made of ridge-to-eaves boards to avoid joints and water infiltration. (Liddell, 2010d).

Fig. 20 Wooden roof with moss growth

However, these precautions were not very effective to avoid decay in the wooden roofing. According to Scott McCombie, who has been the manager of the National

Trust for Scotland in Glencoe since 2009, sections of the wooden roofs have been replaced over the years because of rotting related to water damage and moss growth (Fig. 20) (S. McCombie, personal communication, September 1, 2020). He states in fact that, as long as the untreated wood is vertically placed, such as in the case of cladding, the timber does not rot and it is very durable. On the other hand, as soon as the timber boards are not perfectly horizontal, they become prone to rotting and growing moss because of water stagnation (S. McCombie, personal communication, September 1, 2020). In addition, the surrounding trees contribute to the rotting of the timber roof, because, without periodical maintenance, the fallen leaves block the gutters creating water stagnation (S. McCombie, personal communication, September 1, 2020).

Fig. 21 Steel stilts

Locally sourced timber is also the main material used in the structural frame, external cladding, internal floorboards and finishes, making this project the first major modern building to use only untreated Scottish timber throughout (Locate Architects, n.d. a). Only the heartwood from European larch was used to ensure durability, strength and to make it salvageable and recyclable (Morgan & Fionn, 2005). The wooden load-bearing frame structure was designed to be structurally independent from internal partitions to achieve flexibility of the internal layout (Sassi, 2006). The external walls are moisture transfusive and consist of insulation between the framing elements sandwiched between two timber boards (Sassi, 2006). A waterproof layer was fixed on the external board (Sassi, 2006). The frame was supported by a substructure made of steel stilts (Fig 21), in order to minimise the need of earth works on the sloping side (Network 21, 2005). To limit material consumption, the whole structure lays on concrete pads, (WRAP, n.d.).

A great amount of detailing went into the project of the external cladding in order to make it as low-tech and durable as possible. The 144x25mm vertical cladding boards are made of homegrown European larch heartwood and were fixed 6-8mm apart from each other on 44x25mm battens (Davies, et al., 2002). “The supporting horizontal battens are fixed at 600 mm centres on vertical battens over a high performance breathing membrane” (Davies, et al., 2002, p. 64). It was debated whether the boards should have been sawn or planed. Planing would have reduced the amount of surface exposed to the elements, thus reducing moisture absorption (Davies, et al., 2002). On the other hand, sawing allows the moisture to evaporate more easily and reduces the time the boards stay wet (Davies, Ivor, et al., 2002). For this reason, sawn boards were deemed more suitable in this context (Davies, Ivor, et al., 2002).

In order to be fully recoverable and reusable, the cladding timber should have been screwed on the supports. However, that would have proven too expensive, so it was nailed, and it was agreed that the boards would have only been removed once they were too worn, thus unlikely to be reused in other buildings (Sassi, 2006). The laths were nailed in the centre in order to allow movement on the sides, and the nails were prevented from entering too far into the timber to avoid creating mini-collection points inside the structure (Davies, et al., 2002).

Fig. 22

Another issue in the detailing of the cladding was the differential weathering. The bottom 150-300mm in fact are more prone to be worn out by the back-splashes of the rain, whilst the top areas are protected by the eaves and stay in better condition for a longer time (Davies, et al., 2002). In order to avoid substituting the whole cladding, only the upper part of the walls is cladded with timber, while the lower 150mm are plastered (Fig. 22) (Davies, et al., 2002). According to Scott McCombie, this detailing proved very durable, and as of 2020, they never had to replace the wooden cladding (S. McCombie, personal communication, September 1, 2020).

A fundamental aspect of this project is the scrupulous attention to passive energy gains and the use of natural resources. The building is mainly heated by the sun, and windows are understood as solar collectors (Liddell, 2010a). In order to maximize the solar gains, windows were placed according to orientation and obstructing elements, and native, fast-growing, deciduous plants were placed in proximity of the south-facing windows, so that their leaves could shade in summer and help avoid overheating (Liddell, 2010a). Also, the skylights act as solar collectors which, according to Liddell (2010a), can be manually opened, providing sufficient natural ventilation (Fig. 23). Super-insulation and high levels of air-tightness were necessary to keep the heat indoor during wintertime (Liddell, 2010c). Walls were insulated with cellulose fibre installed between the framing elements and an internal sheathing board (U=0,14 W/m^{2}K) (Sassi, 2006); sheep's wool was used as insulation around the windows (Liddell et al., 2008).

Fig. 23 Note the open skylights

Additional heating was supplied by a 120 kW woodchip boiler (Sassi, 2006). According to Liddell (2010c), there is no fundamental need to heat the building, something that Scott McCombie corroborates by saying that it is rarely too cold in winter inside the building, while in summer they open the skylights to let some warm air out (S. McCombie, personal communication, September 1, 2020), as expected (Liddell, 2010a).

Water consumption was also taken into consideration. As a re-naturalization effort, a stream of water was rerouted into its original bed through the complex, making it self-sufficient in terms of water supply (Liddell, 2010b). Water-conservation fittings were installed in the complex, such as waterless urinals, and low-flush toilets (Liddell, 2010b).

Fig. 24

As mentioned in the previous paragraphs, some changes have been made over the years, such as the periodical substitution of the timber roofing. Also, the metal roof above one of the buildings has been replaced due to rust (S. McCombie, personal communication, September 1, 2020). McCombie states that the major problem the centre faced was the durability of the wooden walkway that connects the buildings. It had to be completely replaced in 2009, less than 10 years after it was installed (Fig. 24). According to him, the untreated wood did not prove as durable as he would have hoped, since it stayed wet too long in the Scottish weather, was too slippery and rotted too fast (S. McCombie, personal communication, September 1, 2020). Also some boards at the doorsteps had to be replaced for the same reason (S. McCombie, personal communication, September 1, 2020). Part of the wood of the entrance portal was also replaced with treated wood after it rotted, creating a visible contrast with the surrounding untreated wood (Fig. 25).

Fig. 25

The heating strategy of the complex proved effective, but the boiler was replaced in the last years even though the old one was working, in order to benefit from a government subsidy for renewable energy (S. McCombie, personal communication, September 1, 2020). A new building with a restaurant has also recently been added to the complex, with a design that reminds the existing houses but that completely abandons the eco-minimalist approach and materials of the original complex (Fig. 26, 27).

Fig. 27

Fig. 26

4. David Douglas Pavilion

The David Douglas Pavilion is a small wooden construction built in 2003 by GAIA Architects in the then newly instituted Scottish Plant Collectors Garden of Pitlochry, Perthshire. The pavilion is named after the Scottish plant collector who imported the Douglas fir in Europe from Canada in the 19th century, the same tree that today is the basis of the Scottish timber industry and that makes up almost the entire structure of the pavilion (Dawson, 2003).

Fig. 28
Source: TRADA

The building was commissioned by the Pitlochry Festival Theatre to Robert Baker (at the time head of GAIA Scotland Aberfeldy) as part of the 2003 celebrations of Scottish botanical explorations (Dawson, 2003). The aim was commemorating the Scottish collectors as well as showing the work of associations such as the Woodland Trust, the Forestry Commission, the Scottish Wildlife Trust and the Scottish Forest Industries (Dawson, 2003). The new park occupies 2 hectares of forestaffera. A winding path brings to a steep north-facing embankment where the pavilion sits (Dawson, 2003).

Baker says that the objective of the project was to “create a focal point in the garden built entirely of Scottish timber” (TRADA, 2008, p. 2) that could blend with the surrounding woodland. The design is a simple, hut-like pavilion which combines modern design with a traditional low-cost timber structure (Dawson, 2003). The leaf-shaped plan consists in a single open room that functions as an exhibition area. The room is enclosed by wooden curved walls on three sides, while the north side is formed by a glazed timber frame with doors leading to a viewing deck on the outside (Dawson, 2003). The space is covered with a high-pitched roof that raises towards the north side and extends over the deck area (Dawson, 2003), creating a structure that recalls “the symmetrically folded seeds of Douglas fir” (TRADA, 2008, p. 4). The pavilion overall is reminiscent of a traditional building, and yet is unmistakably contemporary (Material Considerations, 2017), a recurring feature of some of GAIA’s design.

Fig. 29 Construction process
Source: Robin Baker

The use of wood supports this impression and is also part of the GAIA’s effort to raise awareness in Scotland on sustainable, homegrown timber and its possible use in quality architecture (Atkins & Stephens, 2017). The building is completely made up of untreated Douglas fir timber that had been grown and manufactured in Scotland (TRADA, 2008). A lot of detailing was done in order to avoid any water stagnation and moisture retention while ensuring that ventilation dried any timber that could not become wet. The untreated timber is consistent with GAIA’s approach to avoiding non-natural varnishes or finishings that could peel off and be unsafe for the environment or people both during the life-span of the building and after its disposal.

An important factor to take into account to increase the life of the building is maintenance (Dawson, 2003). Any reparation work should be promptly addressed; any damp leaf-litter and earth should never accumulate against the timber to avoid moisture retention and rotting (Dawson, 2003). In this regard Gordon Macdonald, the carpenter of this project, states: “We work with untreated timber whenever we can. There are persistent misunderstandings about timber preservation within the design and construction community. For instance, that insects will attack untreated softwood construction – but they rarely attack seasoned timber. In fact, the big problem is damp – if timber is sodden it is prone to fungal growth or rot that will then attract insects” (Dawson, 2003, p. 5).

Fig. 30

The 300 mm diameter posts that support the roof stand outside the curved walls and are obtained from debarked Douglas Fir. The top of each post is planed, tapered and machined with a 50 mm wide tenon to accommodate the roof structure. The curved walls consist of a series of studs that hold a double layer of OSB on the inside (TRADA, 2008). The walls have a functional and a structural purpose as they close the space and act as a ring beam, bracing the posts, carrying all eccentric loads, and leaving only the compressive loads to the posts (TRADA, 2008). The cladding consists of vertical Douglas fir boards with strips covering the junctions (TRADA, 2008). The lower part is protected from the rain by horizontal cladding of 150 x 25 mm boards fixed to battens with a 9 mm gap (Fig. 31) (TRADA, 2008). The northern glazed façade is framed and braced with large Douglas fir battens to provide cross-bracing (Fig. 30).

Fig. 31 Source: TRADA

The roof is supported by sloping 350 x 200 mm lentils that extend beyond the walls and the posts (TRADA, 2008). The outer lentils are slightly larger in size (300 x 300 mm) and follow the curve of the eaves and the walls (Fig. 33). Each lentil is braced by the wall and secured to the posts with a 175 x 50 mm tenon and mortice system and secured with two 25mm diameter pegs (TRADA, 2008). An additional 200 x 475 mm ridge beam completes the roof bearing structure and is made up of two parts that are joined with a double scarfed joint (TRADA, 2008). 150 x 50 mm tongued and grooved Douglas fir boards are laid directly on top of the purlins which are left bare on the inside in order to provide a wooden ceiling (Dawson, 2003). On the upper side, the boards are clad with untreated shingles obtained from the heartwood of selected larch and are detailed in order to drain the water away and to be ventilated from below (Material Considerations, 2017). The shingles have pointed ends and are arranged in a pattern that reminds of a fir-cone, except at the eaves where they are rectangular (Fig. 32) (TRADA, 2008). A low-tech expedient in order to avoid algal and moss growth on the shingles was installing a copper ridge (TRADA, 2008). Rainwater running off it will in fact wash them away with diluted copper sulfate (TRADA, 2008).

Fig. 32 Source: The Wood Awards

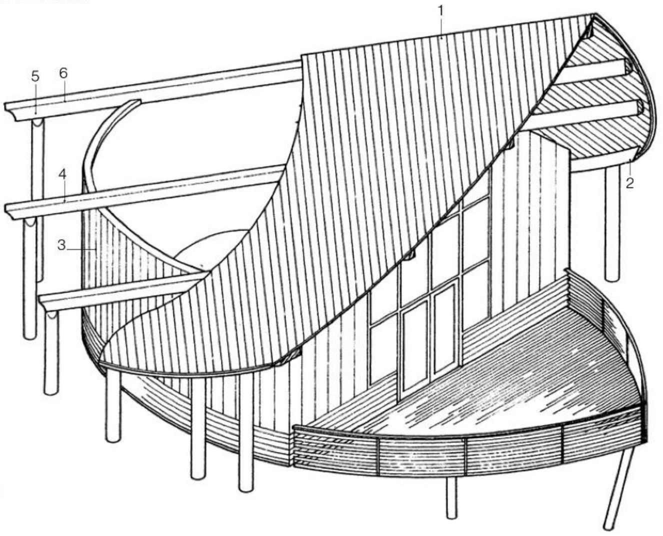
Fig. 33 Source: Urban Realm

The exterior handrail, which runs at the perimeter of the deck, is obtained from a naturally curved oak tree (TRADA, 2008). The floor consists of a combination of 22 mm Scottish ash and elm boards (Atkins & Stephens, 2017) laid on 50 x 50 mm battens. The windows are of laminated Scottish Oak (Atkins & Stephens, 2017).

The wooden posts are resin fixed to concrete foundation pads with threaded rods of galvanized steel (TRADA, 2008). This allows the posts to be raised off the ground and be surrounded by gravel for water drainage (TRADA, 2008), protecting the wooden structure from damp and allowing to leave it untreated. A finish of boiled linseed oil thinned with turpentine was applied to avoid the silvering process of the wood (TRADA, 2008).

The walls are built on a rendered 140mm concrete blockwork supported by a 600 x 200 mm concrete strip foundation. On the interior, the floor is laid on a concrete slab poured on a damp proofing membrane.

Cut-away sketch showing roof construction



1. 150 x 50mm boards as structural roof deck
2. Outer 300 x 300mm purlin fabricated to follow curved eaves
3. Curved stud and OSB wall as ring beam
4. Ex 350 x 200mm purlin supported by gable frame and by 300mm dia post
5. Mortice and tenon joint to purlin and post
6. Ex 350 x 200mm ridge beam supported by gable frame and by 300mm dia post
7. Paired 150 x 25mm fasica boards
8. 19 x 38mm counter-battens at 150mm crs to carry larch shingles
9. 19 x 38mm counter-battens at 300mm crs
10. Breather underlay
11. Roof cut back around existing oak tree
12. 150 x 50mm t&g boards as structural roof deck
13. Viewing deck
14. Outer 300 x 300mm purlin
15. Mortice and tenon joint to purlin and post
16. Curved stud and OSB wall at ring beam
17. Ex 350 x 200mm purlin supported by gable frame and by 300mm dia post
18. Ex 350 x 200mm ridge beam supported by gable frame and by 300mm dia post
19. Pavillion

Roof plan showing structure and larch shingle roof covering

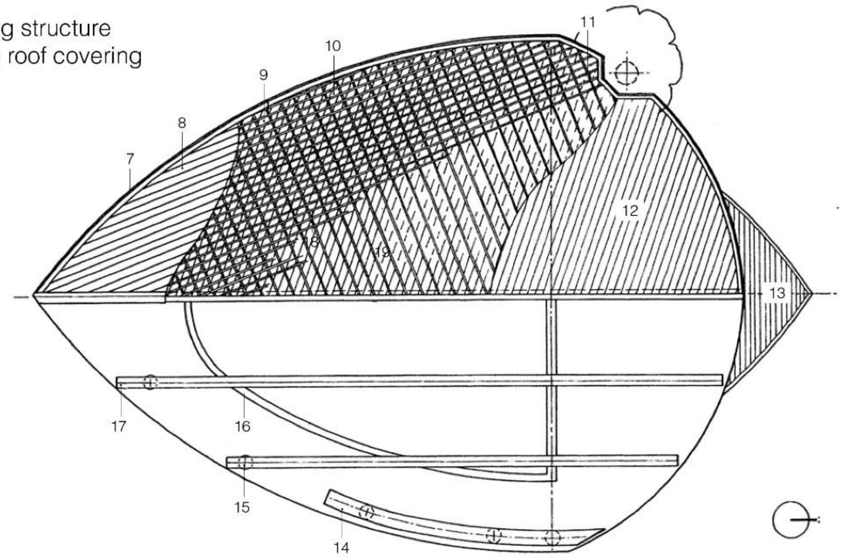
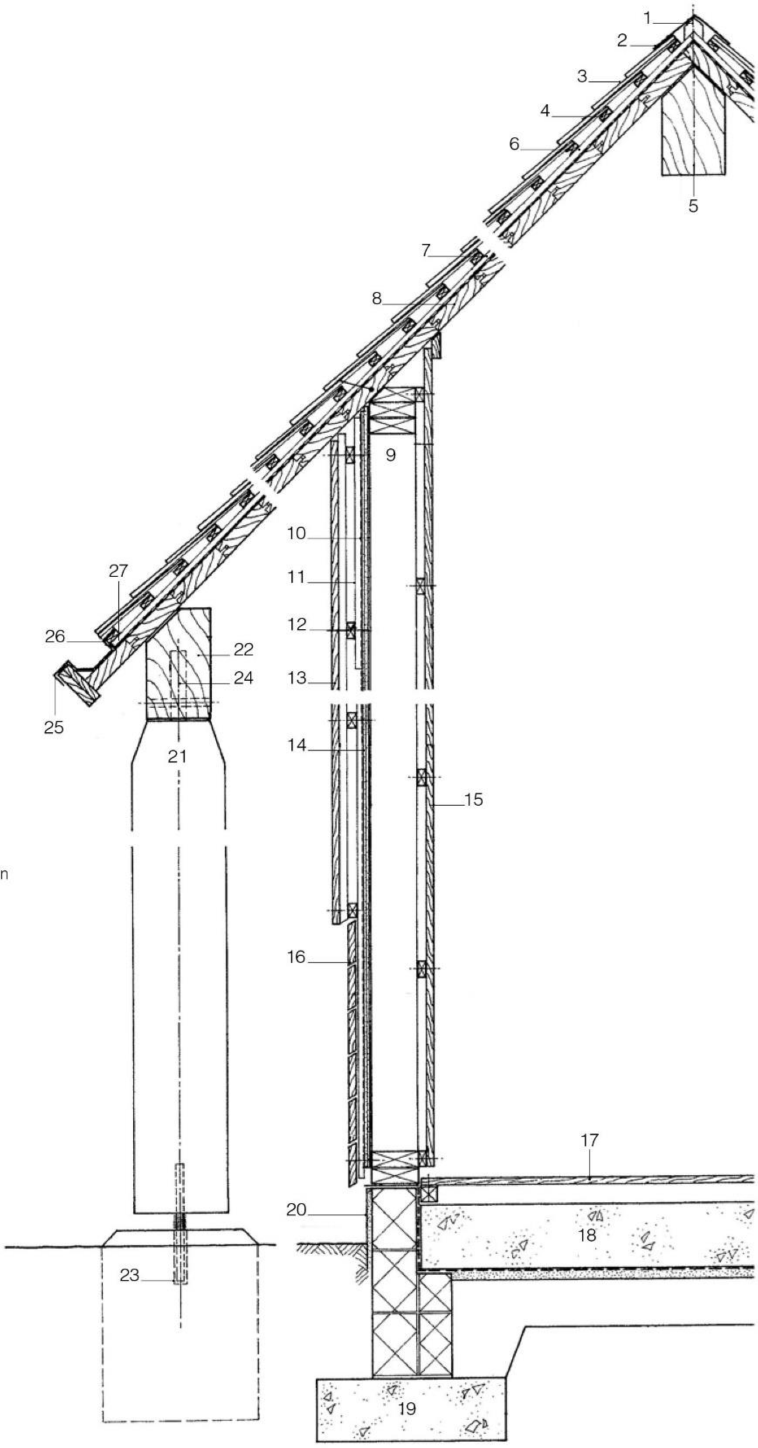


Fig. 34 Source: TRADA

Detail section through wall and roof

1. Ex 100 x 50mm ridge cap fixed to deck
2. 150 x 150mm ridge of corrugated copper sheet
3. 150 x 450mm larch shingles, centre-nailed with 6mm gaps between
4. 19 x 38mm battens at 150mm crs
5. Ex 350 x 200mm ridge beam
6. 19 x 38mm counter-battens at 300mm centres
7. Breather underlay
8. 150 x 50mm t&g boards as structural deck
9. 195 x 47mm studs at 600mm crs
10. Breather membrane
11. 47 x 25mm vertical battens fixed to studs
12. 25 x 47mm battens at 600mm crs
13. Curved wall clad with 250 x 25mm, 200 x 25mm and 150 x 25mm planks with 25 x 47mm cover strips
14. Double layer of 9mm OSB (orientated strand board) with staggered joints
15. Inner lining of 100 x 25mm t&g V-jointed boards
16. Rainscreen of 150 x 25mm boards with 9mm air gap on 47 x 25mm battens fixed to studs
17. 22mm oak and ash floor on 50 x 50mm battens
18. 200mm concrete floor slab on dpm
19. 600 x 200mm concrete strip foundation
20. 13mm render on 140mm concrete blockwork
21. 300mm dia post tapered
22. Ex 350 x 200mm purlin
23. M20 threaded rods, resin fixed to concrete pad foundation
24. Mortice and tenon joint to purlin and post
25. Code 4 lead flashing dressed over paired 150 x 25mm fascia boards
26. Insect Mesh
27. Underlay to lap lead upstand
28. Ex 350 x 200mm purlin
29. 175 x 50mm mortice as housing for post
30. 50mm wide tenon
31. Mortice and tenon joint secured with two 25mm dia pegs
32. 300mm dia post tapers at top



Detail of mortice and tenon joint

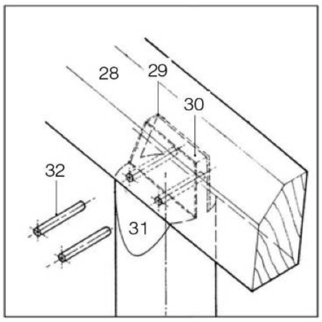


Fig. 35 Source: TRADA

5. Glentress Visitor Centre

In 2006 GAIA was appointed to work together with the Forest Commission Scotland (FCS) and other partners in the design of the masterplan and buildings of the Glentress Visitor Centre (BBC News, 2006). Also known as Glentress Peel, the centre is located in the heart of the Tweed Valley Forest Park, not far from another GAIA's project called Plummerswood.

Fig. 36 Source: McLaughlin and Harvey

The "masterplanning approach" (Wright & Tolson, 2020, p. 49) to the project sought for present and future opportunities for the forest and the whole area through an analysis of the existing market conditions and site infrastructure (Wright & Tolson, 2020). The objectives were to increase the access to the forest to at least 300,000 mountain-bikers each year (BBC News, 2006) compared to the previously estimated 190,000 (Bryden, et al., 2010), as well as to bring tangible benefits to the local economy while balancing the development with the natural environment of the forest (GAIA Architects, n.d. f).

The location of the development was to be on the site of an existing house and parking lot (Patenall, 2006) "following an assessment of the landscape, access to services and utilities as well as through early community consultation" (Scottish Borders Council, 2020, p. 8). The result is a "mixed social/recreational/leisure/commercial development" (GAIA Architects, n.d. f) located on a 7 hectares, hill-side area (Wolchover, n.d.).

Fig. 37 Construction site
Source: Architecture & Design Scotland

The complex consists of a two storey office building and two single storey buildings accommodating a cafe with a mountain-bike shop and a facility for mountain-bikers with an information booth, restrooms, showers, and a wild-life observation room (Urban Realm, 2012). The buildings and an adjacent parking lot with 150 spaces are interconnected through a network of pedestrian paths and bridges (Scottish Borders Council, 2020). The centre was developed as a cluster of buildings in order to minimise their impact on the surroundings "in response to the topography, the proximity to the Eshiels Burn, the site location next to the forest edge and the immediate and distant views offered to the visitors" (Wolchover, n.d., p. 3). During the design process, GAIA provided guidance regarding sustainability, health and the potential use of local resources in the project (GAIA Architects, n.d. f). Most of the timber used was in fact provided by the Scottish Forestry Commission and obtained from the Glentress Forest itself (Urban Realm, 2012).

Local Douglas fir was used for the load-bearing structures, the decking and the external cladding (Architecture & Design Scotland, n.d). The structural element of the external walls is formed by timber I-beams. (Architecture & Design Scotland, n.d). The main load-bearing structure of the single storey buildings consists in a sequence of giant trusses that are connected to the foundations through steel hinges. Additional vertical steel elements connect the trusses to the ground on both ends of the trusses, giving stability to the structure (Fig.38). The wooden elements of the trusses consist of two adjacent Douglas fir trusses interconnected by steel connecting plates and dowels (Fig.39). Even though the Douglas fir used for the trusses is locally sourced, their actual sustainability is questioned by Howard Liddell himself. He states the following *"Whilst the timber is from the forest only metres away, after milling, stress grading, prefabrication, storage and then eventually craning into place its embodied energy (through travel over the length and breadth of Scotland), makes a mockery of using local materials."* (Liddell, 2013, p. vi). This highlights how easy it is to underestimate the environmental impact of apparently 'green' choices.

Fig. 38

Other locally procured timbers include European larch for internal linings and skirting and Scottish birch for the doors (Urban Realm, 2012). The use of heartwood timber, especially for untreated external cladding, ensures the maximum durability of the timber, eliminating the need of preservatives (Architecture & Design Scotland, n.d) that can be harmful for the users' health and the environment. The timber is left either untreated or varnished with formaldehyde- and solvent-free paints

(Architecture & Design Scotland, n.d). Linoleum was used for indoor floors "to maintain a hygienic environment while preventing dangerous off-gassing within the internal spaces, commonly associated with comparable plastic or rubber products" (GAIA Architects, n.d. f). With the objective of maintaining a healthy indoor environment, a clay plaster coated with a mineral paint was used on some internal walls (GAIA Architects, n.d. f). These features, together with the wooden structure, make the walls moisture-transfusive.

Fig. 39

In accordance with GAIA's principles, the design team aimed to implement passive strategies in the building envelope. In fact, "insulation and air-tightness levels far exceed the current Building Regulations" (Urban Realm, 2012). In addition to the previously mentioned hygroscopic finishes, natural ventilation was used to regulate the indoor air quality and levels of humidity (Urban Realm, 2012). The wall insulation is cellulose obtained from recycled newspapers (Architecture & Design Scotland, n.d).

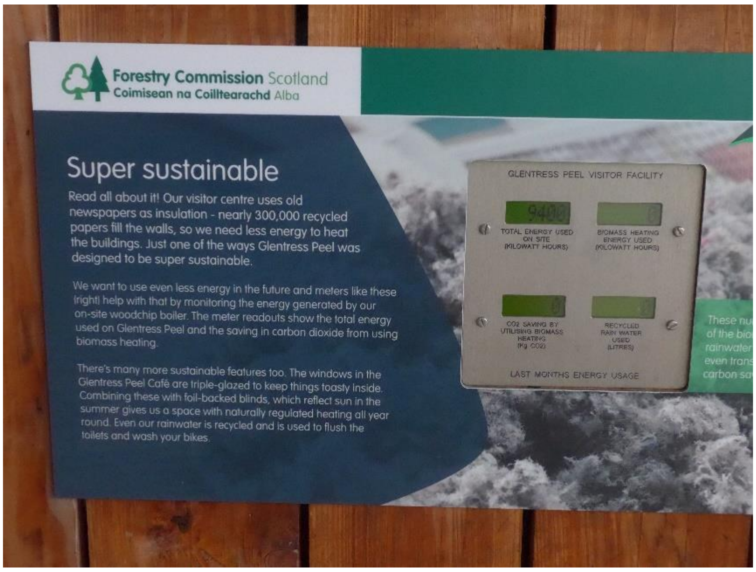
Fig. 40 Source: Urban Realm

The windows were provided by a company called Charles Henshaw & Sons (Urban Realm, 2012) and are made of Scottish oak (Architecture & Design Scotland, n.d). Most of the café's external walls are completely glazed to maximise solar gains (Fig. 40). Stripe-shaped windows are placed on the roof between the trusses both indoor and in the outdoor covered areas (Fig. 41). Due to the large amount of glazed surfaces in the café, the cooling and heating loads of the buildings had to be detailed carefully. The large glazed areas have a south-facing exposure to maximise solar gains in winter, with the addition of overhangs to provide shadow in summer (Architecture & Design Scotland, n.d). Triple glazing was also used to limit heat losses while maximising solar gains (Urban Realm, 2012). Automated blinds have also been installed on the whole glazed surface in order to avoid overheating and glaring on sunny days (Urban Realm, 2012).

Fig. 41

An additional active source of heating to the complex was provided by a district heating system powered by a woodchip boiler and located near the office building (Urban Realm, 2012).

Particular attention was paid to water management. All urinals are waterless, while WCs and taps have been fitted with low-flows adaptors (Urban Realm, 2012). Rainwater is also collected from the roofs, filtered and used to flush the WCs and to wash the bikes in the hiring facility (Urban Realm, 2012). Both energy and water usage are monitored and displayed on analogical screens in the visitors' building for informative and educational purposes (Fig. 42).


Forestry Commission Scotland
Coimisean na Coilltearachd Alba

Super sustainable

Read all about it! Our visitor centre uses old newspapers as insulation - nearly 300,000 recycled papers fill the walls, so we need less energy to heat the buildings. Just one of the ways Glentress Peel was designed to be super sustainable.

We want to use even less energy in the future and meters like these (right) help with that by monitoring the energy generated by our on-site woodchip boiler. The meter readouts show the total energy used on Glentress Peel and the saving in carbon dioxide from using biomass heating.

There's many more sustainable features too. The windows in the Glentress Peel Café are triple-glazed to keep things toasty inside. Combining these with foil-backed blinds, which reflect sun in the summer gives us a space with naturally regulated heating all year round. Even our rainwater is recycled and is used to flush the toilets and wash your bikes.

Fig. 42

The construction process lasted 54 weeks until completion in Autumn 2010 and consisted in three phases: Enabling Works, Timber Fabrication and Building works (Wolchover, n.d.). During the first phase the Civil Engineering contractor (Mott MacDonald Fulcrum) provided access roads, car parks, the installation of a waste water treatment plant, drainage works and a basement of the buildings (Wolchover, n.d.).

The second phase involved the timber manufacture, which was left to a local company with sawmilling, kilning and joinery facilities (Wolchover, n.d.). All the Douglas fir timber was fell and extracted from the local forest, then stored, milled and manufactured off-site (Wolchover, n.d.). The last phase was the building works, left to McLaughlin & Harvey (Urban Realm, 2012), a national building contractor with a Forest Stewardship Council Certification, an essential Forestry Commission Scotland requirement to ensure the sustainable use of timber resources in their projects (Wolchover, n.d.).

Glentress was awarded a Gold star rating in the Green Tourism Business Scheme (GAIA Architects, 2012b) after passing tests on energy and water efficiency, waste management, purchasing, biodiversity. The project was also shortlisted for the 2011 Andrew Dolan Award (Waite, 2011) and the 2012 *Edinburgh Architectural Association's* "Building of the Year" Award (GAIA Architects, 2012a).

6. Acharacle Primary School

Fig. 43 Source: Sam Foster Architects

In 2003 GAIA Scotland was approached by The Highland Council to write the brief for the reconstruction of the Acharacle Primary School building, located in Argyll. Regardless of the architect that would eventually be commissioned for the project, the task of the winning bidder was to maintain the green credentials assessed in the brief (Liddell, 2010). The final brief called for innovation, emphasizing a passive design approach, good quality fabric and smart spending. The design options had to take into account the local skills, materials, water and energy options available, as well as safeguarding and enhancing the natural and built environment (Halliday, 2019; TRADA, n.d.). Other key performance indicators needed to be addressed, such as architectural quality, capital and operational costs, light quality and management, colour schemes, material cycles and air quality (Halliday, 2019).

GAIA also participated in the following competition and ended up being the successful bidder, presenting a project that represented the state-of-the-art, sustainable construction. The initial design schemes were drawn in collaboration with the community, the school staff and the pupils during workshops, to meet the needs of the end users (Halliday, 2011). The new building had to be constructed in the restricted area of the playground of the former school building, which had to stay open during the construction works. Given these limitations, the design and shape had to be well established to avoid changes during the works (Liddell, 2010f).

Fig. 44 Source: TRADA

The final 1,300 m^2 layout consists of a two-winged building, one for the five classrooms of the school and one for the cultural venue of the community, connected in the centre by an entrance (Sam Foster Architects, n.d.). The classrooms wing is south-facing, to maximise solar gains (Material Considerations, 2017) while the WCs, storage, nursery are located in the north side of the building. The classrooms are designed for good acoustics (TRADA, n.d.) and are provided with a breakout space for independent learning (TRADA, n.d.). On the opposite side of the entrance, the community wing, which is expected to be used less intensively, is aligned close to a north-south axis (Material Considerations, 2017).

From an energy point of view, the project exceeds the Passivhaus standards (Material Considerations, 2017). For electricity, both wind and biomass were taken in consideration, and a 6kW wind turbine was erected on a 9m mast on a hill behind the building (Halliday, 2011). Daylight intake was maximized in the learning areas through a careful positioning of windows and roof lights to ensure an average daylight factor of DF_{ave}=4,5%. (Liddell, 2010f). External motorized blinds were installed under the exterior cladding and are controlled by sun and wind sensors. In case of strong wind, these blinds can retract in order to prevent damage

(Sustainability in Practice, 2009). The windows are triple glazed and have a 0,8 W/m^{2}K transmittance (Halliday, 2011).

Under regular occupancy conditions there is no need for heating because of the high level of insulation (300mm of wood fibre panels) and air tightness (Halliday, 2011). The U values are in fact 0,128 W/m^{2}K for the walls and roof and of 0,098 W/m^{2}K for the floors. The air permeability index on the first test was Q_{50} = 0,27m^3 per hour per m^2 at the pressure of 50 Pa, a result that, at the time, was reported as the lowest in the UK (Sustainability in Practice, 2009). The building is mainly heated by the bodies of the occupants and by the low-energy electrical fixtures and equipment (Halliday, 2011). A backup heating system is also installed “to match losses after a few days of no occupancy under cold external conditions” (Halliday, 2011, p. 20), such as after a long holiday break. Heat is generated “by two 9kW highly insulated storage cylinders heated by electric immersion elements powered” by the wind turbine (Halliday, 2011, p. 20).

The Passivhaus standards were achieved without adopting MVHR, which is mandatory for the German institute in order to receive the certification (Liddell, 2010f). All rooms benefit from natural ventilation except for the kitchen, WCs and the utility room (Sustainability in Practice, 2009). Hygroscopic and zero-emission materials throughout the building help guarantee good air quality (Halliday, 2011). Each classroom was provided with displays in order to keep the children aware of the energy and water consumption, temperature, humidity and CO_2 levels (Halliday, 2011). When necessary, the occupants themselves can manually open some of the windows to improve the natural ventilation (Halliday, 2011).

Fig. 45

Water is heated by electric immersion elements and is stored in cylinders (Liddell, 2010f), which are highly insulated with sheep's wool (Sam Foster Architects, n.d.). All water outlets were low-flow and a tank for rainwater was installed in order to collect it for reuse (Halliday, 2011). A pond was also shaped in front of the school from an existing stream to increase biodiversity and reduce storm water runoff (Sustainability in Practice, 2009).

The main construction material in the school is wood; all of the timber was sourced locally except for the load-bearing structure (Halliday, 2011). GAIA Architects initially thought of using a post and beam structure with infill panels, but it resulted to be too expensive. A study undertaken by GAIA and the client led to the choice of the Brettstapel method for the very first time in the UK (Henderson, 2012). Brettstapel consists in panels of softwood (silver fir) where typically diagonal holes are drilled through several studs. Hardwood dowels of much lower moisture content than the softwood are then installed into them (Henderson, 2012). The dowels pick up the moisture from the surrounding softwood, expanding and creating a very strong panel (Henderson, 2012). The Brettstapel method will be described in more detail in the third part of this study.

Fig. 46 Source: TRADA

In this project 140-220 mm fir panels for the roof and 100mm panels for the external walls were produced in Austria and shipped via truck (TRADA, n.d.). Given the remote site, the necessity of precision in the connections, and the need for integrating the services in the panels, the design of each element was carefully detailed during the planning phase by working closely with the manufacturer, in order to overcome any problems before the panel was shipped. To do this, GAIA resided at the factory in Austria for a week to follow the process (TRADA, n.d.).

Locally-sourced timber was provided by the main contractor McGregor Construction Ltd (Halliday, 2011). The cladding was obtained from the heartwood of European larch. (Material Considerations, 2017). Even the dado trunking for the electrical equipment were made of untreated wood instead of PVC (Sam Foster Architects, n.d.). The school furniture supplier (Future Furniture) was asked to rethink all its pieces without any chemical treatment to minimise off-gassing (Sustainability in Practice, 2009). The floors were made partly of oak and partly in linoleum (Halliday, 2011).

All wooden elements were left untreated, as non-toxic materials were a priority, due to such high airtightness (Halliday, 2011). Chemicals for fire resistance were avoided, as the timber mass ensures built-in fire resistance to the structure. Also, preservatives against fungal and insect attacks were not applied, since only materials suitable for the Scottish climate were used, and the good detailing and workers' skills made preservative treatment unnecessary (TRADA, n.d.). However, to increase fire safety, a sprinkler system was provided by the Project Fire company, who installed their Ordinary Hazard 2 system with a total of 185 heads connected to a separate pump and tank storage in the back garden.

The service integration in the fabric of the building was kept at a minimum in order to not alter the air tightness rate (Halliday, 2011). In fact, the services that could not be installed during the fabrication of the Brettstapel panels were surface mounted, to allow easy access for maintenance (Halliday, 2011).

Fig. 47 Source: TRADA

A double-lock, long strip standing seam system made of copper was chosen for the roof (TRADA, n.d.). The rolls of copper sheet were pre-formed on site and fixed on the 24mm timber boards (TRADA, n.d.). The gutters (box gutters, half-round gutters, Inlay gutters, rainwater/downpipes) are also made of copper (TRADA, n.d.). The roof system includes a 100mm cavity for ventilation between the timber boards and a 16mm sheathing of DWD (TRADA, n.d.), a material used in place of external OSB and plywood panels, which allows for racking and enhances vapour transfer (ecomerchant.co.uk). This is mounted on a 280mm timber frame with wood fibre insulation fixed to the Brettstapel panels (TRADA, n.d.).

A 40-80 mm ventilated cavity is also present on the outside walls between the 22 mm European larch cladding and a 16mm formaldehyde-free sheathing board of DWD (TRADA, n.d.). These layers protect the 280 mm thick wood fibre insulation fixed to the 100 mm Brettstapel panels (TRADA, n.d.).

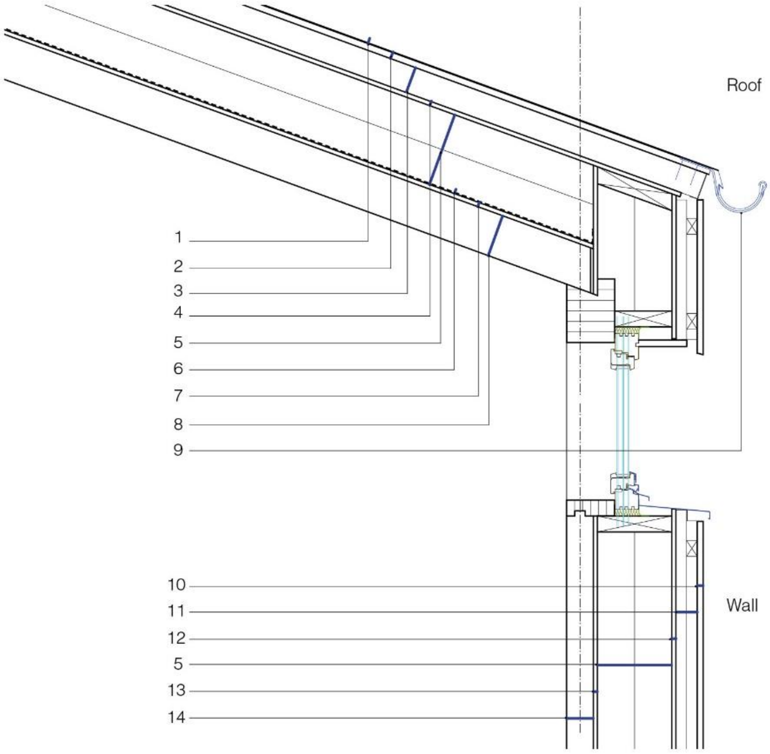
The structure of the floors consists of 240 mm timber construction with blow-in cellulose insulation sandwiched between two 19 mm plywood boards (TRADA, n.d.). An additional layer of wood fibre insulation is present between the 160 mm wood grid that bears the floors (TRADA, n.d.).

After work completion in 2009, GAIA and the M+E consultants (Arup) were also asked to perform the Post Occupancy Evaluation over a period of two years, in order to implement their research on building performance and make adjustments (Liddell, 2010).

Detailed construction sections - roof and wall

Key

1. Copper roofing
2. 24mm timber boarding as substrate for roofing
3. 100mm ventilated cavity
4. 16mm sheathing board (DWD); if roof pitch <15˚ then additional fully adhered sub-membrane
5. 280mm timber construction with wood fibre insulation between
6. Vapour control layer Vap 2000
7. 16mm 3-ply amber board fir, quality C/C
8. 140-220mm double diagonal Brettstapel panels with profiled lamellae, fir, 4mm shadow gap or acoustic profile
9. Copper rainwater goods
10. 22mm untreated heartwood of European larch closed profile cladding
11. 40-80mm ventilated cavity
12. 16mm formaldehyde-free sheathing board (DWD)
13. 16mm 3-ply timber board (fir)
14. 100mm double diagonal Brettstapel panels with profiled lamellae, fir, flush surface



Detailed construction section - floor

Key

1. 16mm formaldehyde-free chipboard
2. 60mm timber battens with woodfibre insulation between
3. 100mm timber battens with woodfibre insulation between
4. 19mm 3-ply timber board, fir with bituminous membrane over
5. 240mm timber construction with blow-in cellulose insulation
6. 19mm 3-ply timber board fir
7. Ventilated cavity below floor panels
8. 50mm washed river gravel solum

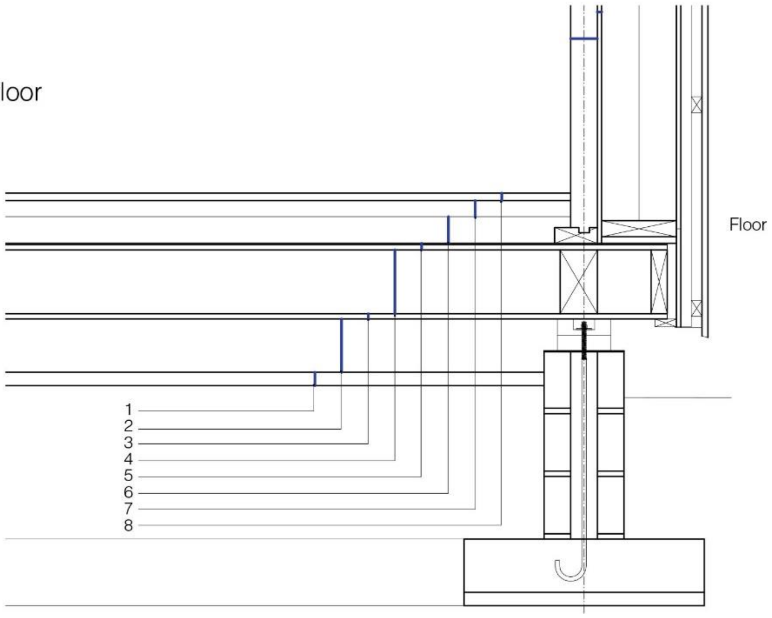


Fig. 48 Source: TRADA

Chapter 3

1. Introduction

Fig. 49 Source: Graham Riddell

The case study for an in-depth analysis of GAIA Architects work of this thesis is Plummerswood, a three bedrooms' Passivhaus-certified dwelling located in the village of Cardrona in the Scottish Borders. This chapter aims to present a detailed description of the technological features of the building with for a particular focus on the philosophy of Eco-minimalism that has been described in the previous chapters. An analysis of the Embodied Energy (EE) and Embodied Carbons (EC) has also been performed in order to provide an ecological evaluation of the building and to verify the effective sustainability of the Eco-minimalist approach in a private building for domestic use. Using the original drawings provided by GAIA and after a tour of the property, a detailed 3D model was constructed using the software Autodesk Revit (Fig. 50), in order to obtain a bill of quantities, necessary for the calculations. The standardized databases used for the calculations are the ÖKOBAUDAT database by the *German the* *Federal Ministry of the Interior, Building and Community* (oekobaudat.de), and the ICE database by the University of Bath. All the calculations have been performed with both databases in order to compare the variation between the two. When the EPD (Environmental Product Declaration) of a specific product was made available by the manufacturer, their values have been used.

Fig. 50

1.1 Acknowledgment of previous study

Plummerswood has been the subject of a case study of another master's thesis carried out at the University of Sheffield, namely *Embodied Energy and Carbon: A Case Study of a Brettstapel Passivhaus in the UK* by Dilek Arslan (2019). The objectives of Arslan (2019) and those of the current study are comparable in that they both provide an ECE analysis of the building, but with substantially different focuses. In fact, while this chapter predominantly focuses on the technological aspects of the with a particular focus on eco-minimalism, the English study has been carried out in light of the methodology of the ECE analysis. The stated objectives of Arslan (2019)'s thesis in fact are:

> (1) analyse the state of the art; (2) define the boundaries and challenges which effect the EE/EC calculations and measurements; (3) establish the ECE and energy data for Brettstapel construction for the UK; (4) compare the ECE and operational energy/carbon in a Passivhaus home; (5) make recommendations for sustaining low impact material choices and decreasing the carbon emission in Passivhaus housing. (Arslan, 2019, p. 3)

1.2 History of the project

The building was erected on a 0.22 hectares (2.200m^2) plot of land that used to belong to the Forestry Commission of Scotland until Ian and Ann Nimmo purchased it in 2006, after seeing an advertisement on the Scotsman newspaper (Antonelli, 2013). At the time, the land consisted of an east-facing slope overlooking the Tweed River and valley (Halliday, 2012) with a dilapidated stone steading building at the bottom. The couple spent the following two years clearing it from tree stumps, bushes and stones while looking for an architecture firm that could help them design their home (Antonelli, 2013). They did not know what sort of building they wanted, nor were they aware of what a Passive House entailed (A. Nimmo, personal communication, August 26, 2020). However, they did know they wanted to build something to be proud of, that could also be friendly to the surrounding wooded land, and they wanted to incorporate sustainable elements to their project (A. Nimmo, personal communication, August 26, 2020). Both Ian and Anne are chemists and, according to Anne, having a scientific background was a key contributing factor in their choice for GAIA Architects, knowing well they had an objective, scientific approach when it comes to sustainability (A. Nimmo, personal communication, August 26, 2020). They valued highly the idea of building something very simple, yet incredibly effective in terms of energy efficiency (A. Nimmo, personal communication, August 26, 2020). Ian Nimmo in fact says the following: "what I liked about the idea of a passive house was that instead of having modern ways of generating energy, it would just save energy by being well insulated" (Antonelli, 2013, p. 34).

For the following three years until completion in October 2011 (Halliday, 2010), GAIA and the design team worked closely with the Nimmos to deliver a design that was as close as possible to the requests of the client, while still meeting the sustainable principles of eco-minimalism (Antonelli, 2013). The clients in fact had a fairly clear idea of what they wanted in terms of the design of the building: “a timber house in a clearing on the slope, but one that would settle into the site. [...] hidden but yet with fantastic views” (Antonelli, 2013, p. 34). Boundaries between the property and the wooded areas surrounding it were to be removed (Halliday, 2012). They were looking for dynamic shapes in the layout as they did not like the idea of a wooden box, (Plummerswood, 2012) and they wanted to incorporate stonewalls on the outside walls (Antonelli, 2013).

The requirements of the design team were to “address issues including resource effectiveness, toxicity cycles, indoor climate, human factors in environmental control, sustainable forestry and place making” (Halliday, 2015a, p.1). Howard Liddell’s eco-minimalist approach was to be followed (Halliday, 2015a), meaning that natural, untreated materials were to be matched with passive design strategies in order to create a “healthy, comfortable, energy efficient home” (Halliday, 2015a, p. 1). It was established that the team would follow the requirements, in order to achieve the Passivhaus certification (Halliday, 2015a). This gave GAIA the opportunity to contribute to the development of a debate surrounding the need to have mechanical systems to achieve the certification (Halliday, 2015a), something that should be avoided according the eco-minimalist philosophy. Durability was also taken into account from the start, with the aim “for the dwelling to last at least 100 years and to take account of the requirements of future generations of the family” (Halliday, 2015a, p. 1). Natural regeneration on the property was to be encouraged “through selective planting of native species” (Halliday, 2012, p. 79) such as birch and rowan.

The end result was 346m^2 house (Halliday, 2015a) with an L-shaped layout. The living area occupies the ground floor, while three bedrooms and two bathrooms are situated on the upper floor. The master bedroom and bathroom are connected with a wooden bridge passing through the double height, glazed entrance. After its completion in October 2011, it received the Passivhaus certification and numerous awards such as the *Scottish Homes Award for Architectural Excellence* in 2012 (Halliday & Butler, 2015) and a Scottish Borders Council Award (Halliday, 2015a).

Fig. 51 Ground floor plan
Source: GAIA Architects

2. Structure

2.1 Foundations

While most of the superstructure of Plummerswood was prefabricated in Austria and shipped to Cardrona only to be assembled, the enabling and foundation works were appointed to a local medium-sized contractor (Antonelli, 2013). The enabling works started at the end of 2009 and consisted in earth movements, the creation of the access road to the house as well as the excavation of the foundation trenches (Halliday, 2015a) and connections to the main services. These works were followed by the laying of the foundations that had been designed based on the drawings of the manufacturer of the superstructure (Halliday, 2015a). It was vital for this stage to be completed before the arrival of the prefabricated superstructure expected in the last months of 2010. Moreover, the superstructure works were to be performed by the Austrian manufacturer (Halliday, 2015a), which meant an increased risk of delays and mistakes where construction responsibilities were overlapping. This also required the works at this first stage to be executed very precisely not to jeopardize the assembly of the superstructure. Fortunately, the great attention in the details of this project prevented any major issues, and there was only one failure in the utility room that was promptly fixed (Halliday, 2015a). According to the schedule, the enabling works should have lasted 8 weeks (Halliday, 2015a) and by the end of the summer of 2010 the foundation works were concluded (Antonelli, 2013). At this point, the site was ready to be handed over to the Austrian contractor of the main superstructure.

The foundations consist in:

- A larger cast-in-place reinforced concrete strip foundation running around the perimeter of the house to support the Brettstapel walls as well as the stone work on the ground floor;
- Smaller concrete strip foundations made of trench blocks to support the load of the internal partitions;
- Four larger reinforced concrete footings with steel columns to support the jutting section of the house and nine smaller ones to support the jutting deck (Fig. 53).

As part of the enabling work, a reinforced concrete slab was also poured as the basis of the ground floor.

Fig. 52

2.2 Load-Bearing Structure

When it came to the point of deciding with which system to build the house, the clients showed their interest in the Brettstapel panels after various study tours and after getting to know the previous works of GAIA Architects. GAIA had in fact already experimented with the use of Brettstapel for the Acharacle Primary School project of 2007, and the clients had been particularly impressed by the visit to the Community Centre in Ludesch, Austria by architect Hermann Kaufmann (Halliday, 2015a). GAIA's interest in promoting Brettstapel in the UK and in particular in Scotland originated after their involvement with the research of possible uses of lower-quality softwood for load-bearing structures as already explained in the Dunning chapter. Given the ecological specifications of the building, the design team would have much preferred using local timber for the load-bearing structure in order to lower carbon emissions. However, by using Brettstapel, GAIA hoped to raise interest in the British market for this technology and to show opportunities in manufacturing it with local low-grade timber, something that GAIA had tried to achieve since the 1990s (Halliday, 2015a). Plummerswood represented in fact the occasion to use Brettstapel for the very first time in the UK in a private house and to achieve a Passivhaus certification with it.

2.2.1 Brettstapel, what is it?

Brettstapel literally translates as “Stacked planks” in German (Péricchi, 2013), and it consists in wooden panels entirely “fabricated from softwood timber posts connected with hardwood timber dowels” (Henderson et al. 2012a), resulting in a glueless, nail-free, load-bearing panel. The system was invented in the 1970s by Prof Julius Natterer, a German engineer and environmentalist who is often quoted for being an innovator in timber engineering and for saying “only the use of wood in the construction field can save and renew the forests of the world” (Julius Natterer, 2017, p.4).

At their inception, the boards consisted in 8 to 20 cm posts that were nailed together using long nails that would penetrate multiple posts, resulting in glueless massive panels (Péricchi, 2013). Although this early system was using only low-grade wood, it had limitations, because it required many nails and had little flexibility, since the panels could not be cut after being manufactured (Péricchi, 2013). In 1999 the technology was improved with the *Dübelholz* system (lit. dowelled wood), which made the panels nail-free (Péricchi, 2013). In this system, stronger, hardwood dowels are perpendicularly inserted in pre-drilled holes in the posts. The moisture content of the dowels (8%) is lower than the one of the posts (15%), which allows the dowels to expand in the holes in order to reach moisture equilibrium, making the structure rigid and load-bearing (Henderson et al. 2012a). The downside of the *Dübelholz* system is that if the panels are exposed to large and sudden changes in temperature and moisture conditions, the posts can contract and expand, resulting in cracks in between the planks, which then need to be fixed with nails and/or glues (Henderson et al. 2012a).

A further evolution of the system came in 2001 when an Austrian company patented the system called *DiagonalDübelholz* (Halliday, 2015a). This system addresses the problems of the *Dübelholz s*ystem by inserting the “dowels at an angle through the posts in V and W formations” (Henderson et al. 2012a), further stiffening the joints between the posts and solving the problems of cracks opening up. The specification for the Brettstapel panels in Plummerswood requires the panels to be knot free (GAIA Architects, 2011), but, in case they are present, it is important that knots and defects are not placed next to each other in order to further strengthen the panel (Péricchi, 2013). Typical Brettstapel panels can span 3 to 15 meters in one direction, depending on the thickness (from 80 to 370mm) (Henderson et al. 2012b). Unlike cross-laminated timber panels though, *DiagonalDübelholz* panels can span only in one direction because the posts follow the same alignment (Lane, 2011).

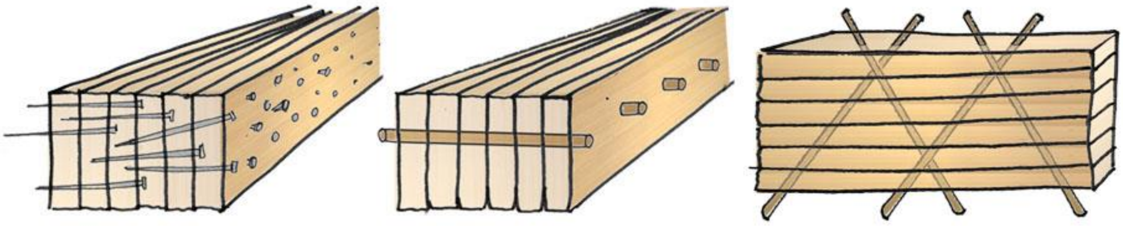


Fig. 53 Nailed panels, Dübelholz, DiagonalDübelholz

2.2.2 The use of Brettstapel in Plummerswood

GAIA came across the *DiagonalDübelholz* system while researching for the Acharacle Primary School in 2004-2005 and chose it because of its stability, sustainability and healthy specifications (Halliday, 2015a). The panels are in fact 100% natural, unlike other types of timber panels that use glues, which makes them free of potential toxins and completely disposable. For these reasons, the design team decided to have the Austrian manufacturer design and produce the panels under their supervision. The design team and the clients were also able to visit the factory in Austria in order to see first-hand the manufacturing process and "to ensure that all the integrated services [...] within the walls were incorporated" (Halliday, 2015a, p. 52). According to Samuel Foster, the architect who followed the project, the benefit of having the manufacturer design and install the envelope was that they had the liability to ensure that the envelope reached the airtightness levels required by Passivhaus standards in order to leave the site and get paid (Lane, 2011).

The panels manufactured for Plummerswood are made of Norwegian spruce timber and were delivered with pre-cut openings for doors and windows, which were also produced in Austria and delivered with the panels (Péricchi, 2013). The external walls consist of 80 mm panels that are mostly left exposed on the inside and are covered by sheathing boards on the outside as the primary airtightness layer. The first floor and the roof also consist of 180 mm Brettstapel panels (Lane, 2011).

The first delivery of Brettstapel panels arrived in October 2010, a few months after the completion of the enabling works and the laying of the foundations (Halliday, 2015a). Getting the massive Brettstapel panels to the construction site proved problematic, since the trucks got stuck in the small dirt road that leads to the house and almost slipped into a neighbour's house (Antonelli, 2013). In order to solve the problem, they had to unload the panels in the carpark of a local retailer, from where the panels could be loaded on a trailer and transported with a tractor to the building site (Antonelli, 2013). The winter of that particular year proved to be extremely harsh, with building works having to stop all over Scotland (Halliday, 2015a). Nevertheless, the Austrian builders were accustomed to working in such low temperatures and weather conditions, and were able to deliver the superstructure after six weeks, as planned (Halliday, 2015a).

Fig. 54 Source: I. & A. Nimmo

Since the construction of the Plummerswood, only a few buildings have been built in the UK using the Brettstapel panels sourced from home-grown timber. In particular, the Welsh architecture firm Archetype designed the extensions of the Coed-y-Brenin Forest Park Visitor Centre and the Burry Port Community School (Taylor, 2014). The timber was sourced from within 50 miles from the sites (Halliday, 2015a) and used Sitka Spruce, Douglas fir and Beech (Taylor, 2014). The panels were not manufactured by producers that are specialized in producing Brettstapel panels, but according to Halliday (2015), the manufacturers were keen on producing the Brettstapel panels for other projects.

Fig. 55 Source: I. & A. Nimmo

2.2.3 Fire protection

Due to the large mass of timber of the panels and the “charring action of timber in a fire” (Henderson et al., 2012b), Brettstapel has very high fire resistance, with 100 mm panels offering a 30-minute fire rating that increases to 60 minutes with 120 mm (Henderson et al., 2012b).

In the case of Plummerswood, most of the internal surfaces are left untreated, which required the application of a fire retardant to meet the UK building regulation, which requires the surfaces to be treated with fire retardant when more than approximately 30% of walls and ceilings are finished with ‘high-risk’ surfaces, such as exposed timber (Building Regulations (2010), n.d.). A non-toxic, solvent free, colourless fire retardant with fungicidal properties was selected to be used on the

Brettstapel surfaces (correspondence between S. Foster and I. Nimmo, n.d.; fireretardantuk.com, n.d.). However, the treatment came with issues. It was in fact decided to apply the fire retardant after the oil finish with the guidance received before the projects had even started (correspondence between S. Foster and I. Nimmo, n.d.). This was later found incorrect, as the particular fire retardant that was chosen could not be applied over the oil finish. When this information came to light, the only room that had not been completely oiled was the entrance hall. Parts of the entrance hall had also been treated with the fire retardant which discoloured parts of it, much to the dislike of the clients (A. Nimmo, personal communication, August 26, 2020).

A more traditional, toxic fire-retardant coating over the oiled wooden walls and ceilings could have been applied. This would have however prevented the wood from breathing, undermining the objective of creating a healthy building. In order to solve this, the design team decided to increase the number of inter-linked smoke detectors, and the internal doors leading to the hall were fitted with seals and self-closing mechanisms that shut the doors when left open over a prolonged period of time (A. Nimmo, personal communication, August 26, 2020). These devices were chosen with the idea in mind that they could contain smoke and fire in any room where a possible fire would start (correspondence between S. Foster and I. Nimmo, n.d.). A fire engineer was asked to prepare a report to show Building Control that these measures can “achieve the ‘functional requirement’ of protecting life” (correspondence between S. Foster and I. Nimmo, n.d.). The clients disabled the self-closing devices after a while because they were annoyed by the doors closing by themselves and sometimes preferred to leave them open (A. Nimmo, personal communication, August 26, 2020).

2.3 Roof

Fig. 56

The clients wanted the roof of their house to resemble the surrounding environment in order to help concealing the house (A. Nimmo, personal communication, August 26, 2020). In his book, Howard Liddell places green roofs among the eco-blings, since the build-up of this type of constructions does not appear to be particularly environmentally friendly (Liddell, 2013). He also points out the uncertainty regarding their durability (Liddell, 2013). Various studies estimate the lifespan of green roofs to be around 45-55 years (Bianchini & Hewage, 2012), which would be half of the durability designed for Plummerswood. At the end of their life, green roofs have to be disassembled, and while turf and plants can be easily repurposed/biodegraded, the disposal or recycling of other parts such as the waterproofing layer is not as straightforward, and it involves the emission of pollutants. Plants on green roofs on the other hand are often cited because they help absorbing pollutants in the external air, providing therefore benefits for the air quality of the area. Bianchini & Hewage (2012) argue that it requires up to 2/3 of the life span of green roofs to balance the pollution created during the production of the materials, without taking the recycling phase into account. It could be also argued that, given the remote location of Plummerswood and its largely wooded surroundings, the absorption of air pollutants could be considered trivial given the extremely good air quality in Cardrona (Average annual Air Quality Index of 16) (Plume Labs Air Report, n.d.). On the basis of these considerations and Howard Liddell's thinking, the choice of a green roof in Plummerswood could be regarded as an aesthetic one. Nevertheless, in order to minimise the pollutants released in the environment by the roof, the design team decided to use a single-ply TPE (Thermoplastic Elastomer) membrane for the waterproofing layer, since it is free from halogens, softeners and heavy metals (singleply.co.uk).

The roof at Plummerswood is built as follows:

- Extensive turf roof build-up; 1.2mm thick single-ply membrane; 360mm rigid wood fibre insulation; Vapour barrier. These layers were assembled on-site by the roofing company (Halliday, 2015a).
- 19mm sheathing board. Timber battens to create the fall layer, infilled with soft insulation; 180mm Brettstapel panels. These layers were provided and assembled by the Austrian manufacturer of the Brettstapel panels (Halliday, 2015a).

The roof proved fairly easy to maintain thanks to the Scottish climate conditions. The owners only have to water it on particularly hot days (A. Nimmo, personal communication, August 26, 2020).

2.4 Metalwork

A substantial amount of steel was used as part of the structure supporting the jutting section of the house. This part of the house sits on a grid of 203x203mm I Universal Columns lentils supported by four stainless steel 193.7∅ mm columns with a hollow section. An additional grid made of 152x 89x10 6kg UKB beams with a 150x90x24 kg UKPFC perimeter beams supports the wooden decking around the ground floor of the same section of the house. This grid is also supported by nine stainless steel 114.3∅ mm hollow columns. All the columns are coated with two coats of bituminous paint to 150 mm above ground level to protect from corrosion. The same grid structure is also used for the external bridge that connects the first floor of the building to the garden behind it. Two 89∅ mm hollow stainless steel columns also support the jutting part of the bedroom above the kitchen.

Additional metalwork in the house include the aluminium sills of the windows, balconies and balustrades of the flat roof, as well as the railings of the deck and external bridge. At an earlier stage of the project it was planned to have glass balustrades on the exteriors, but they were changed to steel railings to save money (Halliday, 2015a)

3. Insulation

The walls, roof and ground floor of Plummerswood are very well insulated with wood fibres insulation (Halliday, 2012). The wood fibres are obtained from low-grade timber, mostly coniferous wood (82.8%) (steico.com, 2016) bonded by tree resin (Halliday, 2015a). The panels have a thermal conductivity of 46 W/(mk) and are effective in soundproofing against impacts on wooden flooring (steico.com, 2016). Given its versatility, it was used to insulate the whole house. In particular, rigid panels (ρ=230 kg/m3; steico.com, 2016) were used to insulate (GAIA Architects, 2011):

- the external walls (280mm);
- the ground floor (140 mm over a DPM membrane on top of the concrete slab);
- the roof (360 mm sandwiched between a vapour barrier and a single ply membrane).

Non-rigid panels (ρ=50 kg/m3; steico.com, 2016) were instead used to insulate (GAIA Architects, 2011):

- the internal partitions (Fig. 65), between timber battens fixed on one side of the Brettstapel walls (60 mm compressed to 50 mm);
- all floors in the space between timber battens (80/120/140mm depending on the floor finishes (Fig.59); over rigid wood fibre insulation on ground floor and over gravel on first floor);
- the roof in between timber battens to create fall.

The exposed Brettstapel structure also improves the thermal mass of the house. In fact, “mass timber has a specific heat capacity of around 760 J/kg. K” (Henderson et al. 2012b) which helps absorbing a lot of heat in winter and keeps the building cool in summer (Wolley, 2013). Timber also has low conductivity, with typical values for softwood of 0.13 W/(mK), making it a good insulating material and helping achieve low thermal bridging values (Henderson et al., 2012b). These characteristics were crucial for achieving the Passivhaus certification, which requires U-values for opaque elements to be 0.1 to 0.15 W/(m^2K) and to be thermal bridge-free with a Ψ value <0.01 W/(mk) (Hines, et al., 2015).

The U-values calculated during the designing phase were 0.11 W/m^2 for the external walls and 0.09 W/m^2 for the roof (Fulcrum Consulting, 2009a) (Halliday, 2015a), consistent with the Passivhaus requirements.

On a morning in February 2012 an infrared thermography survey was conducted to "identify irregularities in the thermal properties of the components constituting the external envelope of [the] building" (Halliday, 2015a, p. 61). An infrared thermography examination detects the electromagnetic radiations of a building, and it is used to identify its surface temperatures, to diagnose irregularities in the distribution of its surface temperature and to help quantifying energy savings (Balaras & Argiriou, 2002). The survey did not identify any missing insulation or discrepancies in temperature both externally and internally, and a few minor thermal bridges were detected around some window frames as expected (Halliday, 2015a).

Fig. 57

3.1 Issues with the insulation

It is important for the wood fibre insulation to be kept dry and protected from water before and after installation (GAIA Architects, 2011). Taking this into account, a major issue occurred in 2016 when Anne and Ian Nimmo noticed rotting in some of the Brettstapel walls. The wooden floor was quickly removed for an inspection and widespread rotting of all the wood fibre insulation on the ground floor was found. The soaked insulation had also transferred moisture to some of the Brettstapel walls causing major rotting at their base. After removing the flooring in the tiled rooms, it was found that the issue had started from the ground floor bathroom. In fact, the plumber had not vented the toilet properly due to oversight and possibly little knowledge of the Brettstapel system, resulting in a water leakage into the wall and insulation every time the toiled was being flushed. The issue went unnoticed for years, leaving the water time to spread throughout the floor, and nobody thought of inspecting the insulation until the damage was visible on the walls (I. Nimmo, personal communication, August 26, 2020).

In order to fix the problem, the owners had to leave their house for weeks, while the ground floor was being gutted, the rotting elements removed and substituted. The rotted lower sections of the Brettstapel walls were sawn away and substituted with new, regular, cross-laminated panels. They were able to recover the wooden floor and reuse it since it had not originally been glued or nailed. Luckily their house insurance could cover the costs (I. Nimmo, personal communication, August 26, 2020).

Fig. 58 Water damage on Brettstapel panels

Source: I. & A. Nimmo

Fig. 59 Source: I. & A. Nimmo

This occurrence shows that it can be very easy to make mistakes with technologies that are not known by local contractors. When hiring workers that might not be specialised in working with such technologies cannot be avoided, it is necessary to identify ahead of time potential issues that might arise and possibly to instruct workers on the specifications and criticalities of these systems.

The Nimmos did not want to run the risk of repeating the ordeal: in fact, they were offered the opportunity to install moisture sensors near the utility room plumbing, the tank room and the kitchen. The sensors consist in probes to be embedded into wooden bits and drilled into the floor up to the DPM membrane without touching it. The sensors work with a moisture meter that gives the moisture level as a percentage. The Nimmos can then keep a log of all the moisture levels autonomously and be aware of new potential leakages in the bathroom (Correspondence between I. Nimmo and J. Robertson, 2016).

4. Cladding

The vast majority of the first floor and part of the ground floor are cladded with larch timber that was sourced, milled and installed locally (Halliday, 2012). The cladding consists of 25x75 mm square sawn rear boards and 38 mm thick, trapezoidal facing boards, with varying widths for aesthetic reasons (GAIA Architects, 2011). All the boards are screwed rather than nailed, to ensure the possibility of reusing the material if removed. The boards are fixed on battens made of home-grown Douglas fir to create a ventilation cavity, protected by a stainless steel insect mesh at both ends (GAIA Architects, 2011). The battens are then fixed to the sheathing boards installed by the Austrian subcontractors (GAIA Architects, 2011). The sheathing boards hold the insulation and also act as the main airtightness layer of the house. Therefore, the battens had to be fixed only in clearly marked locations in order not to undermine the airtightness of the house (GAIA Architects, 2011). Both the battens and the cladding boards were sawn from the heartwood of trees to ensure strength and durability (GAIA Architects, 2011). The timber was in fact left intentionally untreated to avoid the use of toxic preservatives and to let the wood grey naturally. The owners feared that the large mass of wood would have made the house too visible and imposing in the surroundings (A. Nimmo, personal communication, August 26, 2020). Nevertheless, since the wood has now darkened and the newly planted trees have been growing, it is almost impossible to locate the house from the surrounding roads. The attitude of letting the exposed wood age naturally is not common in the British culture, where timber cladding is usually treated with preservatives, making the wood potentially toxic and thus creating problems for its future disposal (Liddell, 2013).

Fig. 60 Source: I. & A. Nimmo

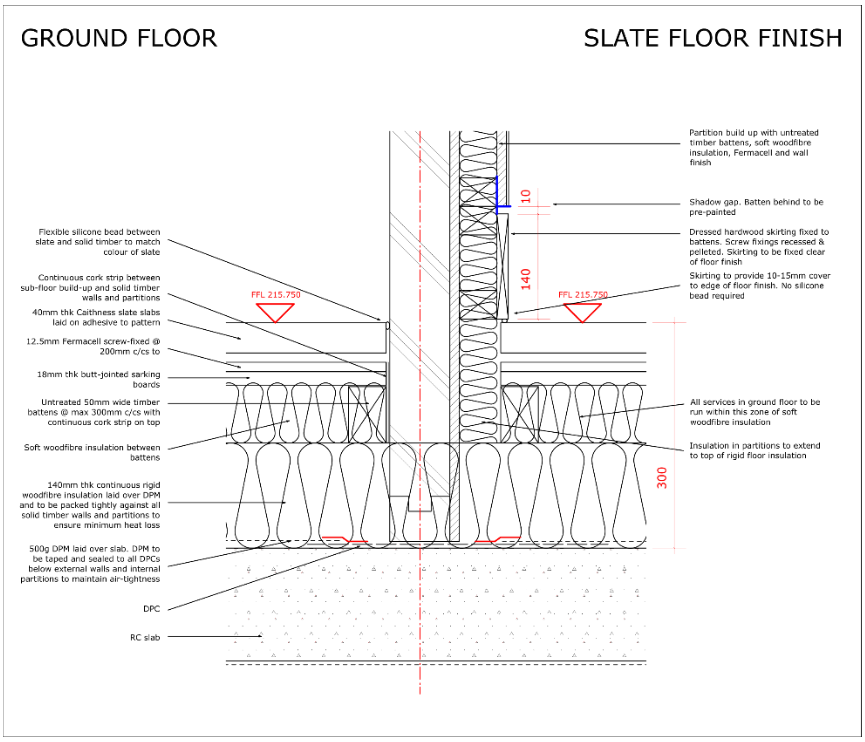
Fibre cement boards were also used to clad the external wall above the entrance hall and the spaces between some windows. As for the timber cladding, the boards are fixed on battens, using coloured screws to match the boards. The reason for using fibre cement boards is purely aesthetic. Nevertheless, the boards are made by 65% of their weight from natural fibres, mostly a by-product wood from the sawmills (FunderMax, 2010). The panels are also free from wood protection agents, heavy metals and organic halogens (FunderMax, 2010).

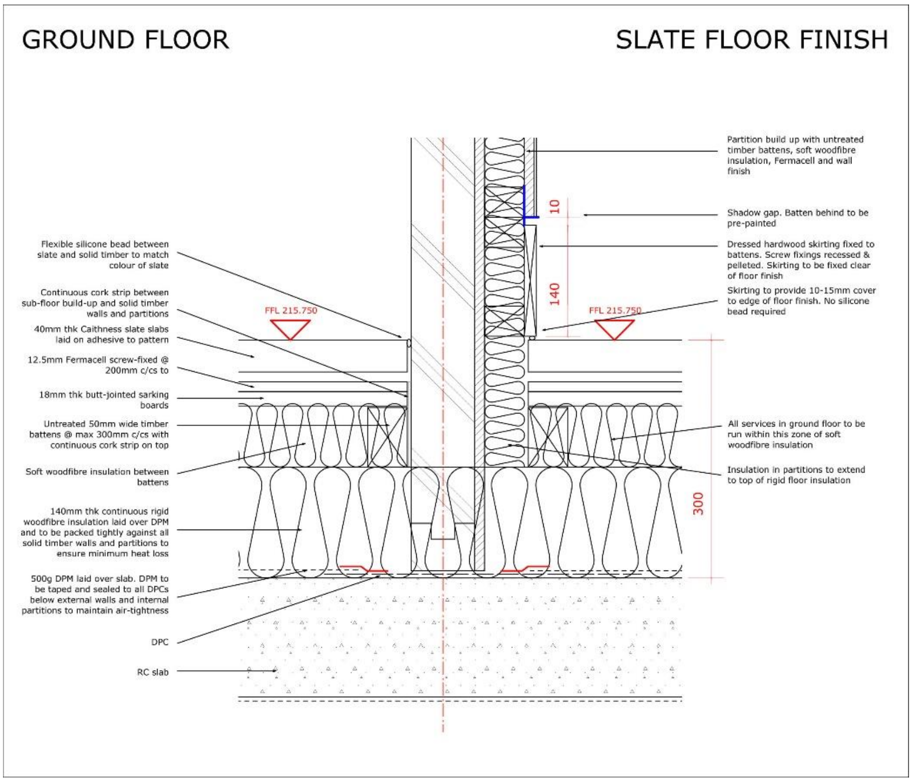
5. Floors

There are three types of floors build-ups at Plummerswood: floor on concrete slab (Ground floor); floor on cassettes (ground floor); floor on Brettstapel panels (first floor). The different finishes are timber, slates or ceramic tiles.

The wooden flooring consists of locally sourced Oak for the ground floor and Ash for the first floor (GAIA Architects, 2011). The floor was assembled without the need of nails with a system that had already been used by GAIA at the Glencoe Visitor Centre, consisting of wooden boards screwed at regular intervals and that loosely hold the rest of the boards in place (The Guardian, 2014). The boards are fixed on wooden battens covered with continuous cork stripes to help soundproofing the floor (GAIA Architects, 2011). The floors are finished with three coats of a natural non-toxic oil made with plant oils and waxes to make it water-repellent and abrasion-resistant (osmouk.com, n.d.).

The entrance hall, the wet room and the kitchen are tiled with Caithness slates, a flagstone from Scotland. The dimensions of each slate and the laying pattern were designed specifically by GAIA to fit the organic forms of the house. Ceramic tiles were also installed in the bathrooms, utility room, workshop and part of the wet room (GAIA Architects, 2011).





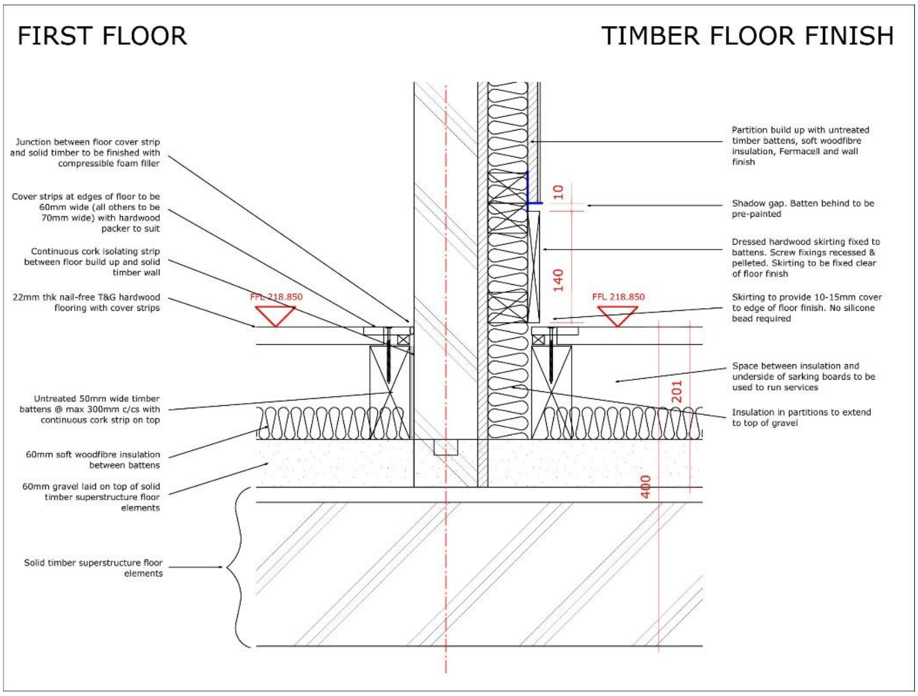


Fig. 61 Source: GAIA Architects

6. Wall finishes

All internal walls are made of Brettstapel panels that contribute to the load-bearing structure of the house. Many of the wooden surfaces are left exposed, while some panels are covered by gypsum-fibre boards fixed to timber battens with soft wood fibre insulation panels in between (GAIA Architects, 2011). The bathrooms and wet room are instead fitted with clay boards coated with clay plaster to help absorb humidity (Halliday, 2015a).

Fig. 62 Source: I. & A. Nimmo

The ground-floor external wall is covered by another wall made of field stone rubbles to resemble the existing bothy in the property (GAIA Architects, 2011). The stones are bound with mortar but made to look like a drywall. The wall is tied through an 80-mm ventilated cavity with the load-bearing layer of the wall; in order to minimise thermal bridges 6 mm thick insolating pads have been associated to each tie. The ventilated cavity was fitted with weep vents to allow air circulation (GAIA Architects, 2011). The top of the stone walls is then capped with inclined Caithness slates in order to push rainwater towards the exterior side of the wall (GAIA Architects, 2011).

Fig. 63 Detail of plaster boards

Fig. 64 Source: I. & A. Nimmo

7. Furniture

The interior doors, the built-in wardrobe doors and fixed furniture were all designed by a Scottish designer and manufacturer who worked closely with GAIA to ensure that only local and natural materials were used. As for the timber flooring, Oak was used for the ground floor doors and furniture, while ash was used on the first floor (Finch, n.d.). The core of the doors was made with Douglas fir, which was then glued and plugged with Oak or Ash panels following a branch-like design (Finch, n.d.). All the furniture and timber elements around the house, including benches, seats, drawers and the bookcase were treated with the same oil finish that was used for the wooden floor (GAIA Architects, 2011).

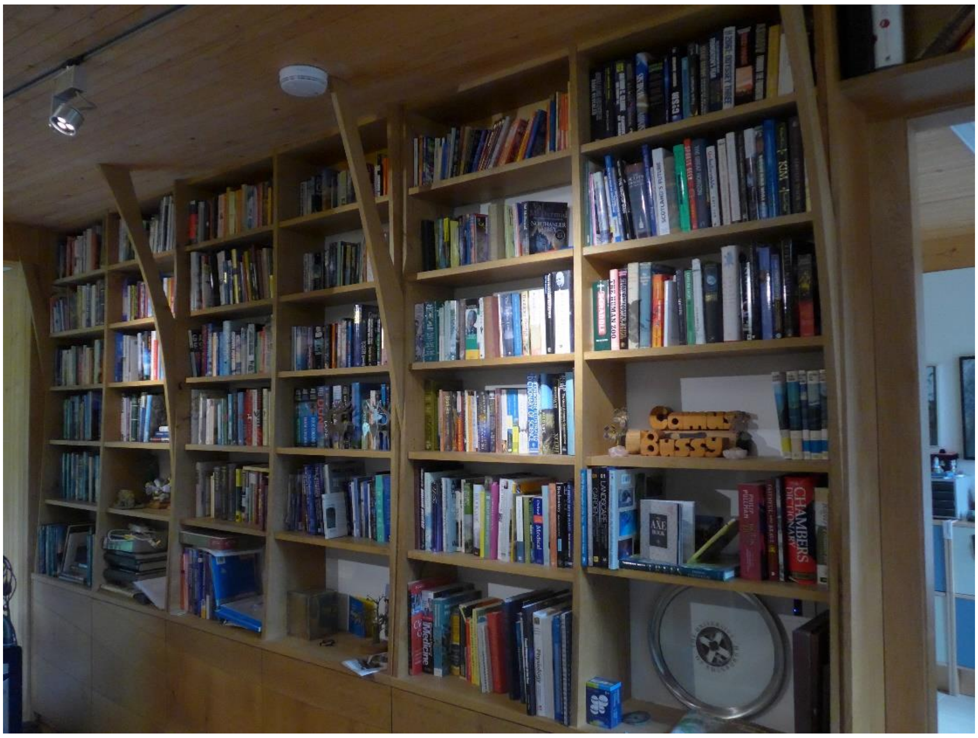


Fig. 65

8. Ventilation and heating strategies

8.1 Ventilation

As stated in the introduction, GAIA followed the Passivhaus standard requirements in order to achieve its certification. In order to do so, it was decided to install a MVHR (Mechanical Ventilation with Heat Recovery) system. This decision goes against the principles of eco-minimalism, which would require the adoption of passive strategies rather than mechanical systems, but it offered GAIA the opportunity to research the topic and contribute to starting a debate over the necessity of using MVHR in Passive Houses (Halliday, 2015a). In Plummerswood, MVHR was to be implemented only when necessary in order to achieve the Passive House certification, while at the same time ensuring it being "a supplement to natural systems, rather than a replacement for them" (Halliday, 2015a, p. 1). GAIA was in fact "keen that Plummerswood was an active house responding to human factors, rather than a passive house responding to a regulated norm" (Halliday & Butler, 2015, p.2), a statement that sounds like a wordplay but that underlines the GAIA's effort in researching and optimising passive design, bringing it beyond the limitations of the regulation. As Paola Sassi indeed says, "the use of MVHR is the recommended method in the Passivhaus model of providing the required ventilation and maintaining a comfortable and healthy environment at minimal energy costs" (Sassi, 2013, p. 63), but it is not the only possible solution. As shown in the case of the Acharacle primary school, Passivhaus standards can be achieved with natural ventilation controlled by CO_2 concentration and temperature sensors (Halliday, 2015a). By including MVHR in Plummerswood and through the subsequent Post Occupancy Evaluation, GAIA aimed to compare the differences in performance under mechanical and natural ventilation regimes in order to optimize them (Halliday, 2015a).

A MVHR system introduces pre-heated, filtered, external fresh air inside the building while extracting stale air (greenbuildingstore.co.uk). The warmth of the stale air is used to pre-heat the incoming fresh air without the two streams of air ever mixing, saving energy while providing fresh, clean air (International Passive House Association, n.d.). The Plummerswood system is designed to grant "control of temperature by providing space heating; control of moisture by providing minimum background ventilation; control of odours; Limiting the build-up of carbon dioxide by ventilating with 100% outside air." (Halliday, 2015a, p. 31). The air is extracted from the bathrooms and the kitchen while being introduced in the living areas and the bedrooms (Halliday, 2015a) as shown in the following scheme:

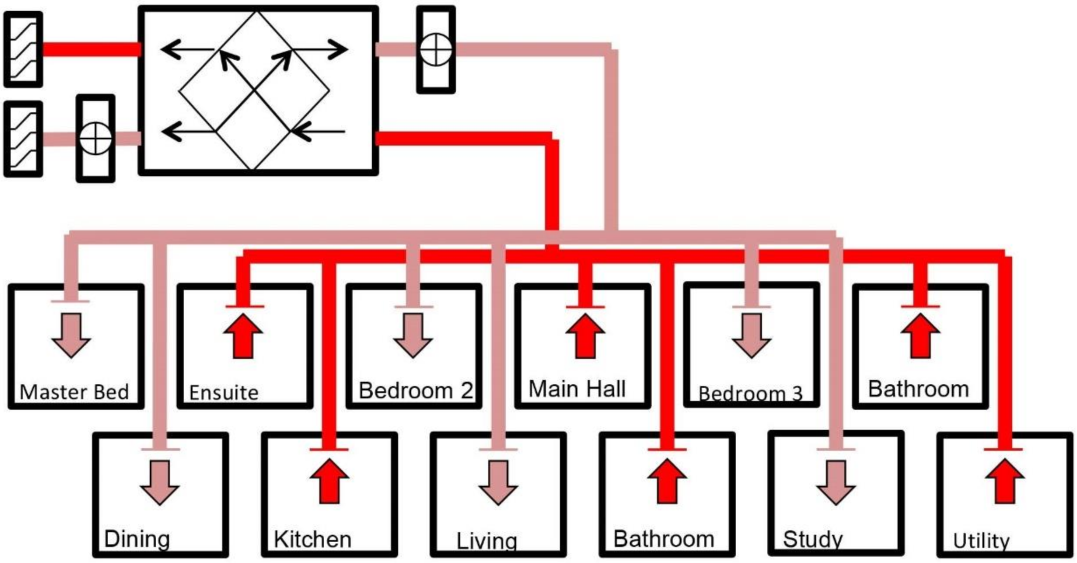


Fig. 66 MHRV Configuration
Source: Sandy Halliday

Sandy Halliday (2015a) points out that this MHVR configuration fails to recognise the varying occupancy profiles over the course of the day in the different rooms of the house and it treats it as a single zone. The risk of this configuration is that non-occupied rooms are going to be over ventilated, thus consuming more energy than needed. (Halliday, 2015a). As already previously described, internal doors are fitted with seals and self-closing devices in order to meet fire protection regulations, which were later disabled by the clients who preferred to leave them open (A. Nimmo, personal communication, August 26, 2020). Leaving the doors open has also the benefit of allowing cross-ventilation and of letting the volume of the house buffer the CO_2 that is produced by the occupants (Halliday, 2015a). Halliday also argues that the frost coil in the MHVR system "consumes a significant proportion of the MVHR energy, and hence [..] it does not offer an energy saving" (Halliday, 2015a, p. V) and a "simpler mostly passive approach would have similar energy consumption" (Halliday, 2015a, p. V). Since its installation, Anne and Ian Nimmo never needed to have the system checked or repaired. However, the system needs maintenance and the air filter needs to be changed three times per year, which is quite costly (I. Nimmo, personal communication, August 26, 2020). Instructions of the MHVR would require the filters to be changed four times per year, but they are likely able to last longer, since t the filters appear to be clean after 90 days (Halliday, 2015a).

To be effective, a MVHR system needs to be integrated with very high levels of airtightness (International Passive House Association, n.d.). This prevents heat losses through drafts and protects the envelope moisture damage (International Passive House Association, n.d.). The requirements for airtightness in a Passivhaus need to "be demonstrated with a pressure test wherein the allowable air change cannot exceed 0.6 times a room's volume per hour and the pressure differential is limited to 50 Pa" (International Passive House Association, n.d.). A first post-construction test found some issues around a few windows since the polyurethane seals above them had not fully expanded due to cold winter temperatures (Halliday, 2015a). Once this issue was corrected, an air permeability of 0.49 m^3/h was measured, well below the design target (Halliday, 2015a). The occupants report that even with this high level of airtightness, the house always feels clean and fresh, as the MHVR functions well. However, they disagree on how often they should open the windows, even when it is not necessary. In fact, Ian Nimmo prefers to keep the windows open (especially in the bedroom) in order to feel the change of air and remove a barrier with the outside. Anne, on the other hand, does not want to open them because of the risk of insects entering the house (A. Nimmo, personal communication, August 26, 2020). Due to the airtightness in fact, insects do not find a way inside. Only in one occasion they had to get rid of an infestation of flies down the chimney of the stove, which is nevertheless closed to the inside (A. Nimmo, personal communication, August 26, 2020).

8.2 Hygroscopic materials

According to Sandy Halliday (2015a)'s research, the relative humidity is between 50-60% during the summer, with an even smaller variation during winter due to airtightness and mechanical ventilation. These ideal conditions are achieved thanks to mechanical ventilation, vapour permeability of the envelope, moisture buffering and an overall good use of moisture mass.

Vapour permeability is the ability of a material to let vapour pass through itself (Vapour Permeability, 2021), and it represents a good passive strategy to keep good levels of relative humidity indoor. In fact, all elements of the external walls are made of untreated wood, and the wood fibre insulation allows the moisture to reach the outside without undermining its insulating properties (Halliday, 2012).

According to Zhang, Mingjie, et al. (2017), “Moisture buffering is the ability of surface materials in the indoor environment to moderate the indoor humidity variations through adsorption or desorption” (p. 337). Due to their large pore that makes them breathable, hygroscopic materials allow for moisture buffering (Wolley, 2013) and were chosen to make up almost the entirety of the surfaces in Plummerswood. This strategy allows most of the surfaces of the building to absorb the moisture in case of higher internal RH levels and to release it with drier indoor conditions (Wolley, 2013). In fact, the untreated Brettstapel walls offer a large hygroscopic surface in the areas of the house with average levels of occupancy and activities (Halliday, 2015a). On the other hand, rooms with a high moisture production such as the bathrooms, the wet room and the kitchen are fitted with clay plaster boards and clay plaster ceiling to maximize moisture absorption and release (Halliday, 2015a).

After the clients moved in, the subsequent evaluation of the building performance showed that the internal conditions have a smaller range of moisture content in relation to the outdoor conditions, particularly in winter and even in the humid Scottish weather (Halliday, 2015a).

8.3 Heating

Since Ian and Anne Nimmo wanted to have a wood burning stove in the living area, a stove incorporating a water-heating heat exchanger was considered an option to heat the whole house (Halliday, 2015a). This was quickly deemed impossible since “the combustion chamber of the stove would have been required to be ventilated directly to outside, undermining the airtightness requirements” (Halliday, 2015a, p. 48).

The next option considered is the MHVR system with “heat exchanger at 80% heat recovery potential but no reheat battery” (Halliday, 2015a, p. 48). This solution would have relied on the heat of the occupants and appliances as the only source of heating, but it was deemed insufficient during the winter (Halliday, 2015a). A supplementary 1.6 kW heating element was then added to the system in order to heat the incoming air when needed (Antonelli, 2013). This shows the importance of starting the decision process from the simplest and most ecological options, and to increasingly add technological and energy consuming systems when strictly necessary.

Fig. 67

Additional 500W electric heated towel rails have also been installed in the bathrooms (Halliday, 2015a), and a simple, 3.5 kW sealed wood burner was placed in the living room (Antonelli, 2013). According to Halliday (2015a), the owners reported to be using around 10kg of timber sourced from the property per day, providing 74% of the total heating.

Overall, Anne and Ian Nimmo are satisfied with the indoor conditions of the house. They never feel cold in winter, while the risk is rather to overheat the house (Antonelli, 2013). When they leave the house for a prolonged period of time, they set the MHVR system in an *unoccupied* mode, which results in the system staying switched on, but with minimal energy consumption (A. Nimmo, personal communication, August 26, 2020). During winter, when the outside temperature is well below 0°C and they return home after a few days away, the indoor temperature is usually not below 14°/15°C. In these conditions, it takes only half an hour to heat the house up to its set point of at least 17°C (A. Nimmo, personal communication, August 26, 2020). 20-22°C can be easily achieved through the solar gains and the loads from people, cooking and house appliances (Halliday, 2015a). This shows that the building benefits from thermal mass (Halliday, 2015a).

8.4 Solar Gains

Location, exposure and window placement have been taken in consideration in order to ensure the best possible solution for maximising solar gains and minimising heat losses in winter. At an early stage, they had considered the option to build the house in the lower part of the property near the bothy, assuming that it would have been more sheltered from the elements (Halliday, 2015a). However, a computational Fluid Dynamics and overshadowing analysis showed that even if "there would be a significant increase in wind speed [on] a more exposed location" (Halliday, 2015a, p. 43), the building would "not [have] suffer[ed] from overshadowing to an extent that would detrimentally affect the daylighting" (Halliday, 2015a, p. 43). A placement higher up the slope was therefore judged more appropriate for the house, while allowing the clients to benefit from better views over the valley and to have a better interface with the dense neighbouring forest (Halliday, 2015a).

Due to the high levels of insulation and airtightness, overheating in summer was a risk, while the large glazed areas could be a source of heat loss in winter. In order to minimise these problems, an external consulting team was asked to produce different models of the house using PHPP (Passive House Planning Package) and Tas Engineering software (Halliday, 2015a). The studies showed that in winter "the house would struggle to adequate temperature levels, especially in cloudy days" (Fulcrum Consulting, 2009a, p. 12). It was therefore suggested that the glazed surfaces should be scaled down (Fulcrum Consulting, 2009a), which was promptly done by diminishing the size of some windows and removing a large skylight on the roof of the entrance (Halliday, 2015a).

During the warmer months of the year, it was also observed that "unless the windows are opened, the bedrooms and the entrance hall are liable to experience excessive resultant temperatures" (Fulcrum Consulting, 2009b, p. 7). To solve these issues, fixed overhangs were modelled above the windows and external motorized blinds were added to some of the windows (Halliday, 2015a). Other windows, such as the ones in the kitchen, showed no need for controlling the solar gains, and therefore no additional elements were installed (Halliday, 2015a).

During the coldest months of the year, it was observed that "without external blinds the anticipated annual heating demand would be 94kWh" (Halliday, 2015a, p. IV), while "with external blinds the annual heating demand [would] increase to 143kW"

(Halliday, 2015a, p. IV), with a reduction of heating demand by 35%. This emphasizes the necessity of operating manually the blinds during winter in order to maximize the solar gains. Ian and Anne Nimmo are happy to do that and they are not bothered by the light coming inside the house as they appreciate being able to look at the view at all times. For this reason, they do not have curtains, a choice that also helps to maximise the heat gains (I. Nimmo, personal communication, August 26, 2020).

Fig. 68

9. Energy Consumption

The total energy consumption of Plummerswood has been closely monitored as part of the Post Occupancy Evaluation led by GAIA in the first years after the completion of the building. In particular, the energy consumption was recorded over a two-year period in 2012 and 2013 to evaluate the efficiency of the adopted passive strategies and to identify ways to further improve energy savings.

The energy consumption was determined to be so divided:

- MHVR. As expected, the mechanical ventilation system makes up most of the energy consumption of the building. The designed objective was that Plummerswood should consume less than 15 kW/m^2 per year for heating as required by the Passivhaus standard (Hines, et al., 2015). However, during 2012 the MHVR system consumed only 2199 kWh or 6.4 kW/m^2, with the rest coming from biomass (Halliday, 2015a). After increasing the time that the building operates in passive mode, the consumption decreased to 2092 kWh or 6.0 kW/m^2 in 2013, despite colder temperatures that year (Halliday, 2015a). This is less than 50% of the requirements of a Level 6 of the Code for Sustainable Homes that at the time was used in the UK as the benchmark for a 'zero carbon home' (Halliday, 2015a).
- Biomass. The stove is estimated to consume 18.5 kW/m^2 of energy per year (Halliday, 2015a).
- Electricity. Energy demand from electric appliances is estimated to consume 6 kWh per day (Halliday, 2015a).
- Bodisk. The biodisk consumes 2kWh per day (Halliday, 2015a).
- Solar energy. The solar hot water system reduces energy consumption by 50% in spring and summer (Halliday, 2015a).

Overall, the averaged consumption of Plummerswood is 9,400 kWh/year (Halliday, 2015a). The total energy consumption does not exceed 47.9 kWh/m^2 per year (Halliday, 2015a). The installation of Photovoltaic Panels was considered to make Plummerswood Net Carbon neutral. This was deemed unnecessary because of the high costs for installing the panels (A. Nimmo, personal communication, August 26, 2020).

Despite being energetically very efficient, Plummerswood is fitted with a few of the technologies that Howard Liddell defines as eco-blings. More passive forms of energy could have proved successful too as in the case of the Acharacle school, where the Passivhaus standards are achieved with no mechanical ventilations. However, as stated in the first chapter of this study, eco-minimalism is an approach to sustainable design whose principles have to be evaluated case by case depending on the requirements/benefits of a specific project. As written in the section about ventilation, the use of MHVR in Plummerswood was chosen after having researched other passive options, and was deemed necessary once it was decided that the house would have sought to achieve the Passivhaus certification. However, the system was optimized to use as little energy as possible and it is operated together with natural ventilation for a good part of year, making it more like a hybrid ventilation system.

10. Embodied Energy and Embodied Carbons

The impact of a building on the environment can be assessed through its Embodied Energy (EE) or Primary Energy Intensity (PEI), and its Embodied Carbons (EC) or Global Warming Potential (GWP). According to Bjørn Berge (2009) “the embodied energy of a product includes the energy used to manufacture it all through the process of mining or harvesting the raw materials, refining, processing, and various stages of transport, to the finished product at the factory gate” (p.19) and it is measured in Megajoules (MJ).

The steps of the manufacturing process are also a source of pollutants, in particular carbon dioxide, and it is useful to quantify it in order to assess the Global Warming Potential of the building. Since the GWP is the “measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of [...] CO2” (United States Environmental Protection Agency, n.d.), its unite of measurement is kgCO_2eq.

According to the EN 15804 standard, the production stages of a building are so divided: raw material extraction and processing (A1), transport to the manufacturer (A2), manufacturing process (A3). The transportation to the building site (A4) was not considered for this study because of the unreliability of the information regarding the location of the manufacturers of many products. This approach is defined as cradle to gate. Nevertheless, most of the materials used in the construction were purposely manufactured locally, showing an attention by GAIA Architects for reducing the impact of transportation, as well as for decentralizing the production. The only material whose transportation had a major impact on CO2 emissions is Brettstapel, that had to be transported from the factory in Austria to the Scottish Borders, with an estimated emission of 16t of CO_2 for transportation (Halliday, 2015a). The design team was aware of this criticality in choosing Brettstapel and they would have preferred using local timber. Nevertheless, the benefits of introducing Brettstapel in the UK was deemed more important and the transportation emissions compare well with the total carbon sequestration of the building materials, as the next pages will show.

To facilitate the understanding of the data, the materials that make the building up are going to be listed as follow:

- Aluminium (including sills, false ceiling structure, roof parapet);
- Bituminous DPM (under first floor slab);

- Brettstapel (counted separately from the other wooden elements in order to see the contributions of this specific construction system);
- Ceramic tiles;
- Clay (including clay boards and plaster);
- Concrete (including the first floor slab, prefabricated trench blocks, the foundations);
- Cork (used on floor battens);
- Earth (on green roof);
- Fibre cement boards (cladding);
- Gypsum (including plaster boards and gypsum plaster);
- Glass (including the glass of the windows and the safety glass parapets);
- Gravel (on green roof);
- Steel (including steel reinforcement, steel columns and beams, hardware, external parapets);
- Stone (including wall and floors);
- Thermoplastic Elastomeric sheet (on green roof);
- Tile adhesive;
- Wood (including timber floors, external cladding, sheathing boards, sarking boards, floor battens, posts, doors, window frames);
- Wood fibre insulation (including both rigid and soft wood fibre panels).

Most of the components listed in brackets have been analysed individually, since the production and characteristics of the materials may vary (i.e. manufacturing process, density etc.). They have been grouped for ease of reading.

10.1 Databases

As mentioned at the beginning of this chapter, the databases used for the calculations are the ÖKOBAUDAT (OBD) by the German the Federal Ministry of the Interior, Building and Community, and the ICE.V2 (Inventory of Carbon and Energy) by the Sustainable Energy Research Team of the University of Bath. Both databases are freely accessible online.

When the manufacturers provided the Environmental Product Declaration (EPD) of product that are known to be used in the building, their data was used in place of those of OBD and ICE, as they were deemed more precise. These products include both the soft and rigid insulating panels which make a considerable portion of the volume of the materials (38%).

Most notably, at the moment there is no available data regarding the EE and EC of Brettstapel in Europe. However, the same construction system is sometimes referred as Dowel Laminated Timber (DLT) in the North American market. The Environmental Product Declaration of DLT panels produced in Canada (Structure Craft, n.d.) was available online and was used for this study. It is of particular interest to see in what the production stages of the panels consist:

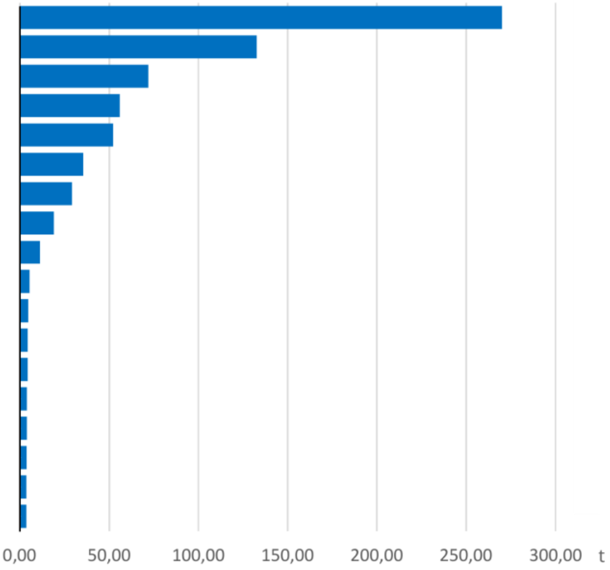
- A1: Harvesting and removal of the timber, site preparation, planting, fertilization, management operations and reforestation (Structure Craft, n.d.).
- A2: Transportation of raw materials (including fuels) from the forest to the factory, recycling of waste materials (Structure Craft, n.d.).
- A3: Manufacturing of the panels, including packaging (Structure Craft, n.d.).

10.2 Bill of quantities

In order to perform the calculations, Autodesk Revit was used to draw a detailed 3D model of the building from which a bill of quantities of the materials has been extracted. The model was built according to the technical drawings of plans, sections and construction details. Photos and measurement taken during the site visit to Plummerswood were also very helpful in building the model.

10.3 Weight calculation.

Material	Weight [t]	Percentage [%]
Concrete	266.43	41
Stone	129.18	20
Wood	68.37	10
Wood fibre insulation	52.38	8
Brettstapel	48.74	7
Earth	31.96	5
Steel	25.69	4
Gravel	15.56	2
Gypsum	7.76	1
Glass	1.97	<1
Tile adhesive	1.14	<1
Ceramic	0.93	<1
Bituminous DPM	0.91	<1
TPE membrane	0.39	<1
Clay	0.36	<1
Aluminum	0.22	<1
Fibre cement	0.20	<1
Cork	0.01	<1
Total	**652.19**	**100**



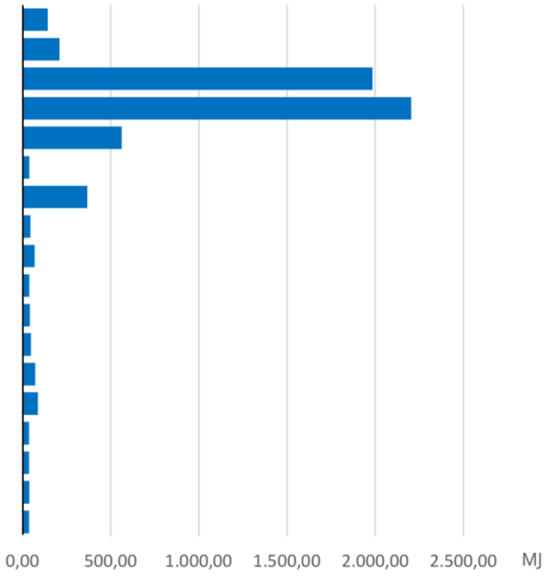
Tab. 1 Weight of the materials

Plummerswood has an area of 346 m^2 and weighs 652.19 tonnes, or 1,88 t/m^2. Concrete makes 41% of the weight of the building, meaning that the substructure is the heaviest part of the building. The second heaviest components are the stone elements, making 20% of the total weight. It is interesting to see how the stone floors and walls, which can be considered as aesthetic features of the house, make only 7% of the total volume of the materials and yet they largely contribute to the total weight of the house. The wooden elements (timber floors, external cladding, sheathing and sarking boards, floor battens, posts, doors, window frames) contribute only 10% of the total weight (16% of the volume), while the Brettstapel panels contribute 7% (8% of the volume). This means that all the wooden elements of the house make 24% of the total weight. The wood fibre insulation, while making up the majority of the volume of the house (38%), contributes only 8% to its weight due to its low density (50 kg/m^3 for the soft panels and 234,4 Kg/m^3 for the rigid ones). Other contributors to the weight are: earth (5%), steel (4%), gravel, (2%) and the plaster boards (1%).

Overall materials with a vegetal origin make up 26% of the total weight, including the wooden elements, Brettstapel, the wood fibre insulation, cork. Other materials of natural origin make up 27% of the weight. This percentage includes the stone floors and walls, gravel, and earth. The last 47% of the weight is made up of non-natural materials.

10.4 Embodied Energy and Carbon calculation with ÖKOBAUDAT

Material	PEI [GJ]	Percentage [%]
Concrete	106.47	2
Stone	173.51	3
Wood	1949.20	36
Wood fiber insulation	2169.14	40
Brettstapel	525.89	10
Earth	1.84	<1
Steel	331.03	6
Gravel	8.67	<1
Gypsum	32.31	1
Glass	2.08	<1
Tile adhesive	5.36	<1
Ceramic	11.85	<1
Bituminous DPM	35.44	1
TPE membrane	51.34	1
Clay	0.26	<1
Aluminum	0.02	<0
Fibre cement	2.36	<1
Cork	0.22	<1
Total	**5406.98**	**100**



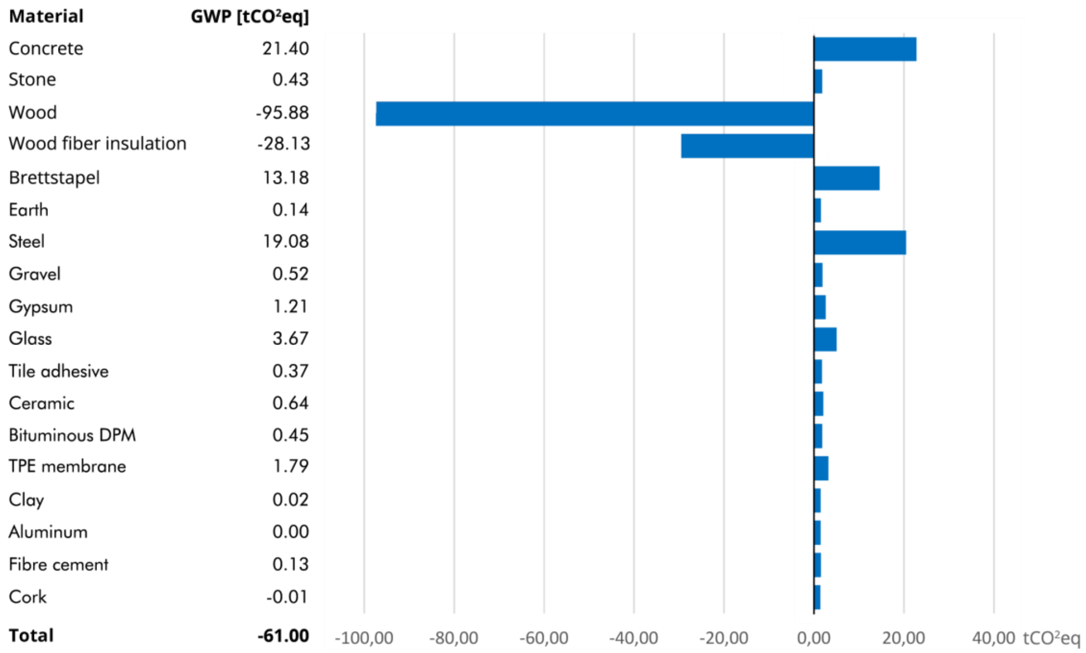
Tab. 2 PEI values according to Ökobaudat

The total PEI value calculated with the ÖKOBAUDAT database is 5406983.51 MJ or 5406.98 GJ. That means that there are 15.63 GJ/m^2. The materials that affect the result the most are the wood fibre insulation with 2169.14 GJ (40% of the total PEI), the wooden elements (36%) and the Brettstapel (10%).

It is interesting to see how very heavy elements such as stone, concrete and steel have a much lower contribute to the total value (Concrete 2%; stone 3%; steel 6%). Nevertheless, according to the database the total non-renewable primary energy resources (PERNT) of non-natural materials are much higher compared to the natural ones. On the contrary, natural materials, especially vegetal ones, usually have a much higher rate of total use of renewable primary resources (PERT). For example:

According to OBD, the PEI of concrete is 1127,26 MJ/m^3 which consists of 17% from renewable energy (PERT) and 82% from non-renewable energy (PERNT).

On the other hand, the PEI for structural oak timber is 16021.16 MJ/m^3 consisting of 89% from renewable energy (PERT) and 11% from non-renewable energy (PERNT).



Material	GWP [tCO^2eq]
Concrete	21.40
Stone	0.43
Wood	-95.88
Wood fiber insulation	-28.13
Brettstapel	13.18
Earth	0.14
Steel	19.08
Gravel	0.52
Gypsum	1.21
Glass	3.67
Tile adhesive	0.37
Ceramic	0.64
Bituminous DPM	0.45
TPE membrane	1.79
Clay	0.02
Aluminum	0.00
Fibre cement	0.13
Cork	-0.01
Total	**-61.00**

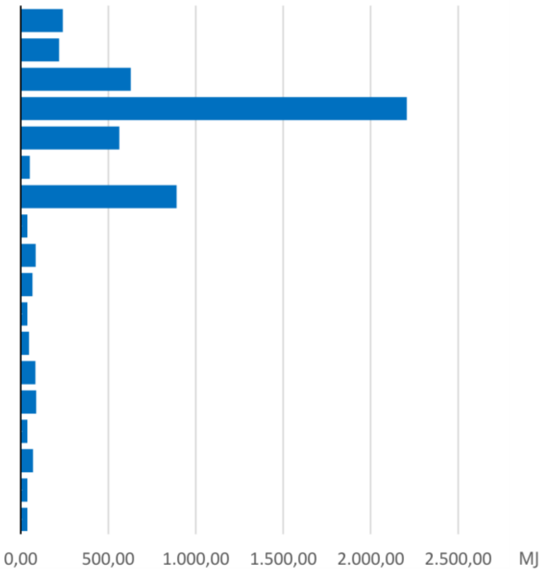
Tab. 3 GWP values according to Ökobaudat

The total GWP of the building is -61,00 tCO_2eq, or -0,18 tCO_2eq/m_2, meaning that according to the OBD values, materials of Plummerswood sequestered more CO_2 than they emitted. This result is achieved by the extensive use of wood and vegetal materials in the building, that in the OBD database usually have negative values of carbon sequestration. In particular, the wooden elements sequester 95.88 tCO_2eq and the wood fibre insulation sequesters 28.13 tCO_2eq. All the values of the other materials are positive, but the total carbon emissions (49.84 tCO_2eq) is far inferior than the total carbon sequestration (-110.84 tCO_2eq). The materials that mostly contribute to carbon emissions are concrete (21.40 tCO_2eq) and steel (19.08 tCO_2eq). The GWP of the steel elements are particularly high considering that they make only 4% of the total weight of the building.

Despite being completely made of wood, the Brettstapel panels have a positive value. This element will be assessed in the following paragraphs.

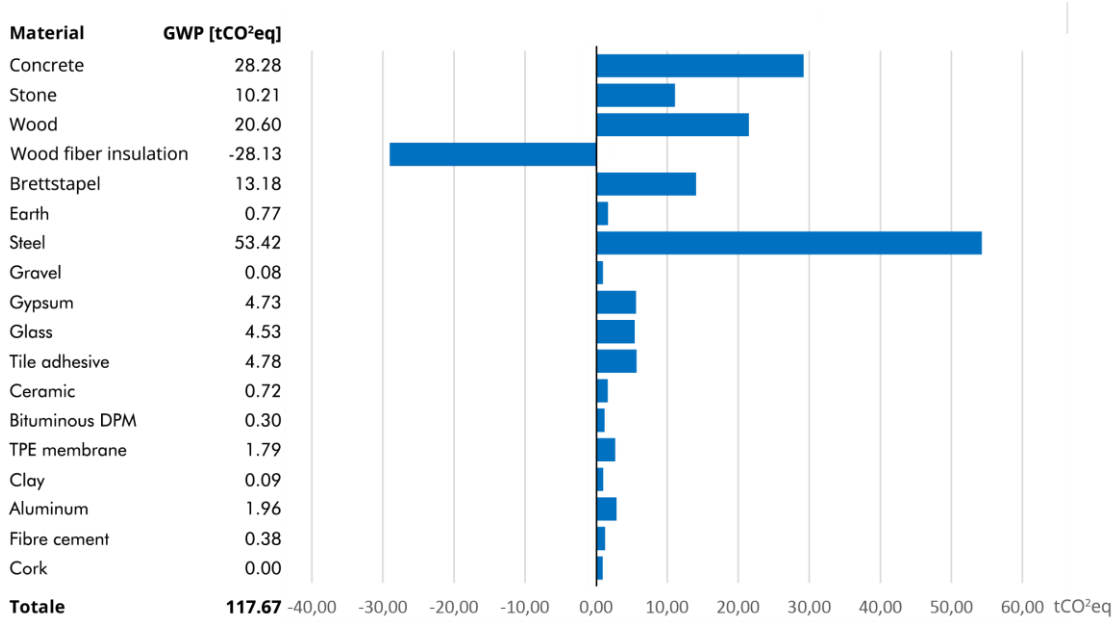
10.5 Embodied Energy and Carbons calculation with ICE

Material	**PEI [GJ]**	**Percentage [%]**
Concrete	203.11	4
Stone	182.67	4
Wood	591.80	12
Wood fiber insulation	2169.14	46
Brettstapel	525.89	11
Earth	14.38	<1
Steel	853.85	18
Gravel	1.29	<1
Gypsum	48.42	1
Glass	29.76	1
Tile adhesive	0.58	<1
Ceramic	11.12	<1
Bituminous DPM	46.45	1
TPE membrane	51.34	1
Clay	1.55	<1
Aluminum	33.26	1
Fibre cement	1.98	<1
Cork	0.03	<1
Total	**4766.63**	**100**



Tab. 4 PEI Values According to ICE

The total PEI value calculated with the ICE database is 4766628.78 MJ, or 4766.63 GJ. This means that there are 13,78 GJ/m^2. This result 11% lower than the values calculated with the OBD database. The similar results can be caused by the fact that in both calculations, the same PEI values from the EPD of the Brettstapel and the wood fibre insulation have been used. The use of the values from the EPD of the wood fibre insulation for both the ICE and the OBD calculations was deemed appropriate since it provides the right numbers for the specific product used in the building. This means a more accurate result in both calculations. On the other hand, the same values from the EPD of the Dowel Laminated Timber was used in both calculations because the databases don't have provide them. Since both materials make up a large portion of the volume of the house, they contribute to making the PEI results of the OBD and ICE calculations similar. However, it is interesting to see that the PEI value of the wooded elements (591.80 GJ) are much lower than the OBD values (1949.20 GJ). This is because the OBD database assumes that timber production requires more energy for forced air-drying process. This is probably not the case for all the wooden elements in Plummerswood, since most of the wood is sourced locally. On the other hand, the ICE values for the steel (853.85 GJ), concrete (203.11 GJ) are higher than the OBD values. There is also a particularly high difference in the OBD values of the aluminium (33.26 GJ in the ICE calculations, 0.02 GJ in the OBD calculations). Other materials vary a lot, but since they make up a very small part of the building, these variations don't affect the end result.



Material	GWP [tCO^2eq]
Concrete	28.28
Stone	10.21
Wood	20.60
Wood fiber insulation	-28.13
Brettstapel	13.18
Earth	0.77
Steel	53.42
Gravel	0.08
Gypsum	4.73
Glass	4.53
Tile adhesive	4.78
Ceramic	0.72
Bituminous DPM	0.30
TPE membrane	1.79
Clay	0.09
Aluminum	1.96
Fibre cement	0.38
Cork	0.00
Totale	**117.67**

Tab. 5 GWP values According to ICE

The total GWP value calculated with the ICE database is 117.67 tCO_2eq, or 0,32 tCO_2eq/m^2. This is a positive value, unlike the one calculated with the OBD database. The second version of the ICE database in fact does not include negative values of embodied carbons, also for vegetal materials. Nevertheless, the use of the GWP values from the EPD of the wood fibre insulation drastically lowers the total carbon sequestration. If the GWP of the ICE database had been used also for the insulation, the total result would have been much higher. In this case, using the correct value from the EPD helped giving more accurate results. Steel and concrete are again giving the highest contribute of carbon emissions. In particular, steel has the highest GWP of all (53.42 tCO_2eq).

10.6 EE and EC of Brettstapel

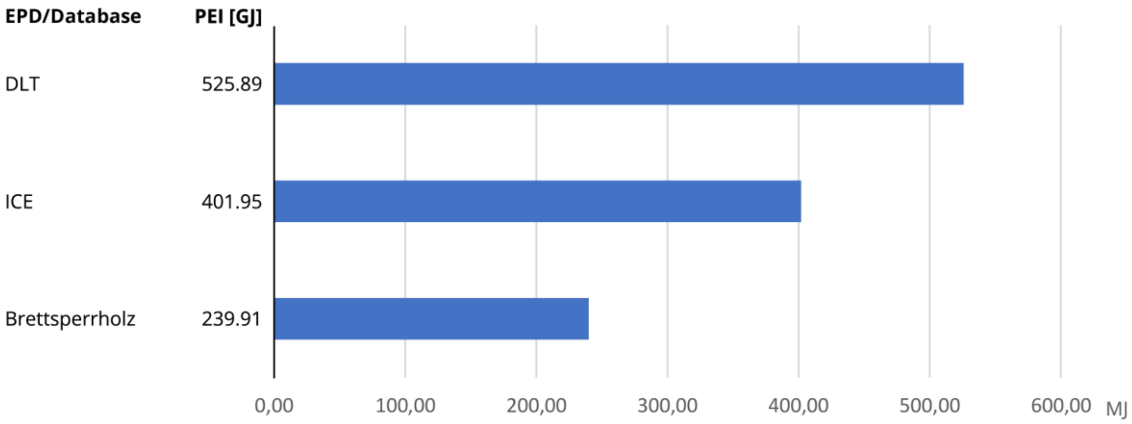
As mentioned above, there is a lack of knowledge regarding the embodied energy and carbons of Brettstapel. While this study calculated the PEI and GWP of the Brettstapel in Plummerswood using the EPD of the same product manufactured in Canada, Sandy Halliday (2015a) and Dilek Arslan (2019) have calculated the GWP with other different methods.

Halliday (2015a) calculates the carbon sequestration of all wooden elements the house as -243 tCO_2eq assuming that 1 kg of dry timber sequestrates 1.8 kg of CO_2. Following this method, the Brettstapel panels have a GWP value of -87.73 tCO_2eq.

Arslan (2019) on the other hand calculates the carbon sequestration of the panels using the ICE.V3 database using the values for softwood timber resulting in 0.033 tCO_2eq.

This study calculates a GWP of 13.18 tCO_2eq using the EPD of a Canadian manufacturer of Brettstapel systems (DLT). However, the PEI and GWP values for Brettstapel have also been calculated during this study using other sources. These sources are the ICE.V2 Database and the EPD for the *Brettsperrholz* (Thoma, 2014) panels by an Austrian manufacturer that produces cross-laminated timber panels using a dowel system similar to that of Brettstapel.

The comparison of the PEI values is shown in the following graph:



Tab. 6 PEI values comparison for Brettstapel

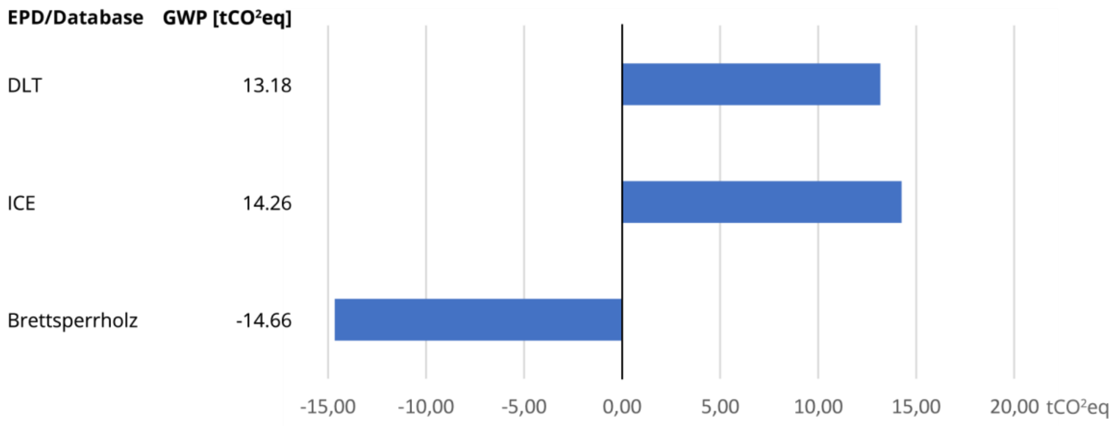
The PEI value of Brettstapel calculated with the Dowel Laminated Timber EPD is 525.89 GJ. That is 10% of the total PEI value calculated with OBD or 11% of the one calculated with ICE. This means that there are 15.63 GJ/m^2 according to the OBD calculations and 13.78 GJ/m^2 according to the ICE.

The PEI value calculated with the ICE.V2 database is 401.95 GJ. That is 8% of the total PEI value calculated with OBD or 9% of the one calculated with ICE. This means that there are 15.27 GJ/m^2 according to the OBD calculations and 13.42 GJ/m^2 according to the ICE.

The PEI value calculated with the EPD of the Brettsperrholz panels is 239.91 GJ. That is 5% of the total PEI value calculated both with OBD and ICE. This means that there are 14.80 GJ/m^2 according to the OBD calculations and 12.95 GJ/m^2 according to the ICE.

This comparison shows that the values can vary according to the chosen database/EPD. The results calculated with the ICE and DLT are similar, while the ones calculated with the Brettsperrholz EPD are inferior. The higher value for DLT panels is due to the fact that in Canada, the energy vectors in the manufacturing process can be substantially different to the European ones. On the other hand, it could be assumed that the energy vectors used for Brettsperrholz are similar to the ones for the Brettstapel panels, since both are produced in Austria. However, Brettstapel and Brettsperrholz are two different kind of panels, even if they are both glueless and use only timber.

The comparison of the GWP values is shown in the following graph:



Tab. 7 Comparison of GWP values for Brettstapel

The GWP value of Brettstapel calculated with the EPD of the Dowel Laminated Timber panels is 13.18 tCO_2eq. This means that in total there are -0.18 tCO_2eq/m^2 according to the OBD calculations and 0.34 tCO_2eq/m^2 according to the ICE calculations.

The GWP value of Brettstapel calculated with the ICE.V2 database is 14.26 tCO_2eq. In total there are -0.17 tCO_2eq/m^2 according to the OBD calculations and 0.34 tCO_2eq/m^2 according to ICE. The results obtained using the values of the DLT panels and ICE database are almost identical.

On the other hand, the values calculated with the EPD of the Brettsperrholz are negative. Its GWP is in fact -14.66 tCO2eq and in total there are -0.26 tCO_2eq/m^2 with the OBD calculations and 0.26 tCO_2eq/m^2 with the ICE calculations.

10.7 Comparison with other case studies

		Area	Weight	EE (OBD)			EE (ICE)			GWP (OBD)			GWP (ICE)		
		[m2]	[kg]	MJ	MJ/m2	MJ/kg	MJ	MJ/m2	MJ/kg	kgCO2eq	kgCO2eq/m2	kgCO2eq/m2	kgCO2eq	kgCO2eq/m2	kgCO2eq/kg
1	Hirose House	114	106.880	196.714	1.726	1,84	46.891	411	0,44	-19.535	-171	-0,18	2.804	25	0,03
1(r)		114	81.637	196.714	1.726	2,41	46.891	411	0,57	-19.535	-171	-0,24	2.804	25	0,03
2	Cheia	23	25.738	119.697	5.204	4,65	41.458	1.803	1,61	-12.665	-551	-0,49	6.055	263	0,24
2(r)		23	21.744	119.697	5.204	5,50	41.458	1.803	1,91	-12.665	-551	-0,58	6.055	263	0,28
3	Casa Steila Mar	572	911.500	2.098.102	3.668	2,30	1.017.282	1.778	1,12	-104.428	-183	-0,11	71.055	124	0,08
3(r)		572	204.818	2.098.102	3.668	10,24	1.017.282	1.778	4,97	-104.428	-183	-0,51	71.055	124	0,35
4	Sandberghof	411	469.598	1.522.870	3.705	3,24	1.129.233	2.748	2,40	-34.911	-85	-0,07	78.847	192	0,17
4(r)		411	305.981	1.522.870	3.705	4,98	1.129.233	2.748	3,69	-34.911	-85	-0,11	78.847	192	0,26
5	Villa Strohbunt	103	106.864	152.943	1.485	1,43	43.035	418	0,40	-47.906	-465	-0,45	22.360	217	0,21
6	Createrra	65	166.427	802.515	12.346	4,82	870.105	13.386	5,23	-14.701	-226	-0,09	43.971	676	0,26
7	Gartist	125	343.872	2.870.826	22.967	8,35	1.462.162	11.697	4,25	-130.775	-1.046	-0,38	110.330	883	0,32
8	Hemp cottage	76	129.560	575.343	7.550	4,44	455.543	5.978	3,52	15.990	210	0,12	34.003	446	0,26
9	Bamboo Ark	176	29.460	253.430	1.440	8,60	253.430	1.440	8,60	4.845	28	0,16	12.223	69	0,41
10	Biestøa	153	329.165	1.373.869	8.980	4,17	968.785	6.332	2,94	25.165	164	0,08	66.277	433	0,20
11	Food Hub	61	67.683	303.307	4.972	4,48	265.489	4.352	3,92	3.604	59	0,05	19.844	325	0,29
12	Wangeliner Garten	156	340.417	810.835	5.198	2,38	1.645.879	10.551	4,83	8.665	56	0,03	103.322	662	0,30
13	WISE	2.212	1.966.399	15.159.743	6.853	7,71	9.732.250	4.400	4,95	-178.197	-81	-0,09	687.557	311	0,35
14	Maruyama-gumi	183	276.623	1.412.038	7.716	5,10	1.205.822	6.589	4,36	9.941	54	0,04	96.973	530	0,35
15	Plummerswood	346	652.188	5.406.984	15.627	8,29	4.766.629	13.776	7,31	-60.996	-176	-0,09	117.673	340	0,18
Average values					6513	5,00		4863	3,53		-179	-0,15		321	0,24

Tab. 8 Summary of the case studies

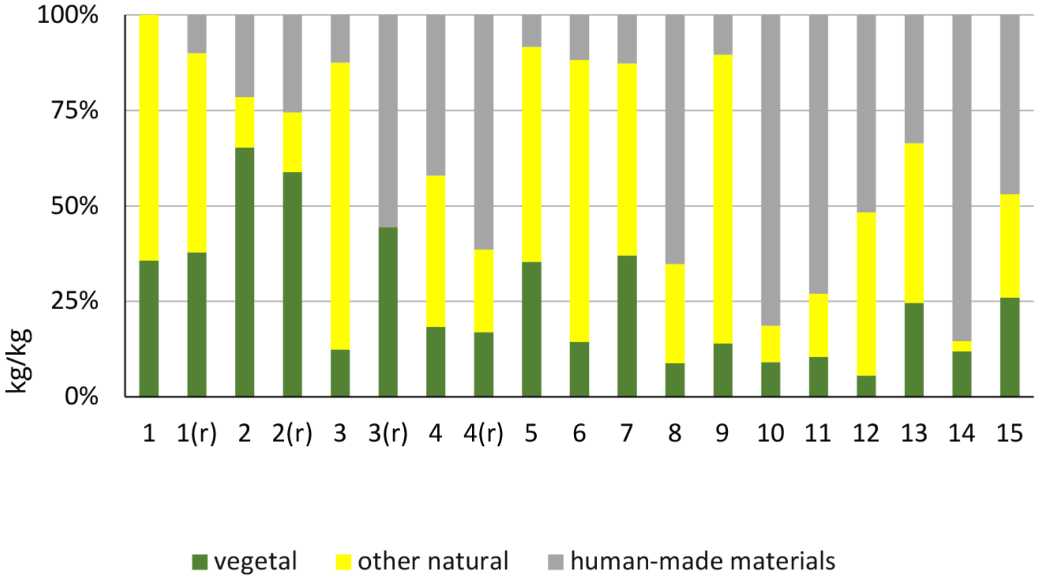
In this paragraph, the PEI and GWP values of Plummerswood will be compared with those of other buildings of high ecological value. It is useful to compare the numbers in order to contextualize the results. The comparison has been done with the 14 case studies from the book *Vegetarian Architecture* by Andrea Bocco (2020).

All the materials of these case studies have been analysed with the same process as this thesis and using the same databases. The materials have been grouped into three categories: materials with vegetal origins (green), other natural materials (yellow) and non-natural materials (grey). This grouping has been done in order to facilitate the comprehension of the graphs and to homogenize the data, since the building materials vary vastly. Since also the size of the buildings is variable, all indicators have been compared to their area and weight.

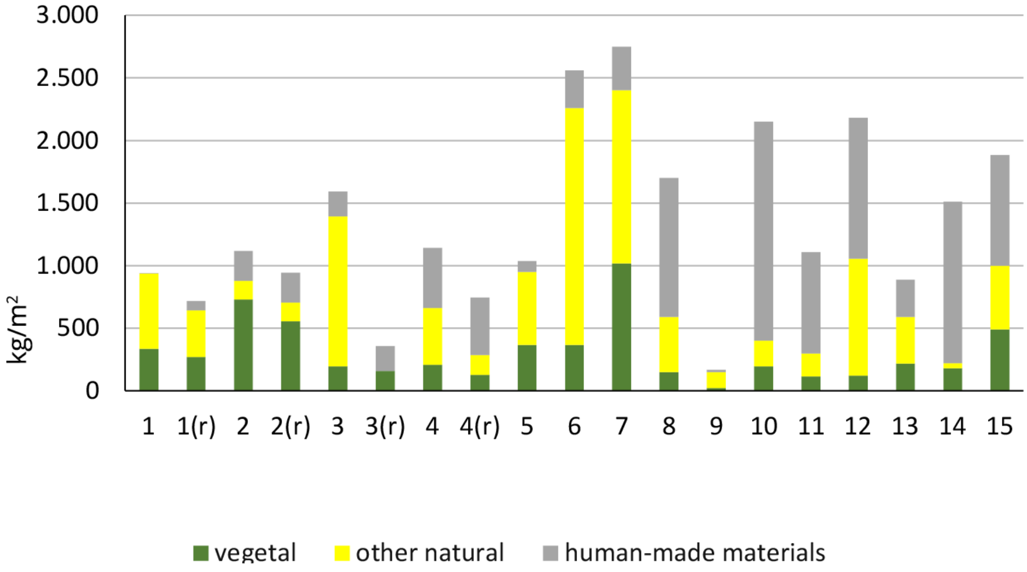
Plummerswood weighs 652188 kg or 1885 kg/m^2. The building is quite heavy but in line with most of the other buildings among the case studies. This is due to the fact that the load-bearing structure is made up of massive timber panels, as well as a large quantity of stone, which makes most of the weight of the natural materials of non-vegetal origin.

Looking at the structure of the case studies, it is clear that buildings with massive load-bearing walls (like straw bales, timber panels) are heavier than the ones that use a frame structure. For example, straw bales buildings (cases 6, 7, 10) weigh more than 2000 kg/m^2. On the other hand, frame structure buildings (cases 1, 4, 5) are more efficient, weighing about 1000 kg/m^2.

In the case of Plummerswood, the non-natural materials also make up a large part of the total weight because of the concrete foundations. Compared to other buildings with large concrete foundations, like case 10, the percentage of non-natural materials in Plummerswood is relatively small.

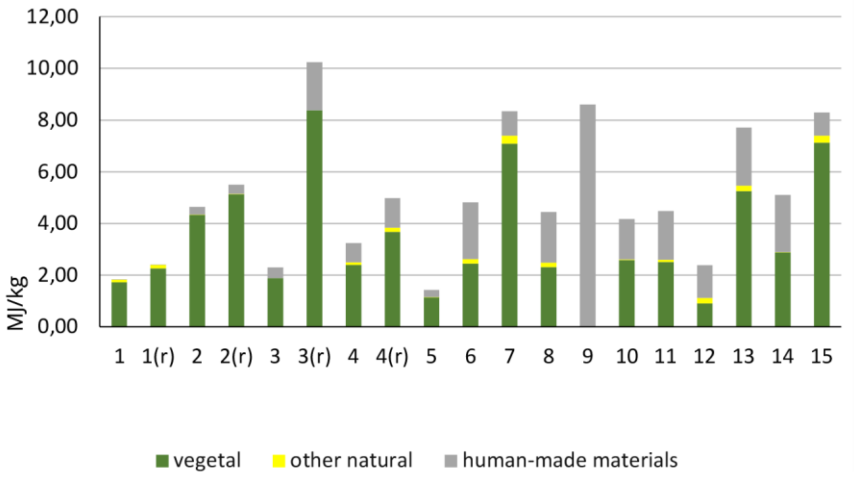


Tab. 9 Building weight by material classes [kg/kg]

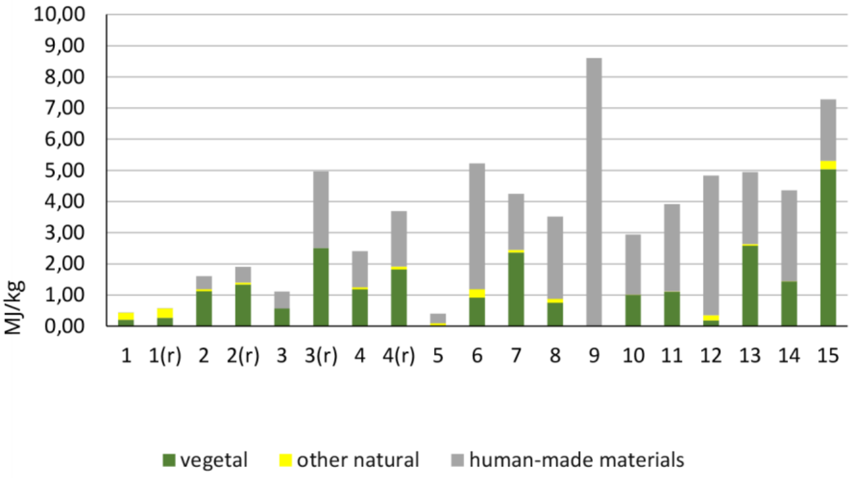


Tab. 10 Unit weight by surface area [kg/m^2]

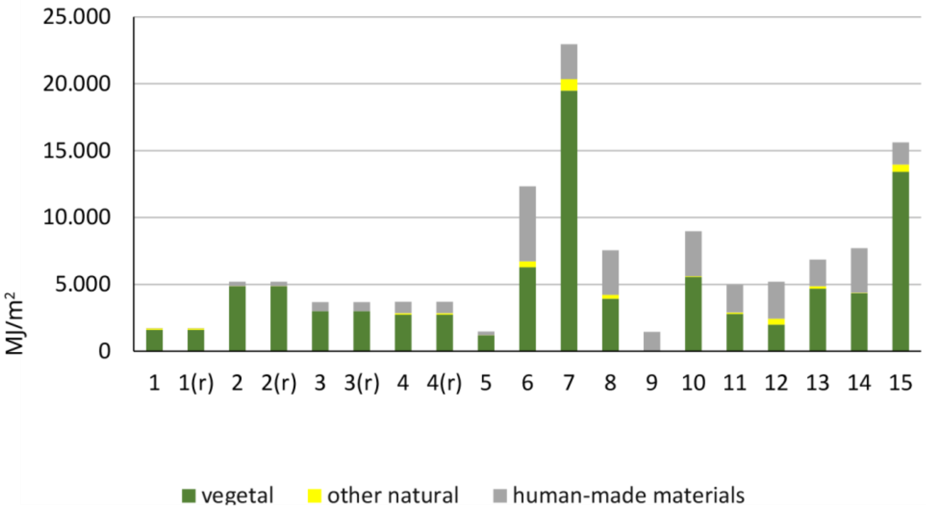
The average PEI value of the case studies are 5 MJ/kg (6513 MJ/m^2) for Ökobaudat and 3.53 MJ/kg (4863 MJ/m^2) for ICE. The lower values in the ICE results are expected since, as explained previously, OBD also considers the energy needed to mechanically treat and dry natural materials such as wood. The PEI values of Plummerswood are 8.29 MJ/kg and 15627 MJ/m^2 (OBD) and 7.31 MJ/kg and 13776 15627 MJ/m^2. These higher than average values are due to the large quantity of wood in the building compared to its weight and surface.



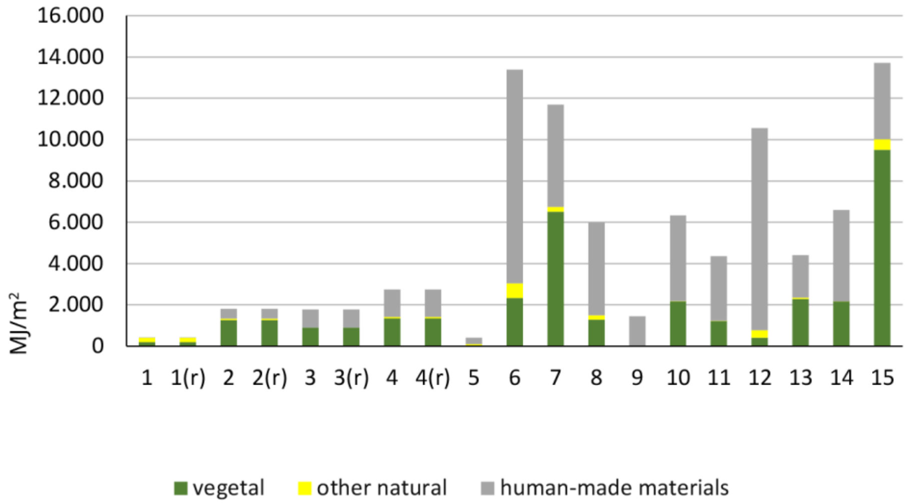
Tab. 11 PEI by weight [MJ/kg] - ÖBD



Tab. 12 PEI by surface area [MJ/m2] - ICE



Tab. 13 PEI by surface area [MJ/m^2] - ÖBD

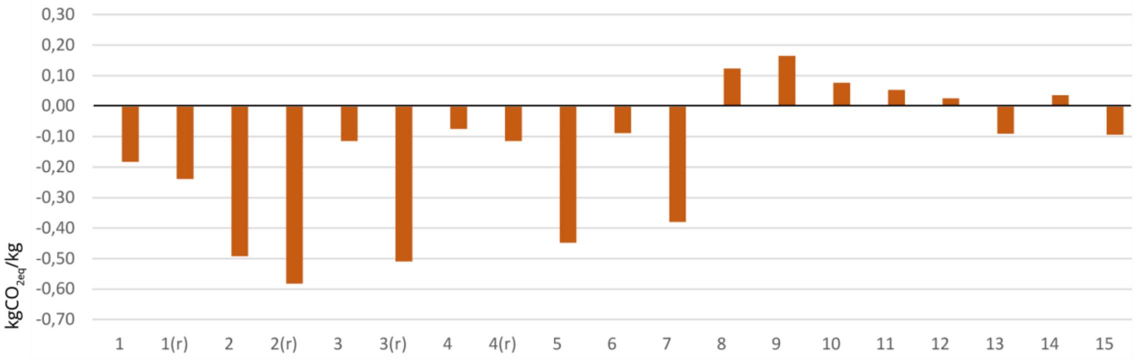


Tab. 14 PEI by surface area [MJ/m^2] - ICE

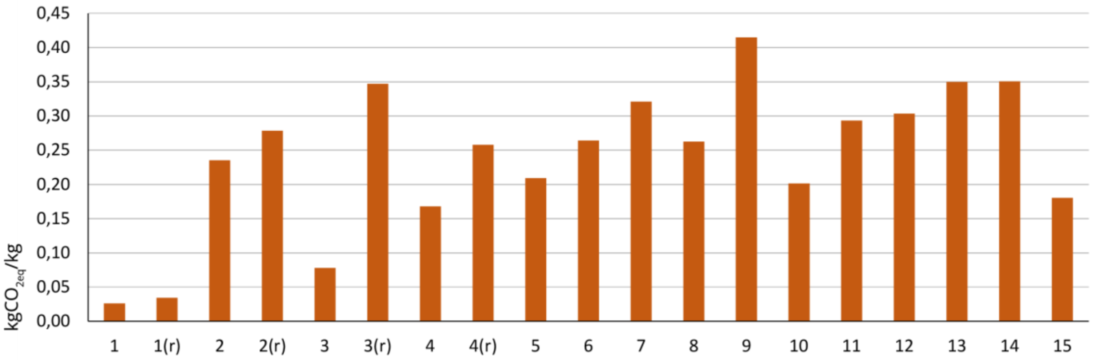
Using both databases. The largest quantity of EE is given by the large volume of vegetal materials. It is particularly interesting to see the difference of PEI values of the vegetal materials calculated with ICE between Plummerswood and the case studies. Plummerswood is much higher because once again, the values from the EPDs of the Brettstapel and the insulation have been used in all calculations.

Regarding the GWP, major differences can be seen between the values calculated with the OBD and the ICE databases. These differences are due to the fact that ICE.V2 does not have negative values for carbon sequestration, while Ökobaudat does. The average GWP value of the case studies are -179 tCO_2eq/m_2 (-0.15 tCO_2eq/kg) for Ökobaudat and 321 tCO_2eq/m_2 (0.24 tCO_2eq/kg) for ICE. These values compare well with those of Plummerswood, which are almost the same: -176 tCO_2eq/m_2 and -0.15 tCO_2eq/kg for OBD and 340 tCO_2eq/m_2 and 0.18 tCO_2eq/kg for ICE.

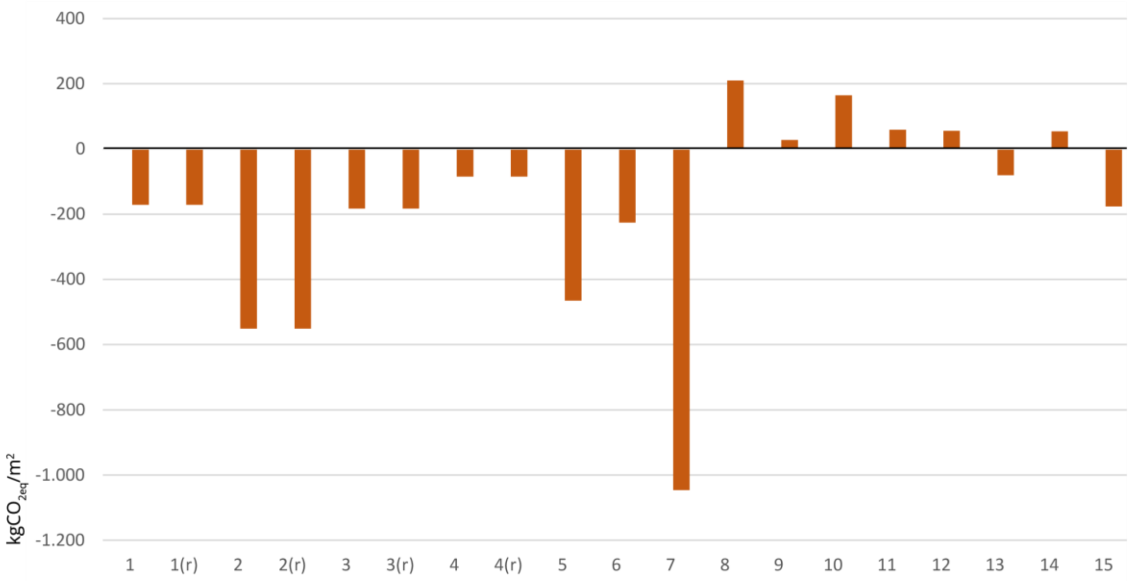
According to the OBD calculations and like most of the other case studies, Plummerswood has negative values of carbon emissions due to its large quantity of vegetal building materials. However, the impact of the carbon sequestration is reduced by the presence of large quantity of concrete.



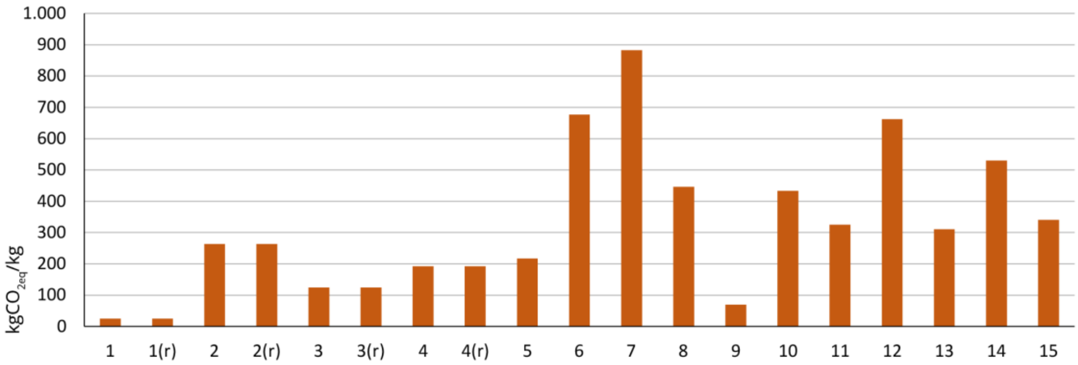
Tab. 15 GWP by weight [$kgCO_{2eq}/kg$] - ÖBD



Tab. 166 GWP by weight [$kgCO_{2eq}/kg$] - ICE



Tab. 177 GWP by surface area [kgCO$_{2eq}$/m^2] - ÖBD



Tab. 18 GWP by surface area [kgCO$_{2eq}$/m^2] - ICE

Conclusion

The large amount of material that was made available for this study made it possible to present a detailed description of the principles of eco-minimalism and how they are incorporated in the design of Plummerswood. These resources also allowed to quantify with precision the materials that make the building up and to produce a reliable 3D model. The calculation of the GWP of Plummerswood shows not only that the house has good ecological qualities, but also that the principles of eco-minimalism can be effective in lowering this indicator. When compared to the case studies of other highly ecological buildings such as the ones presented in the book *Vegetarian Architecture* (2020), the PEI and GWP values of Plummerswood compare well.

By using different databases and Environmental Product Declarations to calculate the Embodied Energy and Carbon, it becomes evident that the results may vary greatly depending on the source of the data. This means that the end results can be ‘adjusted’ using different databases to make the values look better or worse, undermining the objectivity of the analysis. The lack of reliable data for the Brettstapel panels made this issue particularly evident, and more research on this topic should be done. One way to resolve this problem could be to implement policies and laws to standardize the process and the databases at a national or European level. Making the publication of EPDs by the manufacturers mandatory could also be an effective way to make a change.

Overall, this thesis wants to show that a good theoretical basis, such as the one of eco-minimalism, can help to successfully design buildings with very high ecological standards, especially when accompanied with a high level of research and detailing as GAIA Architects have.

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