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Strawbale buildings as carbon sinks: influence of the design and construction process on carbon emissions

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Abstract. Strawbale buildings have drawn attention as a prime example of carbon storage using bio-based materials in construction. However, the question on how to efficiently use the potential of this material in the design and construction processes to achieve carbon negative buildings remains open. The reflections proposed in this paper arise from the comparative analysis of two case studies: Bombasei, a residential settlement located in the outskirts of Zurich, and Biotal, an organic farm shop in southern Germany. While both buildings are designed by Swiss architect Werner Schmidt and use the same materials, they present profoundly different design and construction processes. Bombasei is composed of three timber-framed strawbale buildings of four storeys each, meticulously designed and efficiently built, partly through prefabrication. Biotal is a single storey hybrid strawbale construction, mainly self-built by the staff: the design differs significantly from the as-built situation. We performed a systematic investigation based on verified sources to draw bills of quantities and 3D models representing as-built situations. The comparative Life Cycle Assessment, following EN15978 through Ecoinvent 3.9 database and SimaPro software, is limited to A1-A3 phases, to avoid assumptions and uncertainties. Carbon emissions were evaluated through IPCC2021, and biogenic CO_2 assessment followed EN 16449. The results show that the material production for both constructions has an overall low impact, with the main contributors being energy-intensive products. Biotal tends to perform better, and is a negative carbon building, mainly due to the choice of less-processed materials compared to Bombasei, which is a near net-zero construction. However, the use of large quantities of bio-based materials allows for the storage of significant amounts of biogenic CO_2 in both case studies. In conclusion, strawbale buildings have a regenerative potential for the built environment, suitable for both self-built and scaled-up constructions and adaptable to specific use scenarios.

1. Introduction

The general acknowledgement of the large portion of emissions produced by the construction sector has evidenced the urgent need to achieve carbon neutrality in the built environment, globally challenging a current unsustainable mainstream market and requiring radical changes in the industry [1–3]. The use of bio-based and other low carbon materials and the adoption of sustainable construction practices have been recognised to play a key role to achieving the challenge of energy efficiency and carbon neutrality and furthermore to building healthier indoor environments [4–11].

Strawbale buildings have been gaining more recognition in recent decades among the low carbon construction practices, encouraging interest and continuous development and innovation from researchers and practitioners of the field. This is due to the wide availability in extensive geographical areas, renewability and low cost of this agricultural by-product, coupled with its beneficial thermal and hygroscopic properties, as well as its low environmental impact and relatively simple construction technology [12].

In this paper we propose a comparative analysis on two case studies designed by Swiss architect Werner Schmidt, a well-established practitioner of strawbale construction [13–15]: Bombasei, an housing scheme in the outskirts of Zurich (figure 1), and Biotal, an organic farm shop in southern Germany (figure 2). The buildings present profoundly different design and construction processes: the first was meticulously designed and efficiently built, partly through prefabrication; the latter was mainly self-built by the farm's own staff, diverging significantly from Schmidt's design. Our objective is to analyse the influence of the design and construction method on the environmental savings potential of strawbale construction by quantifying the carbon footprint and biogenic CO_2 storage of the two case studies.

Figure 1. Bombasei housing settlement. Photo: Andrea Bocco, 2021.

Figure 2. Biotal organic farm shop. Source: Biotal Hofgemeinschaft blog, 2020.

1.1. Environmental impact of strawbale buildings

Building with strawbale has managed to slowly gain its own place in a sceptical and inertial construction market, mainly due to the environmental benefit of reducing the overall emissions of the buildings [12,16,17]. Firstly, straw serves as a 'carbon sink' due to its potential to store biogenic carbon. Secondly, its good thermal insulation value facilitates low emissions during the operational phase of the buildings. Lastly, its biodegradability, renewability, and non-toxicity work in favour of minimising significant environmental risks, such as resource depletion and dangerous waste generation, while furthermore facilitating the disposal at the end of life of the building, provided re-use or recycle is not possible. The properties of strawbale allow for flexibility in construction techniques and processes, ranging from in-situ load-bearing and non-loadbearing techniques to prefabricated panels [12,18–21]. This has allowed for a wider development and acceptance in different contexts, including self-built low-rise constructions, housing complexes and even public buildings. Although previous research has shown the low environmental impact of strawbale buildings compared to conventional ones [22–25], an analysis of the influence of the different ways of using this material on the overall environmental impact of the building would be useful to better understand its potential for achieving carbon neutral and even carbon negative buildings.

1.2. Life Cycle Assessment

Life Cycle Assessment (LCA) is a recognised and well-established methodology for comprehending and quantifying the environmental impacts of a product system throughout its life cycle. It is described by the standard series ISO 14040, and it is developed in four methodological steps: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment and (IV) interpretation of results. LCA is gaining attention and is being widely used in the construction sector. It serves as the base methodology for environmental declaration schemes like Environmental Product Declarations (EPDs) [26] and Product Environmental Footprint (PEF) [27]. It should however be noted that when applied to buildings, the process is not straightforward as for many other products – this is due to buildings' complexity, uniqueness, relatively long life, changes throughout the life cycle, unclarity of system boundaries, etc. [28]

1.3. Case studies

The case studies analysed in this paper are chosen from a list emerging from on-going research on ecologically oriented buildings that show not only efforts for a low impact on the environment but also awareness of ecological constraints and attempts to work for the regeneration of the ecosystems and the socio-economic systems they belong to [29–31]. While the case studies comply with several predefined criteria making them worthy of investigation, the reason for selecting Bombasei and Biotal lays in the similarities and at the same time distinctive features these buildings present. Both are designed by the same architect and use, to a great extent, the same materials; however, they present profoundly different design and construction processes.

1.3.1. Bombasei. Bombasei is a residential settlement located in Nänikon, in the outskirts of Zurich. The project was commissioned by Bombasei AG company who, after the demolition of their industrial facility, aimed at redeveloping the area as a multifamily housing. Schmidt won the tender designing a scheme composed of three longitudinal pitch-roofed buildings of four storeys each, circumscribing a T-shaped courtyard (figure 3). The buildings accommodate 28 housing units, six of which are four-storeys terraced individual houses and the rest range from studios to different sized apartments. The courtyard serves as a community place and as an access to ground-floor apartments, while two stairwells with integrated elevators allow the access to upper floors. A semi-private timber deck connects the apartments on the second floor and rests on spruce. On the outer side, the buildings open through large, glazed surfaces into small gardens and communal green areas.

Figure 3. Site plan of Bombasei, Nänikon. Scale 1:1500. Source: Atelier Werner Schmidt.

Initially, the architect conceived load bearing strawbale walls, but the time-consuming processes to obtain the permits led instead to timber modular panels encapsulating 75 cm thick bales for the walls. Renders are lime-based, while internal finishes are either cross-laminated larch panels or lime plaster laid on gypsum fibre boards. The ground floor structure replicates the straw-infilled wall modules, while the intermediate floors are cross-laminated timber panels topped by gravel, a layer of insulation and a concrete screed enclosed by a timber parquet. The openings are triple glazing in spruce frames, equipped with shading elements. The roof modules are composed of a cross laminated timber structure infilled with 76 cm thick straw insulation, with some mineral wool insulation laid next to the galvanised steel gutters, to comply with restrictive fire regulations. Battens and counter-battens hold the integral photovoltaic (PV) modules and hot water collectors that make up for the entire roofing. The underground parking and the stairwell are reinforced concrete. Figure 4 shows a detail of the main building elements.

The 68 prefabricated wall and floor modules were made in two phases: 1) frames were built from cross-laminated timber elements and infilled with straw insulation in Rohrbach/BE during the winter; 2) they were then transported to a rented factory in Langenthal, where they were completed with electrical installations and floor heating and plastered [32]. Larch elements on the façade evidence the joints between the modules. Assembly on site took five weeks for each building. Works were completed in 16 months from the demolition of the old factory to the first tenants moving in.

The energy consumption of the complex is very low; hot water and lift operation are higher in billing than heating. The PV system has an output of 80 to 90 kW peak and feeds the heat pump, generating in-house energy. *[32–40]*

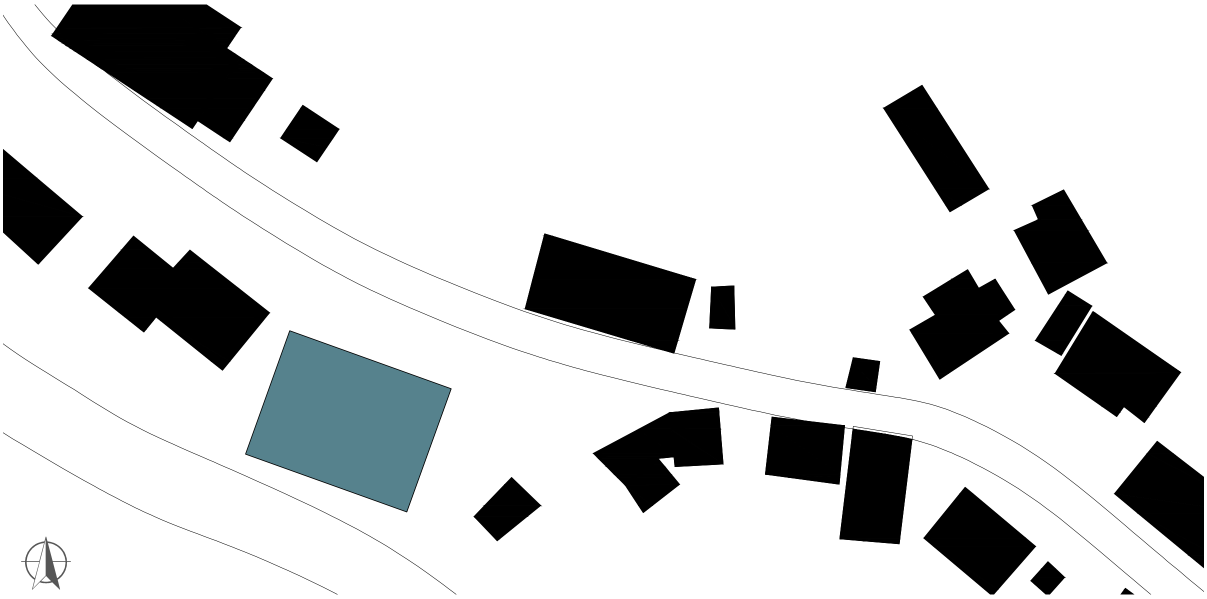

Figure 5. Site plan of Biotal, Eselsburg. Scale 1:1500.

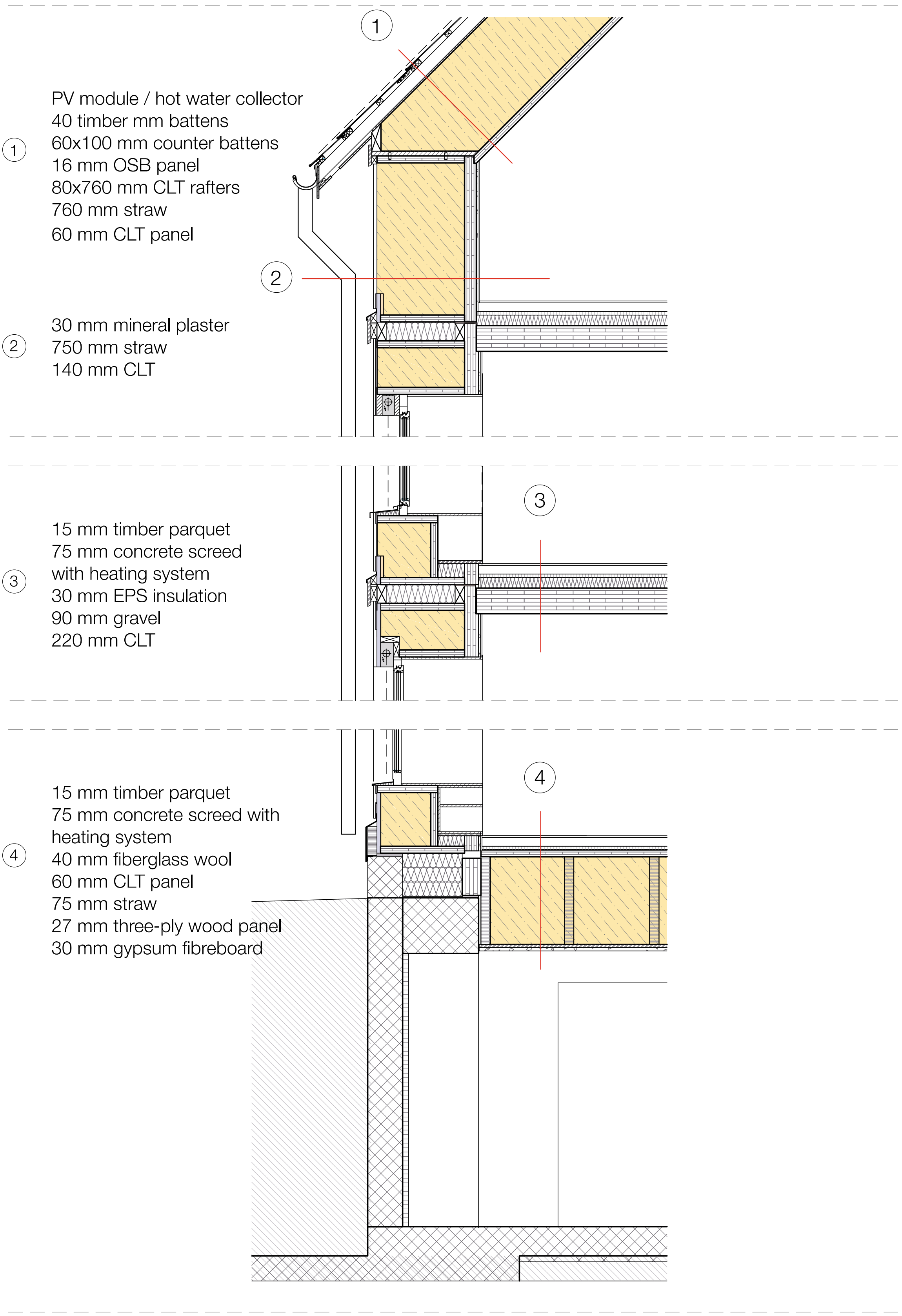

Figure 4. Section of Bombasei external wall. Scale 1:50. Source: Atelier Werner Schmidt.

1.3.2. Biotal. The Biotal building is an organic farm shop located on the banks of the Brenz River in the Eselsburg Valley in southern Germany (figure 5). It is owned and managed by Biotal – an organic farming company that was planning a new commercial building that was to be as energy self-sufficient as possible, made of materials from their own property or the vicinity, and built by the employees themselves. One of the members came across a strawbale house while leafing through a magazine. A meeting with Werner Schmidt and a visit to some of the strawbale houses he had built were arranged, and this made the decision.

The result is a single storey construction with a rectangular floor and a green curved roof overhanging for 4,5 m all around it and opening wide towards the entrance. Along the walls runs a gallery that hosts offices and restaurant spaces in the mezzanine, and toilets, kitchen, scullery, and meat preparation rooms on the ground floor. The central space accommodates the store and is free of partitions so to highlight the impressive logs that support the roof; it is flooded with natural light from a large skylight. A winter garden partially closes the terrace facing the Brenz on the south, and mechanical rooms are attached to the east.

The external walls consist of 120 cm wide jumbo straw bales placed on top of each other. Seventeen floor-to-ceiling windows and two wide doors have larch frames and triple glazing. The finishings consist of clay plaster sprayed layers. The internal columns are manually debarked logs, as are the terrace columns. The designer would have preferred to have only strawbales as structural elements, but, as the regulations in Germany do not allow this, the result is a hybrid construction. The ceiling is made of juxtaposed small logs that are left visible from below; a layer of light-earth (clay and wood chips mix) is laid on top to facilitate the laying of 70 cm thick strawbales fastened with wooden dowels to an upper timber board. Battens create a ventilation gap and support a green roofing. The edges are finished up with a layer of gravel upon which PV panels are positioned. Partition walls are rammed earth infilled within timber studs, as is the spiral staircase of the western gallery. Finishes differentiate in accordance with the function of the spaces: limestone tiles are used in the lower portions of the bathroom walls, linoleum in the kitchen; the rest is clay plaster. The foundations are in reinforced concrete cast on compacted gravel and foam glass, necessary due to the adjacent river. The winter garden walls consist of light-earth cast within a timber frame and are completed with a ventilated timber cladding up to the windows level. The ash decking rests on compacted foam glass laid on gravel. Figure 6 shows a detail section of the main building elements.

The store was inaugurated in November 2019, after approximately four and a half years' work. Most of the work was carried out by the farm staff. The 25 kW_p PV panels are completed by a battery storage system because of the high demand from the lighting of the products on sale. However, self-production is not enough to meet the consumption. Particular attention was paid to the cooling of the food: a tailor-made refrigeration system burns propane and is controlled through a series of sensors and displays. The heat pump supplies domestic hot water through a buffer storage tank and heating through almost 2 km of hose placed in the screed and in the winter garden wall. However, heating is rarely needed in the main building: during the first two winters, for instance, it was not used at all. *[41–45]*

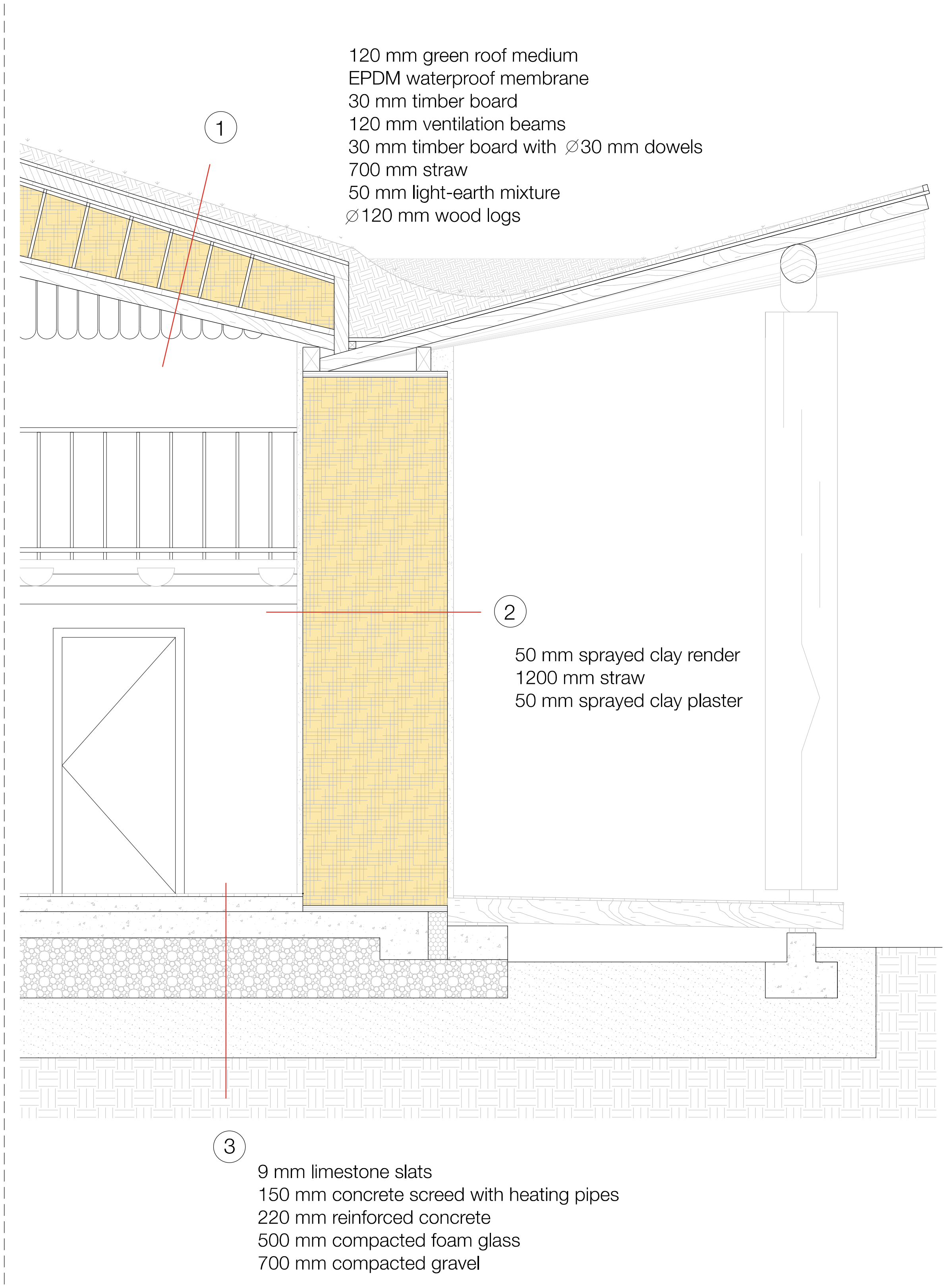

Figure 6. Section of Biotal external wall, entrance façade. Scale 1:50.

2. Data and methods

The technical and constructional features of each building were meticulously investigated based on verifiable resources. Both case studies were the object of exercises for the students of the Low Impact Technology master degree course at Politecnico di Torino during the first semester of the academic year 2022/23, who carried out a basic data investigation process and partial analysis [46]. Based on these first data, the Bombasei settlement was further explored as a master thesis topic at ETH Zurich by Joy Arockiam under the supervision of prof. dr. Guillaume Habert and Yasmine Priore, who kindly shared their data and results with us [40]. The data research was completed by the authors, as were the analyses presented in this paper. Site visits and communication with the architect and the owners/builders helped complete the data. The aim was to develop a comparative analysis of the design and construction processes involved, and to assess the associated life cycle impacts, so to correlate the former with the latter.

2.1. Data investigation and inventorisation

The different design and construction process of the two buildings is reflected in the data investigation process. The documentation kindly provided by the architect for Bombasei is highly detailed, as includes Building Information Modeling (BIM) 3D models and an extensive set of drawings. A comparison with site photos shows that the project differs very little from the as-built situation.

On the contrary, although the overall concept has remained loyal to the architect, project drawings for the Biotal building are significantly different from the as-built situation and details are erratically represented in a few shop drawings provided by the client. However, we managed to draw up a 3D model of the as-built situation with a very low degree of uncertainty, owing to numerous blog entries posted by the owners that illustrate through photos and short descriptions the construction process from 2015 and 2020 [44]. Missing technical details were completed through inquiries and a site visit.

The life cycle inventories (LCIs) for both buildings are drawn up from inventories extracted from the 3D models of the as-built situation.

2.2. LCA framework and boundaries

The framework developed for the LCA of the case studies follows the ISO 14040 norm [47]. The life cycles stages considered are A1 to A3 (‘cradle to gate’) as described by the EN 15978 norm, covering the production of the construction materials [48]. The transport (A4) and construction phases (A5) are excluded due to the lack and/or uncertainty of data. The use stages are excluded from the assessment mainly due to the difficulty to obtain first hand data and to their dependency on building use patterns, which are quite different for the selected buildings – the first one being residential and the latter commercial. End of life hypotheses are also excluded from the boundaries of this study. Building services are excluded due to their difficult quantification [49]. Reused building components are included in the inventories, but their impacts are not accounted for, based on the principle whereby the impacts associated with the production of construction components are attributed to the first use.

Calculations were performed through the SimaPro software [50], using Ecoinvent 3.9 [51] as the reference database and implementing the evaluation method IPCC2021 [52]. The impact category chosen was the Global Warming Potential 100a (GWP100), producing results in kgCO_2eq. The datasets selected are either representative of the context (Switzerland for Bombasei and Germany for Biotal) when available; or of European averages (RER). The biogenic CO_2 was calculated by defining specific carbon and water contents for each bio-based source, as of the EN 16449 methodology [53]. The impact was first calculated in absolute values, that is taking the building as the functional unit (FU), to assess the regenerative potential of each construction. To normalise the impact evaluation and thus compare the two case studies, relative values are presented per square metre of gross internal area (GIA) and per kilogram of building weight, in line with recommendations in literature [54–57]. Other commonly used FUs were discarded: per capita values due to the different function of the two buildings; per year and other time derived FUs for the above-mentioned reasons that led us to consider stages A1 to A3 only.

3. Results

The results of the comparative LCA are presented in figure 7.

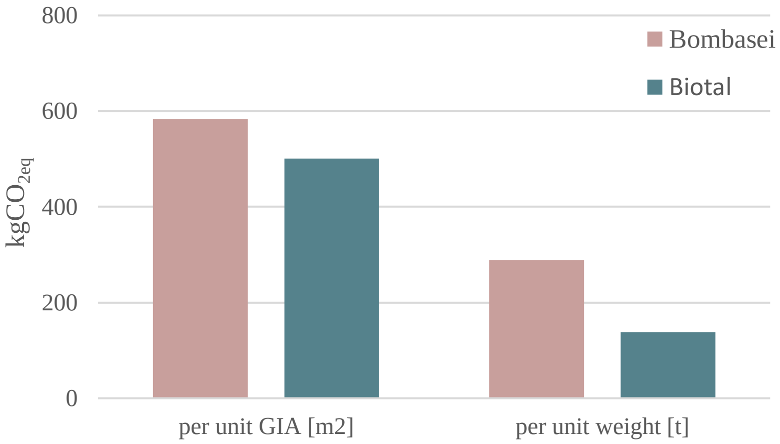

Figure 7. Carbon footprint (stages A1-A3) excluding the contribution of sequestered carbon per unit GIA (m^2) and per unit weight (t)

The results of the calculation of the biogenic CO_2 stored in the bio-based materials of each construction are presented in figure 8.

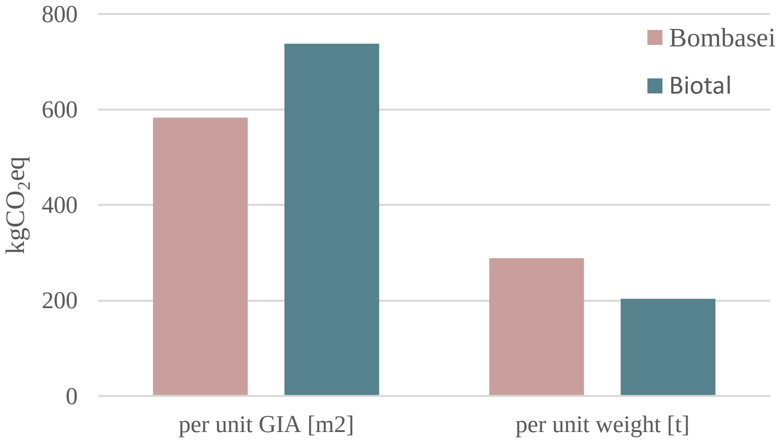

Figure 8. Biogenic carbon sequestered in the building materials per unit GIA (m^2) and per unit weight (t)

By converting the results of the biogenic storage to $kgCO_2eq$ following the IPCC method [52] and by summing up with the result with the carbon footprint, we obtained the CO_2 balance of each case study (figure 9). Biotal is net negative both in reference to the unit area and the weight, respectively -235,9 $kgCO_2eq/m^2$ and -65,1 $kgCO_2eq/t$; while Bombasei is a near-net zero building with a CO_2 balance of 0,4 $kgCO_2eq/m^2$ and 0,2 $kgCO_2eq/t$.

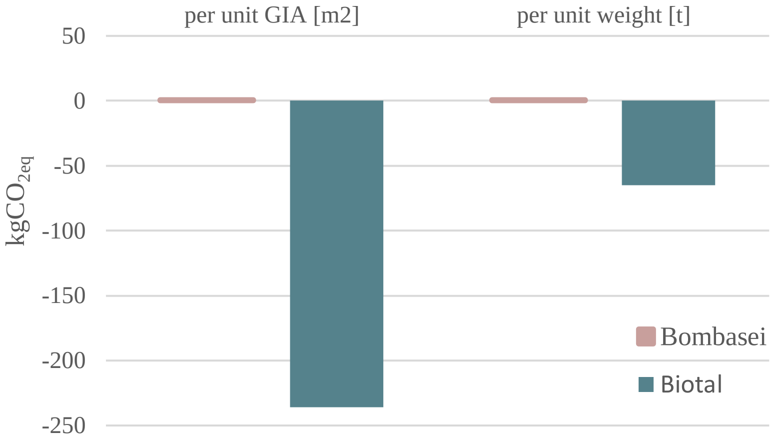

Figure 9. CO_2 balance per unit GIA (m^2) and per unit weight (t)

4. Discussion

4.1. Reflections on the environmental impact results

One of the limits of our analysis is the comparison of the results with other studies: the low degree of harmonisation of systematic reviews of the environmental impact of buildings does not offer reliable benchmarks [30,58,59]. However, for the studied life cycle stages, Bombasei results a near-net zero building while Biotal is net-negative, which per se is a remarkable environmental performance. In terms of biogenic carbon stored within the building materials, the results are close for both case studies. In fact, the difference in the overall results is to be attributed to the positive component of the GWP emissions, which is significantly higher in the case of Bombasei. To better understand this, we delved further into the choice of materials, aggregating the building materials into three macro-categories – bio-based, other natural and other – and quantifying the contribution of each category to the total building weight (figure 10). The materials in the 'other natural' category are of mineral origin and have undergone little processing. All materials that have undergone energy-intensive processing and chemical reactions are contained in the 'other' category. The results are consistent: both buildings have a high quantity of bio-based materials, which are responsible for the carbon storage; however, this is balanced out by the high proportion of 'other' materials in Bombasei – for instance the concrete screeds, synthetic insulation layers and membranes used also above grade. In Biotal, the low amount of 'other' materials and the low impact of 'other natural' materials employed, such as the considerable amounts of clay, are such that they do not even out the carbon storage.

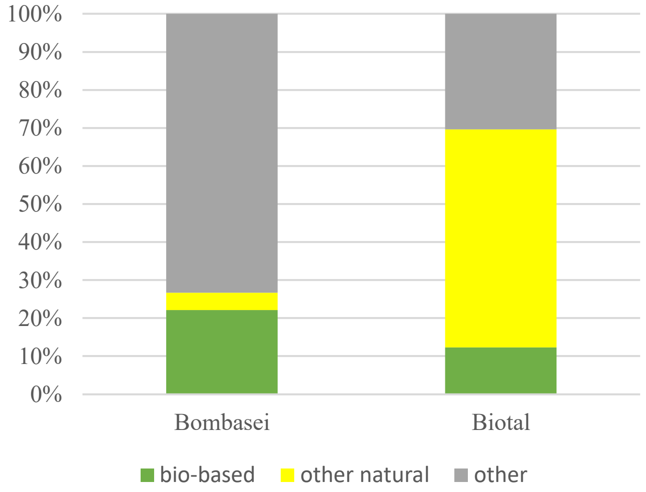

Figure 10. Building weight contribution by material category.

To better understand the results, we performed a contribution analysis by subdividing the constructions into their main parts (figure 11). The main reason behind this is because we had assumed that the foundations would have the higher contribution on the overall impact for both case studies, since it is where the more high-processed materials are located. In both cases the impact is relevant: however, it is decisive in the case of Biotal, while for Bombasei, the biggest contribution to the carbon footprint is given by the above-grade construction. Think for instance at the considerable difference between high-performance new windows, which sometimes extend on large glazed surfaces, in the latter, as opposed to a number of salvaged windows in the first *(see 4.2)*.

Figure 11. Building parts' contribution to the carbon footprint, excluding the contribution of sequestered carbon

4.2. Influence of the context on the choice and processing of materials and building components

The divergence of results is mainly to be attributed to the different contexts and requirements for the design and the construction, resulting in a different degree of processing of the chosen materials: in Bombasei the materials are often more processed, resulting in a higher impact. 'Ready-made' products, such as pre-mixed mortars, were used to a greater extent. The most exemplary case is timber: in Bombasei engineered timber was used for the prefabricated elements (figure 12), and although cross-laminated timber elements were glue free, they underwent a heavier processing (kiln drying). On the contrary, in Biotal all timber elements, except for new window frames, were made on site and are less processed: for instance, log columns were manually debarked (figure 13); cylindrical timbers were sown on site with a special machine attached to a tractor. Waste was minimal: offcuts were creatively used to make furniture and wood chips became part of light earth mixes.

Figure 12. Prefabrication of wall modules for Bombasei. Photo: Damian Poffet, 2019

Figure 13. Manual debarking of wooden logs at the Biotal site. Source: Biotal Hofgemeinschaft blog, 2015

The slow time of construction and the continuous adaptation of the Biotal project also allowed for reuse: all internal windows, doors and frames were retrofitted and completed with new glazing; the winter garden windows were salvaged from a nearby dismissed building. At Bombasei, there was an intention to recycle concrete from the pre-existing building, however this was not implemented probably due to the tight construction schedule.

5. Conclusions

In this paper, we studied two straw-bale buildings – Biotal and Bombasei – for the life cycle stages A1 to A3. The use of a large quantities of bio-based materials has allowed for the construction of near net-zero buildings. Moreover, the calculations of the biogenic carbon show their regenerative potential, which is more evident in the case of Biotal – a building that shows a net-negative balance for the studied life cycle stages. While building with straw bales has intuitively a lower environmental impact compared to conventional construction, this is only backed up by a few full building LCA assessments found in literature [22–25]. Moreover, the aim of the study was to deepen the understanding of the environmental impact when a similar building technique is employed, as it is our view that amidst the current climate emergency we should go beyond "lower than usual" and aim at regenerative solutions. This investigation was possible due to the extensive documentation available and its high degree of certainty, which allowed for a meticulously detailed inventory of each building component. In fact, despite using similar building techniques and, to a certain extent, the same materials, the difference in the brief and the subsequent design and construction choices are reflected in the environmental impact. While the attention to low-impact building choices is commendable in both cases, Bombasei is a commercial operation – a building to be sold to an upper middle-class market – while Biotal is a store built for the client's own use. In the first case, this has led to privilege a highly efficient design and construction process, which was in turn reflected by compromises in the choice of materials, often at the expense of more environmentally friendly materials which are, in the current market conditions, less standardised and more challenging than their conventional equivalents. In the second case, the self-built slower process has allowed for the use of less processed materials and even reused components often sourced from the surroundings: while this was mainly due to practical reasons, it definitely worked in favour of a lower impact, as demonstrated by the final results.

It is also important to underline that the environmental impact of the two case studies would have been much lower, had there been different technical choices for the foundations, which contribute significantly to the overall emissions of both buildings. While in the case of Biotal, the use of considerate amounts of high-impact materials below grade was a necessity due to the proximity of a river, in Bombasei the underground garage showcases a conventional lifestyle choice. Both cases, however, evidence the need for more research for alternative foundations with a lower impact, on one hand; and the need to reflect on how lifestyle choices impact on the environment, on the other.

Further research is needed to calculate the impacts of the construction phase (A5) form first-hand sources to track the influence of the different ways of building, especially between building on site and pre-fabrication. However, despite the different design and construction approaches and their reflection on the buildings' environmental impacts, considering different contexts and use scenarios, we can conclude that overall results are satisfying for both case studies – showing a flexible adaptation of straw-bale building for both small projects and scaling up. In this regard, it is worth noting that the value of Bombasei's embodied carbon is such to make it one more exemplar case of scaled up straw-bale construction. A growing catalogue [60–66] challenges prejudices and regulatory restraints that tend to limit this technique to small scale buildings.

Acknowledgements

First-hand data on the case studies were generously provided by architects Werner and Paul Schmidt, who welcomed us in their atelier and patiently answered to our inquires on the design and construction processes. Further data on the construction of Biotal were provided by Christoph Bosch during a site visit in November 2021 and follow-up online communication. Basic data investigation was carried out by students of the Low Impact Technology master's degree course at Politecnico di Torino during the academic year 2022/23. The inventories for Bombasei were completed and kindly shared with us by

Joy Arockiam in the framework of his master thesis developed at ETH Zurich under the supervision of prof. dr. Guillaume Habert and Yasmine Priore. The BIM 3D model for Biotal was elaborated by José Luis Reyes. The calculation of the carbon footprint was carried out in the LaSTIn lab of the Department of Architecture and Design (DAD) at Politecnico di Torino.

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