Fair Play: Why Reliable Data for Low-Tech Construction and Non-conventional Materials Are Needed

The Urban Book Series

Eugenio Arbizzani · Eliana Cangelli · Carola Clemente · Fabrizio Cumo · Francesca Giofrè · Anna Maria Giovenale · Massimo Palme · Spartaco Paris *Editors*

Technological Imagination in the Green and Digital Transition

OPEN ACCESS

Springer

The Urban Book Series

Igor Vojnovic, Department of Geography, Michigan State University, East Lansing, MI, USA

Claudia Yamu, Department of Built Environment, Oslo Metropolitan University, Oslo, Norway

Qunshan Zhao, School of Social and Political Sciences, University of Glasgow, Glasgow, UK

The Urban Book Series is a resource for urban studies and geography research worldwide. It provides a unique and innovative resource for the latest developments in the field, nurturing a comprehensive and encompassing publication venue for urban studies, urban geography, planning and regional development.

The series publishes peer-reviewed volumes related to urbanization, sustainability, urban environments, sustainable urbanism, governance, globalization, urban and sustainable development, spatial and area studies, urban management, transport systems, urban infrastructure, urban dynamics, green cities and urban landscapes. It also invites research which documents urbanization processes and urban dynamics on a national, regional and local level, welcoming case studies, as well as comparative and applied research.

The series will appeal to urbanists, geographers, planners, engineers, architects, policy makers, and to all of those interested in a wide-ranging overview of contemporary urban studies and innovations in the field. It accepts monographs, edited volumes and textbooks.

Indexed by Scopus.

Eugenio Arbizzani · Eliana Cangelli ·
Carola Clemente · Fabrizio Cumo ·
Francesca Giofrè · Anna Maria Giovenale ·
Massimo Palme · Spartaco Paris
Editors

Technological Imagination in the Green and Digital Transition

Springer

Editors
Eugenio Arbizzani
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Eliana Cangelli
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Carola Clemente
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Fabrizio Cumo
Dipartimento Pianificazione, Design,
Tecnologia dell'Architettura
Sapienza University of Rome
Rome, Italy

Francesca Giofrè
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Anna Maria Giovenale
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Massimo Palme
Departamento de Arquitectura
Universidad Técnica Federico Santa Maria
Antofagasta, Chile

Spartaco Paris
Dipartimento di Ingegneria Strutturale e
Geotecnica
Sapienza University of Rome
Rome, Italy

ISSN 2365-757X ISSN 2365-7588 (electronic)
The Urban Book Series
ISBN 978-3-031-29514-0 ISBN 978-3-031-29515-7 (eBook)
https://doi.org/10.1007/978-3-031-29515-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Chapter 33
Fair Play: Why Reliable Data for Low-Tech Construction and Non-conventional Materials Are Needed

Redina Mazelli, Martina Bocci, Arthur Bohn, Edwin Zea Escamilla, Guillaume Habert, and Andrea Bocco

Abstract The paper proposes considerations stemming from the analysis of twenty-two buildings that show different approaches to 'vegetarian architecture'—a theoretical stance based on principles learnt from agriculture and nutrition. The first phase consisted in a systematic investigation of the constructional characteristics of each building, and the cataloguing of their components. The 'cradle to gate' embodied energy (EE) and 'embodied carbon' (EC) were then calculated, based on two open access databases: ICE and Ökobaudat. The applicability of these databases was considered, as they do not cover low industrialised bio-based construction materials. For some materials, data are missing; while in others, EE values are overestimated since high energy-intensive manufacturing processes seem to be assumed. In a second phase, the uses and production process of some non-conventional materials was investigated, evidencing their variability. Building technologies that are not just aimed at low operational energy but at a more holistic understanding of low

R. Mazelli (✉) · M. Bocci · A. Bohn · A. Bocco
Polytechnic University of Turin, Turin, Italy
e-mail: redina.mazelli@polito.it

M. Bocci
e-mail: martina.bocci@polito.it

A. Bohn
e-mail: arthur.bohn@polito.it

A. Bocco
e-mail: andrea.bocco@polito.it

E. Zea Escamilla · G. Habert
ETH Zürich, Zürich, Switzerland
e-mail: zea@ibi.baug.ethz.ch

G. Habert
e-mail: habert@ibi.baug.ethz.ch

E. Arbizzani et al. (eds.), *Technological Imagination in the Green and Digital Transition*, The Urban Book Series, https://doi.org/10.1007/978-3-031-29515-7_33

environmental impact represent a paradigm shift in 'sustainable' construction practices. Despite ongoing actions and policies, as long as these materials and techniques are not suitably represented in reliable and accessible databases, it will be difficult to make such a shift happen. Manufacturers and contractors who produce and use such materials would benefit from the availability of easily applicable, scientific data demonstrating environmental advantages offered by non-conventional materials.

Keywords Environmental impact · Embodied energy · Embodied carbon · Non-conventional construction materials · Databases

33.1 Introduction

Embodied emissions will likely constitute the majority of emissions generated by new buildings built between now and 2050 (Simonen et al. 2017). It is increasingly recognised that embodied impacts can constitute more than half of the total life cycle impacts from new buildings, and they will grow both proportionally and in real terms with the reduction of operational impacts (Rasmussen et al. 2018). 'Net-zero' or 'near-zero' operational greenhouse gases (GHG) emissions mean that the GHG emissions budget becomes almost entirely allocated for embodied GHG emissions (Röck et al. 2020; Habert et al. 2020; Moncaster et al. 2019).

Current EU regulations mainly cover the operational energy performance of buildings, while the embodied impacts remain largely unregulated, despite the significant carbon reduction potential (Toth and Volt 2021). However, since 2017, the Netherlands has required all new residential and office buildings larger than 1000 m^2 to account for embodied impacts based on a simplified LCA. Switzerland has introduced LCA requirements for public buildings (Swiss Society of Engineers and Architects (SIA) 2017). Denmark's National Strategy for Sustainable Construction will phase a LCA requirement into the building code, enforcing maximum CO_2 emissions of new buildings larger than 1000 m^2 from 2023 and for all new buildings from 2025 (The Danish Housing and Planning Authority 2021).

France's new *Réglementation environnementale* RE2020 includes carbon thresholds for offices and educational buildings starting 1 July 2022; limits will be progressively lowered. France is the first country to apply a dynamic LCA approach to the construction sector (Ministère de la Transition écologique (MTE) 2022a; Ministère de la Transition écologique (MTE) 2022b).

These increasing efforts for setting legally binding limits to the embodied environmental impacts highlight the crucial need for developing accurate, equitable, and easily accessed data for construction materials and techniques.

33.2 Data and Methods

33.2.1 Case Studies

The reflections proposed in this paper stem from the analysis of twenty-two ecologically oriented buildings showing different approaches to 'vegetarian architecture'—a theoretical stance based on principles learnt from agriculture and nutrition (Bocco Guarneri 2020), which advocates:

- natural, renewable, locally available construction materials, free of toxic chemicals, and as little processed as possible (Wolley 2017, 2016; Berge 2009; Ghavami 2014; Walker et al. 2009; Harries and Sharma 2016);
- minimization of energy-intensive, high-tech components;
- labour-intensive, small-scale production processes, and simple constructional techniques;
- passive solar design.

The case studies are located in Europe and Japan and cover a variety of functions—residential, commercial, educational, workspace—and different patterns of use. Their gross internal areas (GIA) range from 23 to 3 232 m^2. Both refurbishment of traditional buildings and new constructions are included to exemplify techniques that make use of bio-based and other natural materials.

33.2.2 Data

The systematic investigation of each building's technical and constructional features allowed to draw inventories and 3D models representing as-built situations. The 'cradle to gate' embodied energy (EE) and 'embodied carbon' (EC) were calculated by adding up the components manually, using a process-based LCA methodology and a purpose-designed spreadsheet. Impact coefficients were retrieved from two open access databases—the Inventory of Carbon and Energy (ICE) (Jones and Hammond 2019; Hammond and Jones 2011) and Ökobaudat (ÖBD) (BMI 2021).

Later, the most relevant non-conventional materials (NOCMAT) used were identified. NOCMAT encapsulate sustainable use of novel technologies and innovative uses of more established materials; many of them have their roots in traditional vernacular construction, including bio-based materials, and other natural materials such as stone, earth, lime (Ghavami 2014). For these materials, EE and EC values are either unavailable or show inconsistencies in the databases used. The production processes and the uses of such materials show a wide variability, which leads to a variability of the associated environmental impacts.

33.2.3 Reference Databases

ICE and ÖBD were chosen because open access and user friendly. More detailed sources are available but are proprietary and/or require a high level of expertise for their use. Using ÖBD and ICE to calculate the two basic environmental indicators was a sensible compromise between data availability and results uncertainty. Using the same set of values for all calculations guaranteed consistency.

ÖBD is managed by the German Federal Ministry of the Interior, Building, and Community; datasets must comply with EN 15,804. Data entries are constantly added, and the entire database is updated once a year. Datasets are based on the background database GaBi. Additional datasets based on EcoInvent background data are provided. In 2020, the new DIN EN 15,804 + A2 was adopted, which includes separate reporting of fossil, biogenic, and luluc GWP.

ICE is managed by Circular Ecology and the University of Bath. Version 2.0 (2011) was based on ISO 1404 and 14,044; 53% of sources dated before 2005. Carbon sequestration was excluded. Version 3.0 (2019) no longer includes energy factors. Carbon storage data are available for timber only. The values are the average of several sources, usually EPDs complying with EN 15,804. Data are updated for some materials. In our study, ICE V2.0 was used for all EE values and some EC values.

33.3 Results

33.3.1 On Case Studies' Embodied Energy and Embodied Carbon Values

While a rigorous internal methodology allowed for a detailed comparison between case studies (Bocco and Bocci 2022), it was difficult to verify whether these buildings have a lower environmental impact than conventional ones (Bocco Guarneri 2020). Systematic reviews (Simonen et al. 2017; Rasmussen et al. 2018; Birgisdottir et al. 2017; Dixit 2017; Hoxha et al. 2017; Röck et al. 2019; Säynäjoki et al. 2017; Schwartz et al. 2018) have not yet reached the degree of harmonisation which would offer benchmarks. The completeness of the underlying inventories is doubtful; the variations are up to two orders of magnitude (Rasmussen et al. 2018).

The average results of the analysed 'vegetarian' buildings do not appear significantly lower than those found of more conventional buildings. Moncaster et al. (Moncaster et al. 2019) found an average of 125 $kgCO_{2eq}/m^2$ for retrofitted buildings and of 254 $kgCO_{2eq}/m^2$ for new ones; we obtained 127 and 328, respectively, with ICE, and −132 and −74 with ÖBD (Fig. 33.1). The question about the reliability of databases, methodologies, and benchmarks stays open.

bldg. no.	GIA	weight	EE (ÖBD)		EE (ICE)		GWP (ÖBD)		GWP (ICE)	
	m^2	kg	MJ/kg	MJ/m^2	MJ/kg	MJ/m^2	$kgCO_{2eq}$/kg	$kgCO_{2eq}/m^2$	$kgCO_{2eq}$/kg	$kgCO_{2eq}/m^2$
1	114	106 983	2.38	2 235	0.41	381	-0.18	-170	0.02	20
1(r)		80 934	3.15		0.54		-0.24		0.03	
2	23	25 738	4.75	5 318	1.36	1 524	-0.51	-570	0.12	131
2(r)		21 744	5.63		1.61		-0.60		0.14	
3	572	911 500	2.50	3 985	1.05	1 666	-0.09	-136	0.07	115
3(r)		204 818	11.13		4.65		-0.38		0.32	
4	411	469 598	3.35	3 823	2.30	2 633	-0.08	-92	0.15	174
4(r)		305 981	5.14		3.54		-0.12		0.23	
5	103	106 869	1.78	1 843	0.36	369	-0.46	-474	0.09	97
6	65	166 427	5.01	12 821	4.95	12 664	-0.09	-241	0.11	286
7	125	343 872	8.73	24 019	4.09	11 252	-0.37	-1 015	0.23	627
8	76	129 560	4.44	7 550	3.52	5 978	0.12	210	0.26	446
9	176	29 476	8.60	1 441	8.62	1 443	0.16	28	0.42	70
10	153	330 945	4.67	10 105	3.37	7 286	0.03	55	0.32	687
11	61	67 683	4.57	5 067	3.56	3 949	0.04	46	0.22	242
12	156	340 417	2.51	5 471	4.72	10 290	0.02	39	0.18	389
13	2 212	1 966 360	7.90	7 019	4.98	4 429	-0.05	-41	0.35	307
14	183	267 401	4.69	6 858	3.84	5 614	-0.01	-12	0.27	393
average			5.43	6 449	3.59	4 261	-0.07	-89	0.23	277

Fig. 33.1 GIA, weight, EE, and GWP of each case study, calculated both with ÖBD and ICE

33.3.2 On Vegetal Materials

The analysis highlighted a divergence of the profiles for timber and timber-based products in the two databases. Data for highly industrialised products such as timber-based boards and window frames are widely available and cover a good range of variations; this comes less for untreated solid wood. ÖBD provides very high values for EE, reflecting German processing: kiln drying; industrial debarking and sawing machinery; and an average distance between forest and sawmill of 144 km (Fig. 33.2). While timber was widely used in most of our case studies, it was often low processed and underwent little treatment, if any. In most cases, timber was air-dried, while most sources for both databases consider kiln drying at high temperatures—an energy—and carbon-intensive process that alters timber's properties. Where elements were hand-sawn (5), debarked and cut on site (21), and untreated (5, 6, 21), the impact risked to be overestimated (Fig. 33.3). In case 21, the whole structure—which makes a relevant portion of the building's weight—was manually debarked, and most of the lumber came from the site or district forest. In 5, timber was obtained from the ecovillage's forest and transported with horses to the site, where it was assembled with hand tools. No data are available for *brettstapel* (7, 13, 17, 22) as opposed to various entries for laminated timber: the lack of glue and nails reduces the environmental impacts of the first. Wood chips (21) and loose wood fibre (10) are not covered, as opposed to wood fibre boards for which ÖBD includes five entries and ICE two.

Straw was employed in ten case studies in a range of ways: load-bearing bales (6, 7, 21), thatch (2), bale infill (12, 20), bale retrofit (3), loose insulation (1, 6, 15, 21); ropes, mats (1), and chaff (2) are also used. Only values for standard size bales

Fig. 33.2 Timber dried at low temperatures in a greenhouse at Kitokuras sawmill (Kagawa prefecture). *Photo* Andrea Bocco Guarneri

Fig. 33.3 Manual debarking of trees at Biotal site. Untreated logs are used as structural columns in the building. *Photo* Christoph Bosch

with a density of 100 kg/m^3 are given in the databases, forcing an approximation for products like jumbo and round bales and loose straw. Not only does the crop cultivation vary (in 5 and 21 it is harvested from local organic farms), but also the baling process is expected to influence the overall impact. In many of these buildings, straw represents a large portion of the weight: divergences can therefore influence the overall environmental impacts. Reported values for straw bales are disorienting: in ÖBD, the EE value for straw (17.13 MJ/kg) is seventy times higher than that found in ICE 2.0, and higher than that of structural steel (14.14 MJ/kg) and more than three times higher than that of fired, solid bricks (4.85 MJ/kg). The reliability of the EE value for straw in ICE may be low, since it is based on four references only, the latest dating from 2003; but that in ÖBD (based on an EPD provided by FASBA) is high compared to recent studies: e.g., nearly 5 times higher than Upstraw School of Natural Building's 2021 EPD (Up-Straw—School of Natural Building (SnaB) 2021).

Databases seem also ill-suited for representing other vegetal materials. No data are present in either database for bamboo, not only for whole culms but also for products such as mats, panels, and laminated bamboo. In 9, locally harvested bamboo culms make up the entire structure (Fig. 33.4). Loose hemp shiv is not covered, which makes it difficult to assess, for instance, hemp-lime building components (8, 13). Only hemp mats are found in ÖBD (Fig. 33.5): these include 15% polyester fibres and are impregnated with soda.

Fig. 33.4 Structure of the Bamboo Ark consists of radially arranged frames, composed of a base truss and arches. The culms were harvested from a nearby grove. *Photo* Toki Hirokazu

Fig. 33.5 Bamboo mats in Iya Valley, Japan. *Photo* Andrea Bocco Guarneri

Analogously, there are no data for loose flax fibres (21), just for mats. In ÖBD, the same assumptions as for hemp fibre mats are applied. ICE V2.0 reports that most of the impacts are due to the polyester binders and fire retardants (Schmidt et al. 2004). No data are present in either database for reed mats (4, 6) and jute (6), while building paper (10, 13) is covered by ÖBD only.

33.3.3 On Other Natural Materials

Earth construction techniques are poorly represented: ICE just reports data on earth (it is unclear whether this is rammed or bulk earth); ÖBD includes data on rammed earth, adobe, plaster, earth panels, and bulk earth. Data sheets do not provide enough information on basic features, such as the presence of additives or fibres, or the size of the adobes. The entry for earth plaster in ÖBD has an ambiguous description, which does not even seem to refer to an earth-based product. ÖBD also assumes processes such as the artificial drying of adobes (Fig. 33.6).

Fig. 33.6 Light-earth external skin applied onto battens in a new house in Darmstadt. *Photo* Franz Volhard

No data are provided for earth paints, which are usually ready-made products (4, 8).

In many case studies, earth products were made at the construction site (Fig. 33.7): adobes in 10 and 12; manually compressed earth blocks in 13; earth plasters in 2, 5, 6, 10, 12, and 21 made with various mixtures, in some cases including fibres, sand, or lime; clay mortar in 4; tamped earth floors in 1, 4, 5, 6, 12, and 14 (coated with earth finishing in 6 and 12). Earth was also used with straw for infilling wooden or bamboo frames (1,2,4,15,21).

Fig. 33.7 Construction of the lecture theatre of the WISE at the Centre for Alternative Technology. The attractive load-bearing rammed-earth walls, 500 mm thick, are pneumatically tamped and left unfinished on both faces. *Photo* Pat Borer

Emblematic is the case of stone: while being one of the most common materials in vernacular constructions, its use has drastically shifted from massive blocks that require minimal (if any) dressing to 1 ~ 3-cm-thick cladding slats. Both databases just provide values for thin elements that underwent cutting and finishing processes. In ÖBD, entries for 2 ~ 4-cm-thick granite and limestone elements assume processing—steel grit, grinding road, saw, and multi-blade saw. ICE V2.0 acknowledges that data sources were generally poor, except for stone slates. Quarried stone blocks are then associated with a risk of overestimating their embodied impacts if the custom values are employed. Even in cases when thin paving stone slabs were used, ecological considerations resulted in specifying little-processed elements: in 7, 50 ~ 70-mm-thick soapstone flooring slabs were obtained on site by cutting conglomerate rock boulders; in 21, 9-mm natural stone tiles were hand-cut with pliers and left unpolished.

Animal-origin products are also little represented, if at all: for felt (7), the only data available is the EE value in ICE V2.0; for sheep's wool (8, 18), no values are available in either database.

33.4 Conclusions

The quality of the environmental assessment of buildings depends heavily on the quality of the data used, which remains a major challenge. Most of the processes mentioned here could be modelled with tools such as EcoInvent: but doing so requires skills and time that are beyond the possibilities of an average designer or contractor. ÖBD and ICE, while open source and easy to use, are focused on conventional materials and do not satisfactorily cover bio-based and little-processed materials. Even when they do, the values provided are regional or global averages, not representative of specific production patterns in terms of processes or efficiency, electricity mix, and transportation distance (Zea Escamilla and Habert 2014).

A proper assessment requires significant expertise, time, and financial resources, which are less likely available for alternative construction materials. Furthermore, meeting the impact thresholds set by current and future regulations pushes towards using certified conventional construction materials, a tendency that is not consistent with decarbonizing the building trade. Data availability is then a key issue in the implementation of environmental reduction policies.

The development of appropriate data for non-conventional construction materials should be supported by a bidirectional technological transfer between the research and industry sides. Current research efforts should be aligned to make the results reliable and widely available. This will rebound on an easier introduction of these materials in the construction market and help achieve the ambitious emissions reduction targets.

References

Berge B (2009) The ecology of building materials, 2nd edn. Architectural Press, London

Birgisdottir H, Moncaster A, Wiberg AH, Chae C, Yokoyama K, Balouktsi M, Seo S, Oka T, Lützkendorf T, Malmqvist T (2017) IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction.' Energy Build 154:72–80. https://doi.org/10.1016/j.enbuild.2017.08.030

BMI (2021) Deutsche Bundesministerium des Innern, für Bau und Heimat. Ökobaudata 2021

Bocco A, Bocci M (2022) Reflections on the environmental impact of "vegetarian" buildings, and on the reliability of databases. Constr Technol Archit 1:395–404. https://doi.org/10.4028/www.scientific.net/CTA.1.395

Bocco Guarneri A (2020) Vegetarian architecture: case studies on building and nature. Jovis Verlag GmbH

Dixit MK (2017) Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters. Renew Sustain Energy Rev 79:390–413. https://doi.org/10.1016/j.rser.2017.05.051

Ghavami K (2014) Non-conventional materials and technologies for sustainable engineering. In: Proceedings of 14th NOCMAT, 24–27 Mar 2013, João Pessoa. Trans Tech Publications, Dürnten

Habert G, Röck M, Steininger K, Lupisek A, Birgisdottir H, Desing H, Chandrakumar C, Pittau F, Passer A, Rovers R, Slavkovic K, Hollberg A, Hoxha E, Jusselme T, Nault E, Allacker K, Lützkendorf T (2020) Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. Build Cities 1:429–452. https://doi.org/10.5334/bc.47

Hammond G, Jones C (2011) Inventory of carbon and energy. Circular Ecology and University of Bath

Harries K, Sharma B (2016) Nonconventional and vernacular construction materials. Woodhead Publishing, Sawston

Hoxha E, Habert G, Lasvaux S, Chevalier J, Le Roy R (2017) Influence of construction material uncertainties on residential building LCA reliability. J Clean Prod 144:33–47. https://doi.org/10.1016/j.jclepro.2016.12.068

Jones C, Hammond G (2019) Embodied carbon—the ICE database. Circular Ecology and University of Bath

Ministère de la Transition écologique (MTE) (2022a) Décret n° 2022a-305 du 1er mars 2022a relatif aux exigences de performance énergétique et environnementale des constructions de bâtiments de bureaux et d'enseignement primaire ou secondaire en France métropolitaine, Journal officiel, n°0052 du 3 Mars 2022, Texte n°48

Ministère de la Transition écologique (MTE) (2022b) Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Cerema). Réglementation Environnementale des Bâtiments Neuf (RE2020)

Moncaster AM, Rasmussen FN, Malmqvist T, Houlihan Wiberg A, Birgisdottir H (2019) Widening understanding of low embodied impact buildings: results and recommendations from 80 multi-national quantitative and qualitative case studies. J Clean Prod 235:378–393. https://doi.org/10.1016/j.jclepro.2019.06.233

Rasmussen FN, Malmqvist T, Moncaster A, Wiberg AH, Birgisdóttir H (2018) Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. Energy Build 158:1487–1498. https://doi.org/10.1016/j.enbuild.2017.11.013

Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T, Passer A (2019) Embodied GHG emissions of buildings—the hidden challenge for effective climate change mitigation. Appl Energy 258:114107. https://doi.org/10.1016/j.apenergy.2019.114107

Röck M, Balouktsi M, Saade M, Nygaard Rasmussen F, Hoxha E, Birgisdottir H, Frischknecht R, Habert G, Passer A, Lützkendorf T (2020) Embodied GHG emissions of buildings—critical reflection of benchmark comparison and in-depth analysis of drivers

Säynäjoki A, Heinonen J, Junnila S, Horvath A (2017) Can life-cycle assessment produce reliable policy guidelines in the building sector? Environ Res Lett 12:013001. https://doi.org/10.1088/1748-9326/aa54ee

Schmidt AC, Jensen AA, Clausen AU, Kamstrup O, Postlethwaite D (2004) A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Int J LCA 9:122. https://doi.org/10.1007/BF02978571

Schwartz Y, Raslan R, Mumovic D (2018) The life cycle carbon footprint of refurbished and new buildings—a systematic review of case studies. Renew Sustain Energy Rev 81:231–241. https://doi.org/10.1016/j.rser.2017.07.061

Simonen K, Rodriguez BX, De Wolf C (2017) Benchmarking the Embodied Carbon of Buildings. Technol Archit Des 1:208–218. https://doi.org/10.1080/24751448.2017.1354623

Swiss Society of Engineers and Architects (SIA) (2017) SIA 2040: Effizienzpfad Energie

The Danish Housing and Planning Authority (2021) National strategy for sustainable construction. Ministry of the Interior and Housing, Copenhagen

Toth Z, Volt J (2021) Whole-life carbon: challenges and solutions for highly efficient and climate-neutral buildings. BPIE

Up-Straw—School of Natural Building (SNaB) (2021) Environmental product declaration In accordance with ISO 14025 and EN 15804:2012+A2:2019 for: Straw as insulation material-UK

Walker P, Ghavami K, Paine K, Heath A, Lawrence M, Fodde E (2009) 11th International Conference on Non-conventional Materials and Technologies—NOCMAT 2009 Proceedings. University of Bath, Bath

Wolley T (2016) Natural building: a guide to materials and techniques. The Crowood Press, Ramsbury

Wolley T (2017) Building materials, health and indoor air quality. Routledge, Abingdon

Zea Escamilla E, Habert G (2014) Environmental impacts of bamboo-based construction materials representing global production diversity. J Clean Prod 69:117–127. https://doi.org/10.1016/j.jclepro.2014.01.067