WEENTECH Proceedings in Energy ISSN:2059-2353

Available online at www.weentechpublishers.com

WEENTECH Proceedings in Energy 6 (2020) 136-153

5th Virtual International Conference on Energy, Environment and Economics, ICEEE2020, 18-19 August 2020

Materials in the built environment – Whole life energy / carbon

Vicki Stevenson*

Welsh School of Architecture, Cardiff University, UK

*Corresponding author's mail: stevensonv@cardiff.ac.uk

Abstract

Buildings are responsible for approximately 40% of global CO2 emissions – one quarter of these being Embodied Carbon, which is front loaded to the construction period (months) in comparison to operational carbon emissions which usually occur over decades.

Emerging concern about this issue is noted to have driven recent guidance publications and a few countries are preparing legislation to address the issue. The opportunities with most impact lie at the planning and design stage and require a committed client to ensure that early decisions are carried through to completion.

This paper analyses the whole life carbon emissions for four façade options in a case study. Three further case studies are analysed for the impact of material choice on embodied and operational carbon emissions. All case studies show potential carbon savings depending on material choice. Even with minor carbon savings for one unit, there is potential for increased saving across multiple units (e.g. hotels and dwellings). Finally, opportunities to utilize waste products are considered, not only reducing carbon emissions, but meeting the Circular Economy principle of "keep products and materials in use".

Keywords: Embodied carbon; Whole life carbon; Built environment, Circular economy

https://doi.org/10.32438/WPE.2920

Manuscript History

Receipt of completed manuscript: 20 August 2019

Receipt of Revised Manuscript: 26 August 2020

Date of Acceptance: 26 August 2020

Online available from: 28 August 2020

Abbreviations

BREEAM	Building Research Establishment Environmental Assessment Method
CO2e	carbon emissions equivalence in CO2
EC	Embodied Carbon
EPD	Environmental Product Declarations
G	giga (10^9)
GGBS	ground granulated blast furnace slag
HDPE	high density polyethyelene
ICE	Inventory of Carbon and Energy
km	kilometer
LEED	Leadership in Energy and Environmental Design
OC	Operational Carbon
OPC	Ordinary Portland Cement
PET	polyethylene terephthalate
PFA	pulverised fuel ash
PVC	polyvinyl chloride
RHA	Rice husk ash
RIBA	Royal Institute of British Architects
RICS	Royal Institute of Chartered Surveyors
SIPs	Structural insulated panels

1. Introduction

There was an eight-fold increase in global material use in the 1900s [1]. With buildings consuming approximately 40-50% of raw materials globally [2, 3]. Data for 2017 shows that 89 Gtonnes of construction materials were used, which is anticipated to increase to 167 Gtonnes by 2060 [4]. The sourcing, processing, use and disposal of materials has other environmental impacts including pollution of air, water and land [1] which affect all the species on the planet including humankind. In Europe, the building industry is responsible for 35% of all solid waste [5]. This paper focusses on the energy consumption / carbon emissions associated with the built environment whole life cycle which is associated with materials.

A frequently quoted figure is that buildings are responsible for approximately 40% of global CO2 emissions; however, it is less frequently acknowledged that over a quarter of these emissions are due to construction of buildings (Embodied carbon - EC) rather than their operation (Operational carbon - OC) [6]. It is considered that embodied carbon is increasing as a proportion of total carbon because building operation is becoming more energy efficient in many countries [7,8] (although overall number of buildings is increasing) [9]. It is a sobering thought that cement generated 2.8 Gtonnes of CO2 in 2015 (8% of global emissions). If the cement industry were considered as a country, it would be the third highest global emitter of CO2 [10].

Fig. 1 shows life cycle energy and carbon emissions in the built environment; from sourcing of raw materials to dealing with materials at end of life [11]. A particular issue with the EC emissions is that the majority are front loaded to the relatively short construction period (months), in comparison to the OC emissions which occur more gradually during the lifetime of the building (decades). Despite this significant contribution to whole life built environment carbon emissions, there is little regulation of EC. However, innovators such as The Netherlands, City of Oslo and Finland are leading the way: a) The Netherlands are credited with being the first country to implement legislation which imposes limits on embodied carbon emissions from buildings; b) City of Oslo (Norway) is working towards zero emission construction sites by 2030; and c) Finland have launched a consultation aiming to implement whole life carbon foot-printing for new buildings by 2025 [9]. Companies and organisations are also showing increased awareness of the contribution of embodied carbon to whole life built environment emissions, examples of this include Burro Happold from as early as 2011 [12], RICS [13], BREEAM [14], LEED [15], World Green Building Council [9], RIBA [16], Frasers Property [17].

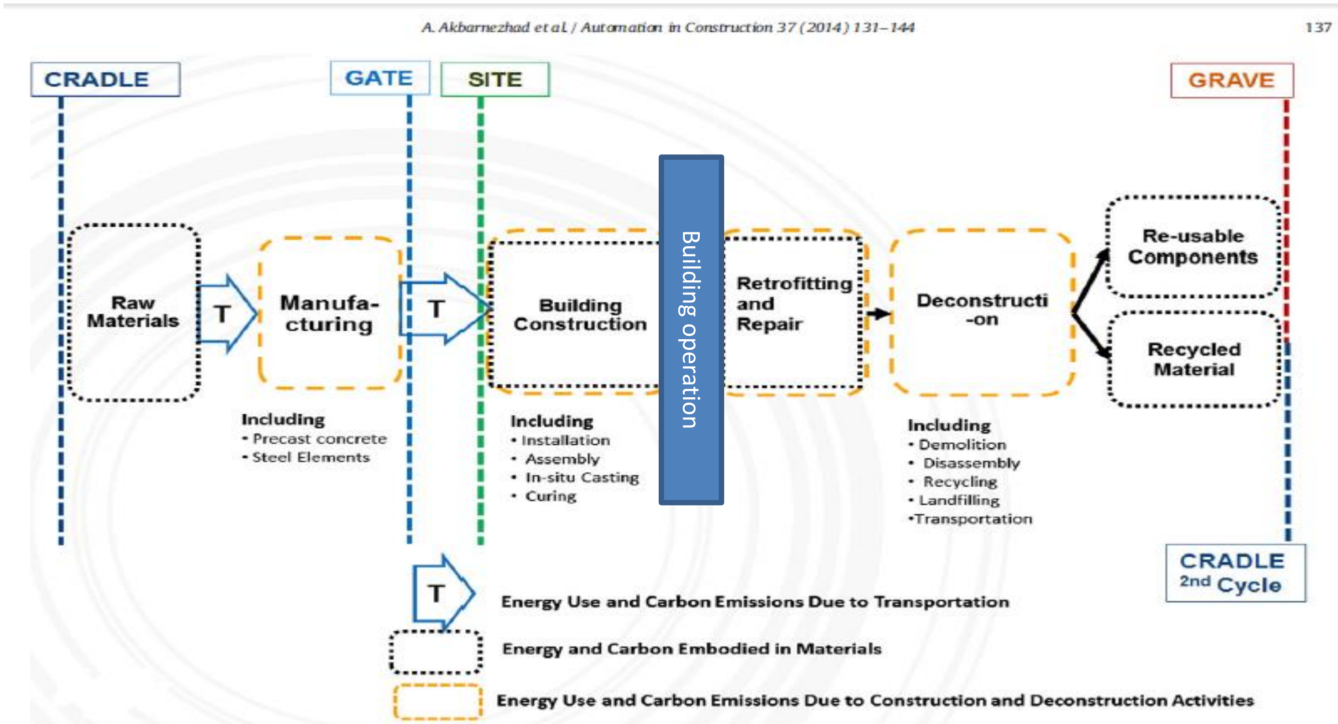

Fig. 1 Life Cycle energy and carbon in the built environment – operational energy highlighted in blue (Adapted from [11])

As Fig. 2 indicates, the major reductions in embodied carbon emissions rely on due consideration at the planning/design stages [18]. A circular economy viewpoint is useful in reducing embodied emissions. This can be through reusing existing building stock via adaptation and refurbishment, or by using parts of an existing building or existing components. Where new construction/components are required, the aim should be to reduce the embodied carbon of the materials used, while ensuring that occupation and operational efficiency requirements continue to be met [19]. To facilitate future reuse of components, new buildings should incorporate reversible design (e.g. through decoupling elements with different life cycles and including demountable constructions) [20].

The aim of this paper is to show examples where design analysis can lead to reduction of carbon emissions. The focus is on façades as they account for 13-21% of a building's embodied carbon [21].

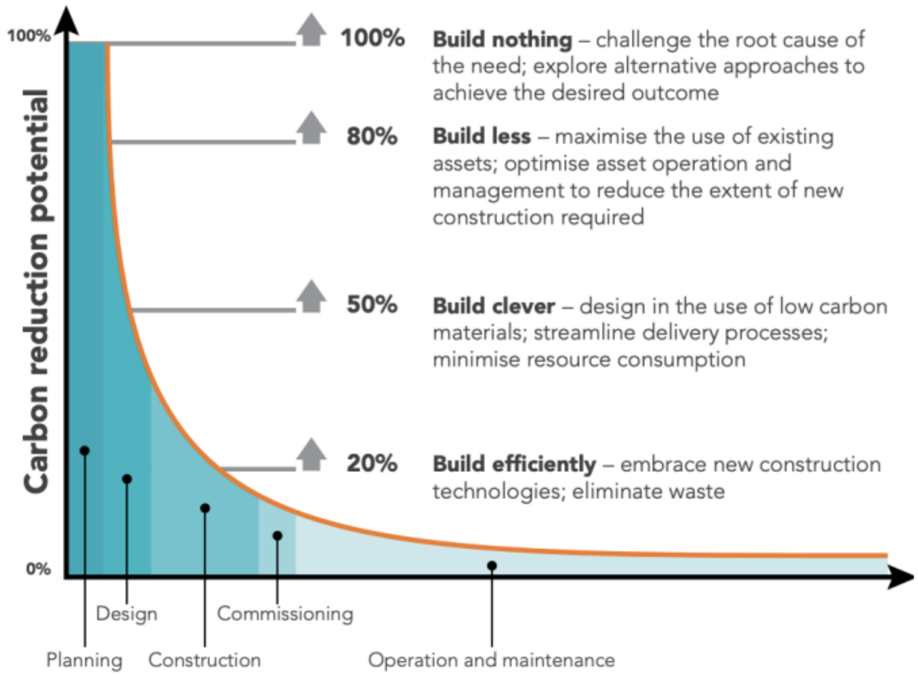

Fig. 2 Embodied Carbon reduction potential at design/construction stages [18]

2. Methodology

There are two main approaches to calculating embodied energy (and thereby the embodied carbon emissions); these are:

- Input-ouput approach which is based on a country's economy inputs (e.g. materials) and outputs (e.g. emissions. This is not specific to a particular manufacturing process or product and has issues relating to data aggregation, homogeneity assumptions, age of data etc. [22]
- Process based approach which relies on tracking individual processes used in the manufacture and transport of the product. This suffers from truncation errors associated with the level of detail required to carry out the approach in detail [23]

An investigation of each approach in relation to the scale of the study concluded that the input-output approach is only suitable for large scale studies (e.g. countrywide) [24]. For this reason, the process approach was chosen for the embodied energy calculations within this study.

The use of building simulation tools is well established for the calculation of operational energy/carbon.

Four case studies will be selected to consider material options, three of these will focus on facades while the last will consider green (vegetated) roof options. The case studies are:

- Resort bungalow façade, Peru
- Hotel façade, Greece
- Townhouse façade, UK
- Lecture Rooms, green roof, Mexico

In all cases the construction stage has been addressed considering the sourcing of materials (including transport to site from source, not retailer). Some have also considered the installation phase with waste disposal, construction equipment and personnel transport. Where possible, local EC data for the material is used e.g. from Environmental Product Declarations (EPDs) of local manufacturers. If local EC data could not be found, data from the ICE Database V2.0 has been used [25] with personnel transport emissions of 172.5 gCO2e/km, and 106.7 gCO2e/km for road haulage [26]. OC has been addressed by specifying equivalent U-value façade materials or by building simulation using Design Builder software. The impact of maintenance and end of life was analysed for the Resort bungalow (Peru) to ensure whole life carbon has been analysed.

In addition, the potential of incorporating waste products into façades will be considered, through two different approaches.

3. Case Study Results

3.1 Resort Bungalow façade, Peru

The bungalow represents guest accommodation at a proposed ecolodge in Lima, Peru. There will be eighteen earth embedded bungalows of the same design with a footprint of 54.7m^2. The walls (90.18m^2) must be capable of supporting 200mm reinforced concrete slab roofs. A 50 year life period was assumed for the whole life analysis, this was based on studies of construction lifetime in seismic zones [27].

The façade options considered were:

- steel reinforced concrete (150mm thick); however, this is uncommon in such rural areas,
- fired clay brick (230mm thick) reinforced with concrete columns,
- dressed stone (350mm thick) reinforced with concrete columns (due to absence of local regulation for use of stone in structural walls),
- adobe bricks (400mm thick) reinforced with bamboo cane and geogrid.

These are presented in Fig. 3.

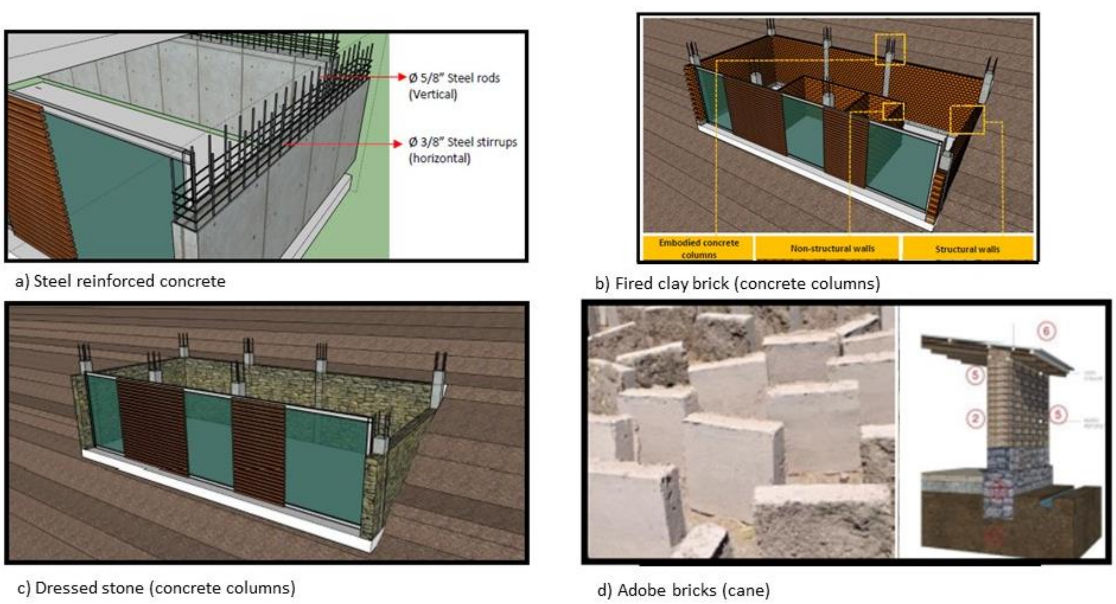

Fig. 3 Façade options for Resort bungalow, Peru ©Alvaro Ponce de Leon Saavedra, 2018

The material embodied carbon per mass and transport distances, along with personnel transport data are indicated in Table 1. Due to the remote location and scale of the project, powered construction equipment is limited to concrete mixer, concrete vibrator and steel cutter. The comparative embodied carbon for each bungalow is presented in Fig. 4. Quarried material and concrete are the major carbon emitting components for each façade option, with reinforcement being the next major component (plastic geogrid for adobe and steel for the others).

OC simulation was based on 4 occupants from 17:00 to 08:00 for each bungalow. Heating (setpoint 19°C) with mechanical ventilation provided 17:00-08:00 May-November. Cooling is provided December-April (setpoint 26°C) from 17:00-20:00 with mechanical ventilation from 17:00 to 08:00. In months when heating/cooling are not provided, natural ventilation is used.

Table 1 Material embodied carbon and transport distances – Resort bungalow façade, Peru

	Transport distance – road (km)	Embodied carbon tonne CO2e/tonne material
Aggregate	49.7	0.005 [25]
Bamboo canes	84.9	0.720* [25]
Bricks	44.2	0.240 [25]
Earth	2	0.024 [25]
Geogrid (polypropylene)	64.5	3.430 [25]
OP Cement	47.3	0.950 [25]
Sand	49.7	0.0051 [25]
Steel reinforcement	273	1.400 [25]
Stone	6.24	0.079 [25]
Straw	15	0.010 [25]
Personnel	28.6 (return journey)	0.1067E-3 per km [26]

* Embodied carbon data for bamboo canes could not be found – it is often assumed to be negligible or even negative (presumably not allowing for emissions at end of life) [23, 28]. To avoid unfair bias, data has been taken for general timber [25] instead – this is expected to slightly overestimate the emissions attributed to bamboo.

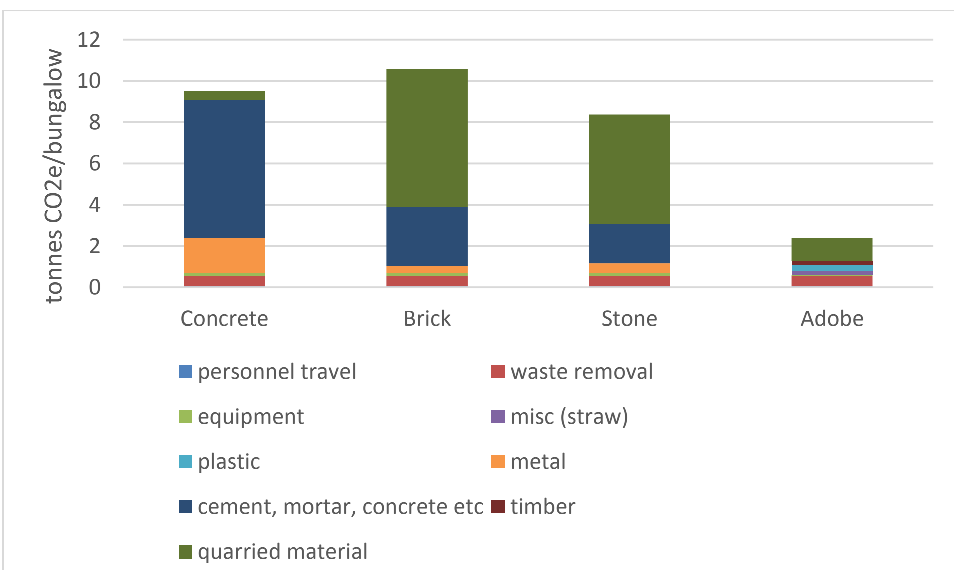

Fig. 4 Embodied carbon components of façade options for Resort bungalow, Peru

Annual maintenance during operational phase included wall washing (pressure washer) twice a year for concrete and stone, or repainting twice a year for fired clay brick and adobe. Seismic-effect maintenance included wall surface repair for minor damage, with more significant reconstruction once in a 30 year period for fired clay and adobe structures.

End of life assumes deconstruction using pneumatic demolition hammer as required. Reusable materials (eg. stone, earth) would be used locally, with metal transported 50km for recycling, while residuals would be transported 3km to landfill.

Fig. 5 illustrates the relative significance of carbon emissions across embodied, operational, maintenance and end of life. This has been normalised to one square meter of bungalow footprint.

From the four façade options, it can be observed that potential embodied carbon including installation (façade only) ranged from 10.2% of whole life carbon emissions for adobe, through 31.2% for concrete and 31.8% for stone to 33.9% for brick. It is acknowledged that the operational carbon emissions are particularly low in this scenario. It is also noted that the end of life emissions were relatively low; however, this doesn't account for the loss of material resource which could reduce carbon emissions in a future construction project, particularly important for concrete and brick options. The adobe wall offered a 25% reduction in lifetime carbon emissions compared to brick – offering a saving of 142 tonnes lifetime CO2 over the project (eighteen bungalows).

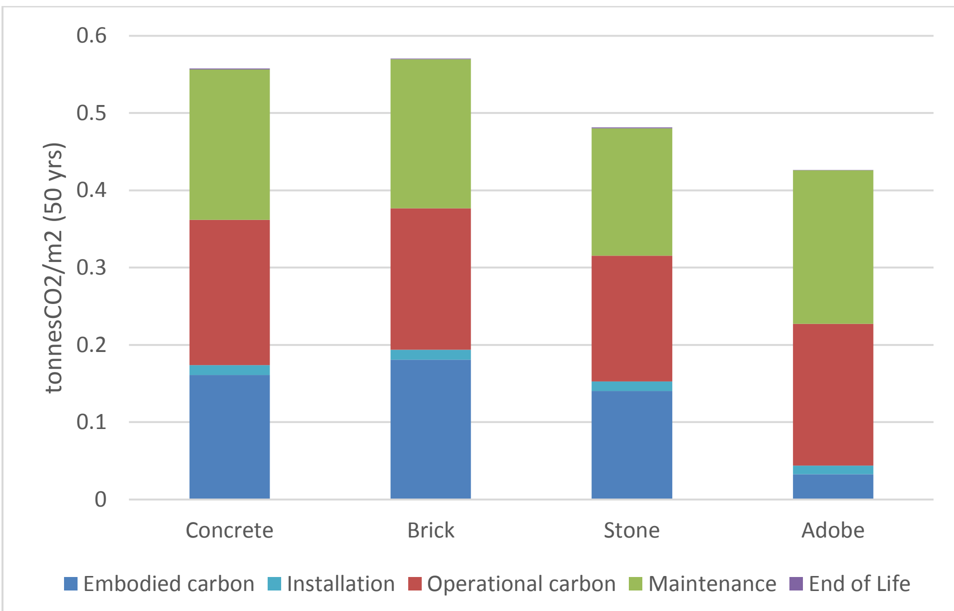

Fig. 5 Whole life (50 yr) carbon/m^2 footprint of façade options for Resort bungalow, Peru

3.2 Hotel façade, Greece

Typically, Greek three-star hotels use the ground floor as a reception zone and have four guestroom floors with the layout presented in Fig 6. A 35 year lifetime was assumed for the whole life analysis based on EPD lifespan for the expanded polystyrene insulation [29], as this is a key component of the façade structures. Fired brick (high thermal mass) and steel drywall (galvanised studs with dry applied layers resulting in low thermal mass) options were analysed, each with cavity and external insulation structures –all with a total thickness of 320mm. Simplified representations of the structures are illustrated in Fig. 7. The EC per mass and transport distance of each material is presented in Table 2.

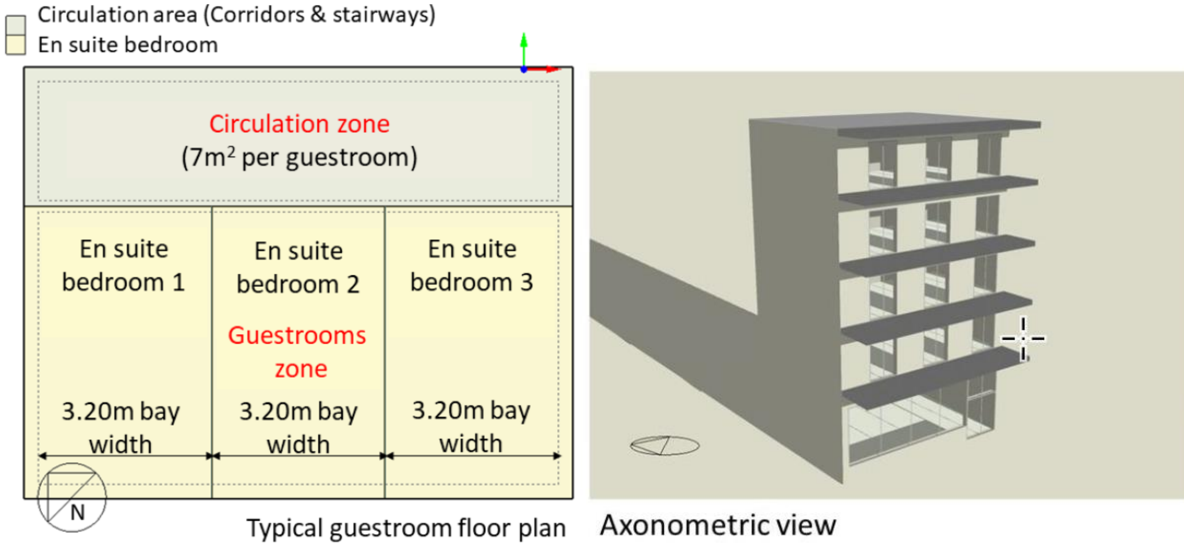

Fig. 6 Three-star Greek hotel guestroom floor plan and Axonometric view ©Konstantinos Koletsos

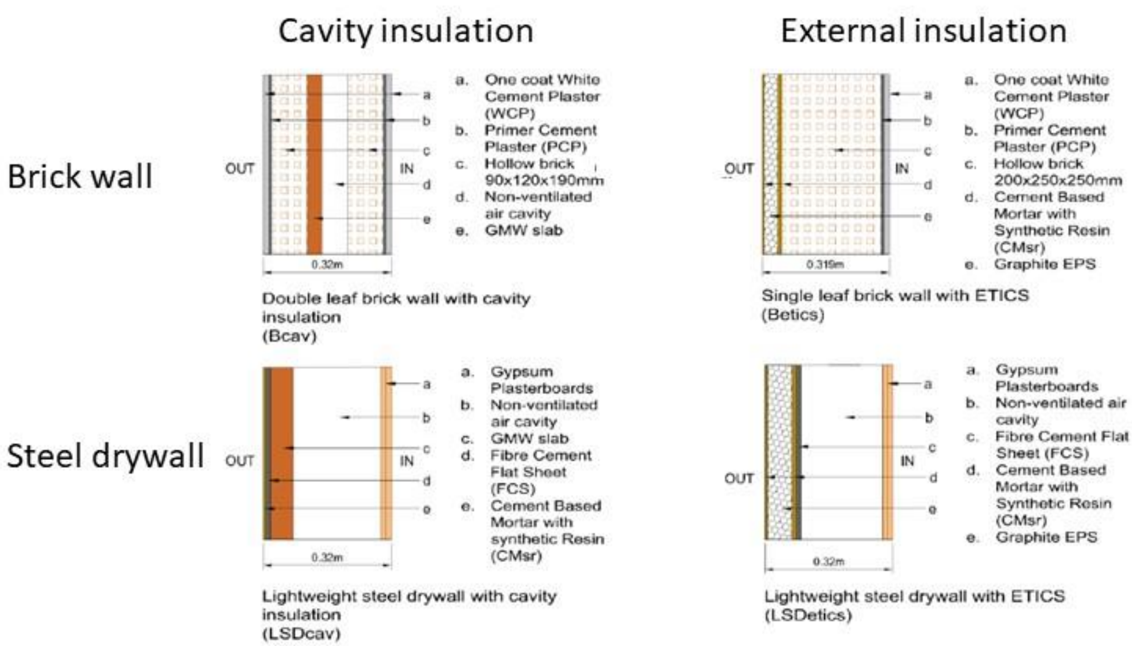

Fig. 7 Façade options for hotel, Greece ©Konstantinos Koletsos

Table 2 Material embodied carbon and transport distances – hotel façade, Greece

	Transport distance – road (km)	Embodied carbon tonne CO2e/tonne material
Brick	110	0.240 [25]
Cement based mortar with synthetic resin	38 + 972km by sea	0.230 [30]
Fibre cement flat sheet	322	0.356 [31]
Galvanized steel sheet	319	1.540 [25]
Glass mineral wool	806	1.278 [32]
Graphite expanded polystyrene (15kg/m^3)	227	3.111 [29]
Gypsum plasterboard	319	0.209 [33]
High density polyethylene membrane	2571	
Plastic fixings	2294	3.725 [34]
Primer cement plaster	88	0.213 [25]
Steel fixings	2294	1.460 [25]
Steel reinforcement	44	1.400 [25]
White cement plaster	88	0.213 [25]
Road travel		0.15E-3 per km [25]
Sea travel		0.009E-3 per km [25]

OC simulation was based on average occupancy of 0.08m^2 in guest rooms. The heating setpoint was 20^{o}C and the cooling setpoint was 26^{o}C with mechanical ventilation available all year. As each façade has a U-value of 2.8 W/m^{2}K, there was little difference in the operational carbon emissions. The higher summer temperatures and resulting use of mechanical services in Greek hotels significantly increases OC (per m^2) in comparison to the Peruvian resort bungalows (Fig. 8). In this case, the proportion of façade EC is between 2.5 and 10.5%; however, it is still the critical factor between lowest and highest overall emissions. Steel drywall with external insulation had the lowest combined emissions over construction and operation; followed by steel drywall with cavity, then brick with cavity and finally brick with external insulation. The overall saving between the best and worst case here is 0.098 tonne CO2e/m^2 (Fig. 8). Considering this difference in an application which currently has 414,127 rooms in a growing market [35], the difference could accumulate to 608.8 ktonnes CO2.

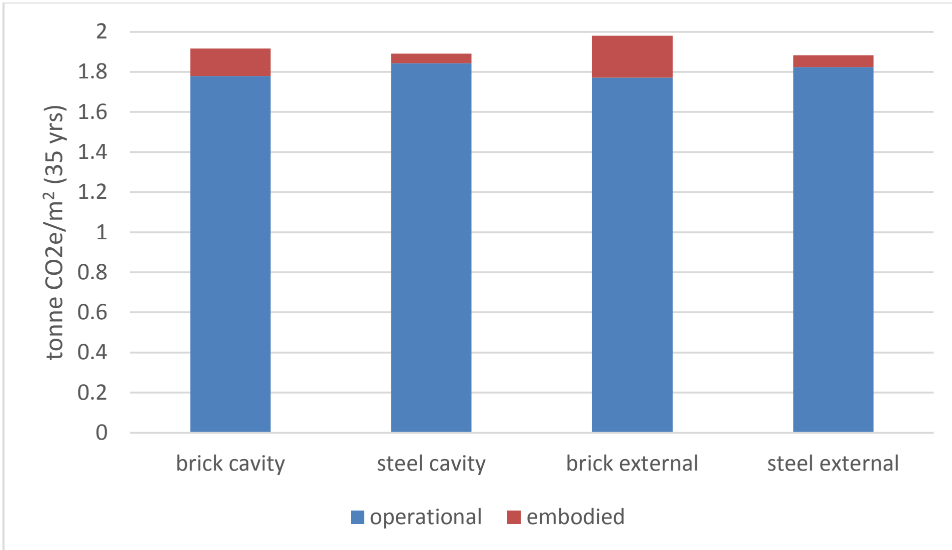

Fig. 8 Operational and Embodied carbon of façade options for hotel, Greece

3.3 Townhouse façade, UK

The UK government has acknowledged that approximately 200,000 new homes per year are required to address a housing shortage – many of these need to be affordable homes [36]. In order to provide affordable homes it is essential that construction costs are minimised. Potential methods for this are to a) keep the land footprint small (e.g. 3-storey townhouse), b) share common walls and c) utilise prefabricated construction. A façade comparison for a 3-storey townhouse with footprint 4*8m was made between: a) Traditional brick and block façade b) fully prefabricated Structural Insulated Panels (SIPs) and c) a hybrid structure of brick and block ground floor with SIPs for upper floors (more resilient than full SIPs in event of flood).

The EC per mass and transport distance of each material is presented in Table 3. OC has not been calculated in this scenario as the U-value of each façade type was kept constant. The EC of the three structures is presented in Fig. 9. A 42.3% EC saving was found between brick and block and SIPS. The hybrid structure still saved 22.3% in comparison to an entire brick and block façade. There is also potential to reduce the EC of the brick and block structure by swapping PUR foam for an alternative insulation with less impact. Foamed insulation is integral to the SIPs structure so more difficult to substitute in this scenario.

Table 3 Material embodied carbon and transport distances – townhouse façade, UK

	Transport distance – road (km)	Embodied carbon tonne CO2e/tonne material
Brick	98.3	0.240 [25]
Cement	36	0.880 [25]
Concrete block (13MPa)	65.8	0.107 [25]
Mortar	80	0.140 [25]
OSB (SIPs)	76.1	0.450 [25]
Plaster	79.6	0.130 [25]
Polyurethane foam	160	4.840 [25]
Timber (support)	2480	0.310 [25]

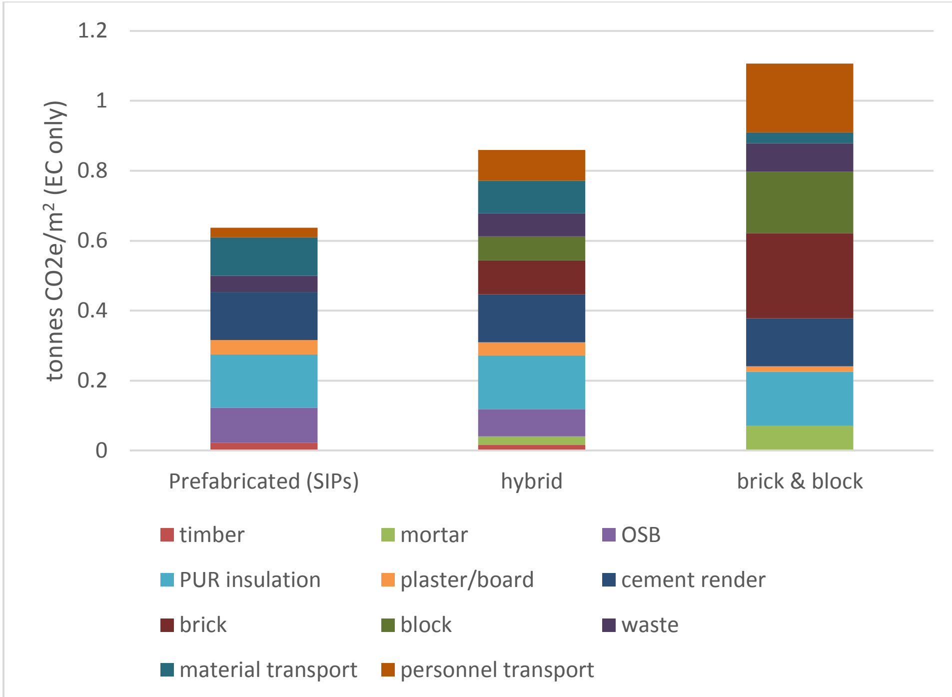

Fig. 9 Embodied carbon of façade options for townhouse, UK

3.4 Lecture Rooms Green Roof, Mexico

There are many benefits to a green roof. These include reducing urban heat island effect, helping to manage storm water, improving biodiversity and extending the longevity of roof waterproofing. In countries where roof insulation is not common, they can also provide a significant reduction to operational carbon.

This scenario considers a green roof across five adjacent lecture rooms (total 50*10m) based on the existing 205mm thick cast concrete roof, waterproofed with red asphalt roll (5mm thick) resulting in U-value of 0.706 W/m^{2}K. Adding a green roof (150mm thick) resulted in a U-value of 0.39 W/m^{2}K. OC simulation was based on average occupancy of 0.5523m^2. There is no heating setpoint, but the cooling setpoint was 28^{o}C with mechanical ventilation available all year.

The addition of a typical green roof (Fig. 10) reduced the heat gains and losses through the roof, resulting in an annual energy saving of 123kWh/m^2. However, it is still essential to minimize the impact of the embodied carbon. Eco-friendly alternatives were sought for the substrate and drainage layers. The selection criteria were: a) must be available within a 160km radius (based on sourcing requirement from LEED) and also b) at least one of: reusable, recyclable, recycled or natural. Recycled crushed brick (with the additional benefit of fire resistance) was selected as an alternative to 90% of the compost for substrate. While recycled synthetic rubber crumbs were selected as an alternative to high density polyethylene (HDPE) for drainage (see Table 4 for transport distances and EC per mass). The resulting "eco" green roof reduced EC by 54.7%.

Table 4 Material embodied carbon and transport distances – Lecture rooms Green roof, Mexico

	Transport distance – road (km)	Embodied carbon tonne CO2e/tonne material
Compost	54.4	0.020 [25]
Brick – crushed, recycled	3.8	0.180 [25]
Clay - expanded	110	0.02 [25]
High density Polyethylene (HDPE)	7	1.57 [25]
Rubber crumbs, recycled	60	0.244*

* 10% of rubber embodied carbon derived from The Institute for Environmental Research and Education [37].

Fig. 10 Typical green roof structure (substrate 100% compost, filter polyester, drainage HDPE, root barrier (PVC) ©Margarita Cuesta Lopez

3.5 Case Study Summary

The varying applications and locations of the case studies represent significantly different climate and occupant expectations, these greatly influence the resulting operational carbon emissions – this is particularly obvious when comparing the resort bungalow in Peru with the hotel in Greece.

The detailed embodied carbon analysis of the resort bungalow in Peru, showed particularly low installation and end of life carbon in comparison to embodied, operational and maintenance carbon emissions. However, the low end of life carbon does not represent the lost opportunity of using the materials in a future structure.

Each of the case studies showed that careful material choice for construction influenced the whole life carbon emissions, even when the embodied carbon was a relatively low proportion of the whole life carbon:

- Using an adobe facade, saved 25% of whole life emissions for the resort bungalow in Peru in comparison to fired brick (and 23% in comparison to concrete).
- Using a hybrid brick and block bottom storey with SIPS for remaining 2 storeys in a UK townhouse saved 22% of embodied carbon in comparison to a full brick and block structure. If conditions allow a full SIPS structure, a saving of 42.3% embodied carbon is possible.

- For a Greek 3-star hotel, material choice enabled a small reduction in carbon emissions when considered over construction and operational periods.
- Finally, it was found that the many benefits of a green roof could be obtained while reducing the embodied carbon by 54.7%. Two of these case studies (Greek 3-star hotel and UK townhouse) represent growing markets and have potential for application on a much wider scale.

4. Use of waste materials

Although typical construction materials are required in certain projects, there are many building projects where other materials can be used. In particular the use of waste materials facilitates the Circular Economy principle of "keep products and materials in use" [38]. The green roof example in case study 4 made use of waste bricks and rubber crumbs recycled from tyres as an example of this approach.

Another option is to use pozzolans from waste to replace a proportion of Ordinary Portland Cement (OPC). Pozzolans can come from industrial wastes (e.g. ground granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA)) and also from agricultural wastes (eg rice husk ash (RHA), oil palm ash from processing waste).

Rice Husk Ash has been investigated as a partial cement replacement in compressed earth blocks for dwelling construction in Nigeria. Solid blocks with 30% cement substituted with RHA were found to be structurally and hygrothermally suitable for up to 3 storey load-bearing external structures, while hollow blocks with up to 50% cement substituted with RHA was found to be structurally suitable for internal non-load bearing structures (partitions). The partial replacement of cement reduces the cost of materials which is essential for a country which requires 17 million units of affordable housing. The supply of affordable homes can also be facilitated by the use of compressed earth block which opens up a self labour option for dwellings, again increasing their affordability [39].

Avoiding cement entirely, Ecobricks are waste PET bottles stuffed with waste plastic film. These can be embedded in earth to create structures such as those illustrated in Fig. 11. This uses one form of waste to capture a second form of waste while producing a self supporting façade (in conjunction with earth). The façade will be plastered with mud, capped with an overhanging green roof to protect it from rain and can be treated in the same way as a cob wall once complete. The entire structure can be deconstructed so that the earth would be safe to return to a field, while the plastic bottles could be reused. Even the plastic film could be recovered if a use could be found for it.

Fig. 11 Ecobricks used in a community garden project - Bwyd Bendigedig Port / Incredible Edible Porthmadog, UK ©Lizzie Wynn, 2020

5. Conclusions

Embodied carbon of buildings constitutes approximately a quarter of building associated carbon emissions; however, it has largely been ignored. The concentration of these embodied carbon emissions in the first few months of a building's life (compared to decades for the remaining three quarters of the building emissions) are particularly worrying.

A few innovative countries are preparing to introduce legislation to address this issue and there is increasing awareness from guiding institutes with international reputations, such as RICS, RIBA, BRE and World Green Building Council.

This paper presents four case studies where analysis of material options have enabled embodied carbon and whole life reductions, even when embodied carbon has been a relatively low proportion of the whole life carbon.

One potential approach to reducing embodied carbon in the future is to embrace the Circular Economy and use waste materials. Two examples of utilising waste in façade construction have been presented: a) Rice Husk Ash as a pozzolanic substitute for a proportion of the cement in compressed earth blocks and b) Ecobricks which use waste PET bottles stuffed with waste plastic film as a structural block set in earth. This has myriad other environmental benefits as it reduces the impacts associated with the acquisition of virgin materials.

Although it is acknowledged that modern construction materials are required for some projects, there is significant potential to utilise low embodied energy and waste materials in less challenging structures. This paper sets out a small fraction of those options; however, it is acknowledged that the role of client is key in ensuring that environmental design decisions are carried through to construction.

ORCID ID of authors

Stevenson, Vicki: https://orcid.org/0000-0002-8531-2091

Acknowledgements

I am grateful to the following for their contributions to this paper:
Alvaro Ponce de Leon Saavedra: Case Study – Resort Bungalow façade, Peru
Konstantinos Koletsos: Case Study – Hotel façade, Greece
Jessica Cunningham: Case Study – Townhouse façade, UK
Margarita Cuesta Lopez: Case Study – Green roof, Mexico
Adedamola Ojerinde: Rice Husk Ash in Compressed Earth Blocks, Nigeria
Lizzie Wynn: Ecoblocks, UK

References

[1] Pacheco-Torgal F. (2014) 1 - Introduction to the environmental impact of construction and building materials. In: Pacheco-Torgal F, Cabeza LF, Labrincha J, de Magalhães A, editors. Eco-efficient Construction and Building Materials: Woodhead Publishing; p. 1-10. ISBN 978-0-85709-767-5

[2] Akadiri PO, Chinyio EA, Olomolaiye PO. (2012) Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. Buildings. 2, 126-152.

[3] Ruuska A, Häkkinen T. (2014) Material efficiency of building construction. Buildings. 4, 266-294.

[4] OECD. (2019) Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. Paris: OECD Publishing; ISBN 978-92-64-30745-2.

[5] De Wolf C, Hoxha E, Fivet C. (2020) Comparison of environmental assessment methods when reusing building components: A case study. Sustainable Cities and Society. 61, 102322.

[6] UN Environment, International Energy Agency.(2017) Towards a zero-emission, efficient and resilient buildings and construction sector. Global Status Report 2017 ISBN 978-92-807-3686-1.

[7] Banteli A, Stevenson EV. (2017) Building Information Modelling (BIM) as an enabler for whole-building embodied energy and carbon calculation in early stage design. WIT Transactions on the Built Environment. 169, 89-100.

[8] Iddon CR, Firth SK. Embodied and operational energy for new-build housing: A case study of construction methods in the UK (2013). Energy and Buildings. 67, 479-488.

[9] World Green Building Council. (2019) Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon. www.worldgbc.org/news-media/bringing-embodied-carbon-upfront

[10] Timperley J. (2018) Q&A: Why cement emissions matter for climate change: Carbon Brief; 2018 [Available from: https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change#:~:text=If%20the%20cement%20industry%20were,than%20China%20or%20the%20US.]

[11] Akbarnezhad A, Ong KCG, Chandra LR. (2014) Economic and environmental assessment of deconstruction strategies using building information modeling. Automation in Construction. 37, 131-144.

[12] Sauven E. (2011) Buro Happold - Embodied Carbon. Buro Happold; https://www.britishland.com/~/media/Files/B/British-Land-V4/documents/case-studies/buro_happold_embodied_carbon.pdf

[13] Royal Institute of Chartered Surveyors. (2017) Whole life carbon assessment for the built environment: RICS professional statement, UK. London: Royal Institution of Chartered Surveyors (RICS); ISBN 978 1 78321 208 8.

[14] BREEAM. (2019) Embodied carbon - how much longer can we say "too difficult" [Available from: https://www.breeam.com/news/embodied-carbon-how-much-longer-can-we-say-too-difficult/].

[15] LEED. (2019) How LEED v4.1 addressed embodied carbon [Available from: https://www.usgbc.org/articles/how-leed-v41-addresses-embodied-carbon].

[16] RIBA. 2030 Climate Challenge (2020) [Available from: https://www.architecture.com/about/policy/climate-action/2030-climate-challenge].

[17] Frasers Property. (2020) Minnippi Quarter: Build neutral - an Australian first [Available from: https://www.frasersproperty.com.au/QLD/Minnippi-Quarter/Sustainability#:~:text=Build%20Neutral%20%2D%20an%20Australian%20first,and%20construction%20of%20their%20homes].

[18] Pomponi F, Giesekam J, Hart J, Bernardino DA. (2020) Embodied Carbon: Status quo and suggested roadmap. https://zerowastescotland.org.uk/sites/default/files/Embodied_carbon_spreads%20final.pdf

[19] Pomponi F, Moncaster A. (2016) Embodied carbon mitigation and reduction in the built environment – What does the evidence say? Journal of Environmental Management. 181, 687-700.

[20] Durmesivic E. (2019) Circular Economy in Construction – Design Strategies for Reversible Buildings. The Netherlands: University of Twente; ISBN 9789082169843.

[21] Cheung L, Farnetani M. (2015) Whole-life carbon: facades: Building; [Available from: https://www.building.co.uk/whole-life-carbon/whole-life-carbon-facades/5078620.article#:~:text=To%20put%20all%20this%20into,19%25)%2C%20at%20practical%20completion].

[22] Crawford RH. (2004) PhD Thesis: Using Input-Output Data in Life Cycle Inventory Analysis: Deakin University. https://dro.deakin.edu.au/eserv/DU:30023201/crawford-usinginputoutput-2004.pdf

[23] Salcido JC, Raheem AA, Ravi S. (2016) Comparison of embodied energy and environmental impact of alternative materials used in reticulated dome construction. Building and Enviornment.96, 22-34.

[24] Bassett T, Waldron D, Iorwerth H, Lannon S. (2013) Embodied Energy at an Urban Scale: A paradigm shift in calculations. PLEA 2013 - 29th Conference, Sustainable Architecture for a Renewable Future; 10-12 September 2013; Munich, Germany.

[25] Hammond PG, Jones C. (2011) Inventory of carbon & energy (ICE) version 2.0. BSRIA: Sustainable Energy Research Team (SERT); Contract No.: v 2.0.

[26] Defra. (2011) Guidelines to Defra/DECC's Greenhouse Gas Conversion Factors for Company reporting, v1.1. http://www.defra.gov.uk/environment/economy/business-efficiency/reporting/

[27] Buyle M, Braet J, Audenaert (2013) A. Life cycle assessment in the construction sector: A review. Renewable and Sustainable Energy Reviews.26, 379-388.

[28] Xiao Y, Yang RZ, Shan B. (2013) Production, environmental impact and mechanical properties of glubam. Construction and Building Materials. 44, 765-773.

[29] EUMEPS EMoEP. EPD as per ISO 14025 and EN 15804: Expanded polystyrene (EPS) foam installation (with infra-red absorbers, density 15kg/m^3) [Available from: https://epd-online.com/].

[30] Sto AG. EPD according to ISO 14025: mineral ready-mixed render: rendering mortar - fibre-reinforced flexible plasters [Available from: https://ibu-epd.com/]

[31] Knauf. EPD as per ISO 14025 and EN 15804. Aquapanel®: Cement board indoor/outdoor [Available from: https://epd-online.com].

[32] Knauf Insulation. EPD as per ISO 14025 and EN 15804. Glass Mineral Woold 032-033 slabs [Available from: https://www.knaufinsulation.com/downloads/environmental-product-declaration-epd/glass-mineral-wool-ecose%C2%AE-gmw].

[33] Bundesverband der Gipsindustrie. EPD as per ISO 14025 and EN 15804: Gypsum plasterboard in accordance with DIN EN 529 and DIN 18180. [Available from: https://epd-online.com/].

[34] EJOT. ESD as oer /usi 14025 and EN 15804:Befestigungssysteme für Wärmedämm-Verbundsysteme. Institut Bauen und Umwelt e.V (in German) [Available from: http://www.ejot.com/medias/sys_master/002/h31/hc5/8851353993246/EPD-Befestigungssysteme-fuer-Waermedaemm-Verbundsysteme-de.pdf].

[35] Consulting G. Size and performance of the 5-star hotel chains in Greece 2018 [Available from: https://www.gbrconsulting.gr/downloads/Size%20and%20performance%20of%205-star%20hotel%20chains%20in%20Greece.pdf].

[36] UK Government. (2017) Fixing our broken housing market. https://www.gov.uk/government/publications/fixing-our-broken-housing-market

[37] The Institute for Environmental Research and Education. (2009) Carbon footprint of USA rubber tire recycling 2007. https://cmshredders.com/wp-content/uploads/2017/03/FinalRubberTireRecyclingCarbonFootprint.pdf

[38] Ellen MacArthur Foundation. The Circular Economy in Detail 2017 [Available from: https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail].

[39] Ojerinde AM, Ajao AM, Ogunbayo BF, Stevenson V, Latif E. (2018) The partial replacement of ordinary portland cement with rice husk ash to stabilize compressed earth blocks for affordable building materials. PLEA 2018: Smart and healthy within the 2 degree limit; Hong Kong2019. p. 321-325.