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Considering embodied energy and carbon in heritage buildings – a review

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Abstract. Approximately 20% of UK buildings can be defined as ‘heritage buildings’, offering unique values that should be preserved. They tend to use more energy than newer buildings, creating a strong case for energy retrofits to reduce energy use, greenhouse gas emissions, and improve thermal comfort. However, few studies of heritage retrofits examine embodied impacts, which are the energy and carbon impacts required to manufacture, transport and construct materials and components. This study considers the whole life (embodied plus operational) impacts of retrofitting heritage buildings, through a systematic literature review and thematic analysis. It concludes that; both embodied and operational impacts should be considered in retrofitting projects, retrofitting is better than demolish and rebuild in lifecycle terms, there is a lack of policy mandating for the measurement of lifecycle impacts and low impact retrofitting can be better for conserving heritage values and reducing embodied carbon.

1. Introduction

Heritage buildings have important cultural roles and help to shape the character of our rural and urban areas [1]. Heritage buildings are variously and broadly defined, and they can have a range of historical, aesthetic and communal values [2, 3]. Estimates suggest that approximately 20% of UK buildings could be considered to have heritage value and many of these have varying levels of protection/exemptions in planning law [4].

Reducing energy use and greenhouse gas emissions (referred to herein as carbon) is vital for mitigating climate change. The building sector is responsible for approximately 36% of global energy consumption and 39% of carbon emissions each year [5]. In the UK the building sector is responsible for around 30% of annual carbon emissions, with similar figures for other European countries [6]. There is growing evidence that heritage buildings can have better energy performance than standard models predict and there are strong arguments for their preservation [7]. It is also recognised however that most of these buildings should still be retrofitted to reduce their energy and carbon, while taking their heritage values into account [8, 9].

Currently energy retrofits of heritage buildings, and indeed buildings more generally, often only consider operational energy and carbon savings [10], that is, the energy/carbon spent during the building’s use. At present the embodied energy and carbon impacts of retrofit, from the manufacture, transport and construction of retrofit components and their maintenance and replacement throughout a building’s lifetime, are rarely examined [10]. This is part of a lifecycle assessment (LCA) approach that considers both embodied and operational energy/carbon to determine lifecycle impacts [11] The potential value of taking a lifecycle perspective on heritage building retrofits has occasionally been



identified but not explored in detail [12]. The use of LCA for buildings is becoming more mainstream but is still not commonplace and the need to take this approach is currently not recognised in national UK policy, or used to any great extent in practice [13].

This paper explores the literature on embodied energy/carbon in heritage buildings and addresses the following question: What academic research has been carried out into the embodied carbon and energy of heritage buildings to date, and what are the main conclusions and gaps? This study will inform a forthcoming research project that will include a consideration of any research gaps identified.

2. Methodology

This paper is based on a systematic literature review of embodied energy/carbon in heritage buildings followed by an identification of themes that emerge from the literature. This review offers a thorough and structured search of the literature with clear inclusion criteria [14]. A thematic analysis is then used to identify key areas in the literature that are pertinent to the research question; this is deemed an effective tool for synthesising papers with a broad diversity of methods [15]. In addition, the system boundaries and scope of the papers that undertake LCA is identified. This study will follow a similar method to that of Pomponi and Moncaster [15], who systematically reviewed the literature on embodied carbon in the built environment; this study however will focus on heritage buildings.

2.1. The literature review

The review searched: title, abstract and keywords, in Scopus, Science Direct, Web of Science and Google Scholar, as these represent four of the largest scholarly databases covering this topic. Because LCA in buildings is still a developing field the search was limited to the last decade and included only peer reviewed journal articles in English. The terms in Figure 1 were searched as indicated below, in individual combinations for thoroughness.

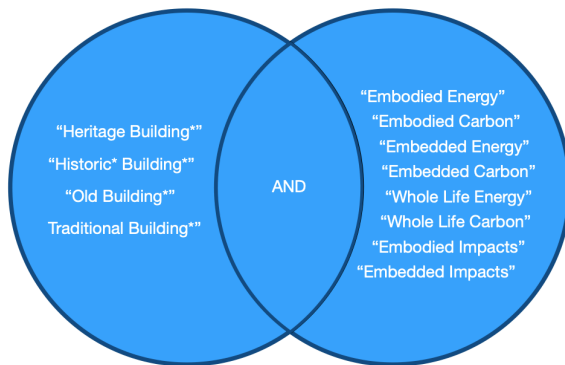


Figure 1. Venn diagram of Search Strings.

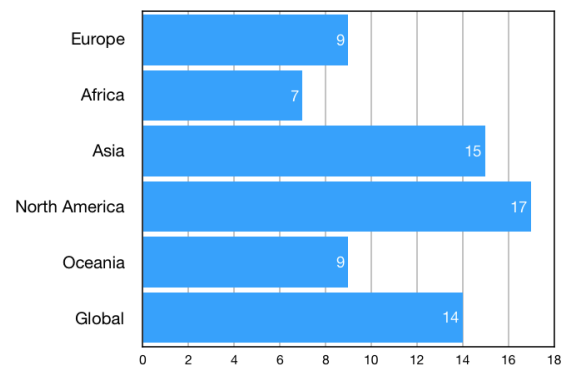


Figure 2. Research distribution by continent.

An initial 948 publications were returned by the search and their titles and abstracts were reviewed to identify meaningful use of the search terms. If there was any uncertainty about a paper's relevance it was retained at this stage. After this process and the removal of duplicates 141 papers remained, which were then read in full and further irrelevant papers were removed, leaving 87 papers relevant for inclusion. It is worth noting that not all of the papers included in this review deal specifically with heritage buildings. 34 of the 87 studies are LCA studies, of which 38% examine heritage buildings while the others assess particular traditional materials or older buildings more generally. These, non-heritage building, LCA studies have been included in the review because they may still have relevant information, transferrable to a heritage setting.

2.2. Thematic Analysis

Summaries of the papers were then created, grouped into broad themes and then refined through several iterations consistent with the principles of thematic analysis as described in [16]. Six key themes were identified through this process. In addition, a quantitative breakdown of the studies by country and publication date was undertaken. The system boundaries, which define the scope of the study, and data sources of the 34 LCA studies were identified, as were the methodologies of the non LCA studies.

2.3. Limitations

Potentially relevant publications from conferences, in books or the technical literature were excluded from this study. Initial examination suggested that conference papers were similar in scope and content to the journal articles reviewed. The effectiveness of the review process is also determined by the search terms meaning that some relevant papers may have been missed.

3. Results and Discussion

3.1. Breakdown of papers reviewed

Figures 2 and 3 show research by continent and country. Research is represented from all continents showing broad global interest in this topic, although almost 40% of papers explore European contexts.

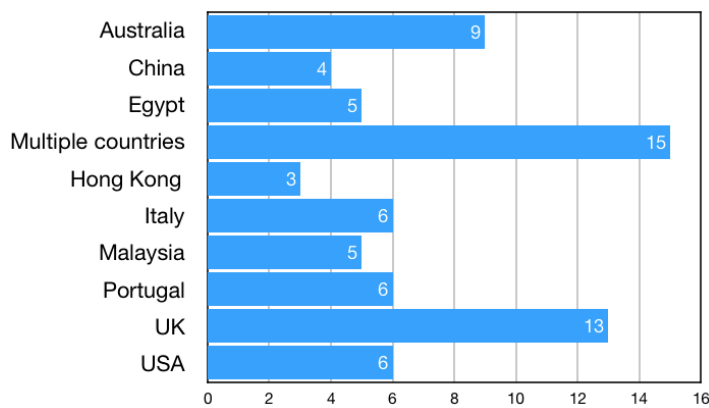


Figure 3. Top ten countries for research.

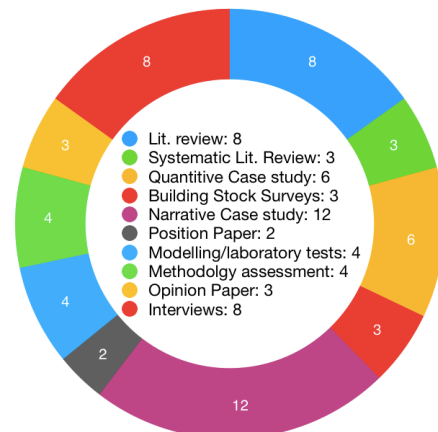


Figure 4. Methodologies of non LCA studies.

The methodologies of the 53 non LCA studies are shown in Figure 4. 34% of papers use narrative or quantitative case studies, making this the most common method, followed by narrative and systematic literature reviews at 20%. This appears consistent with other research identifying the prevalence of the case study method for heritage building research [12].

The publication trends of the papers studied appear to show an overall increase during the period reviewed, Figure 5. There is also an apparent step change in 2012 which, given the preponderance of European studies, could be linked to the publication of the European TC350 LCA standards in 2011-2012 as identified in [17]. This trend follows a general increase in heritage buildings research, evident in recent years. The diversity of journals in which these studies were published is broad, totalling 55 different publications. This indicates the lack of a dedicated journal for heritage buildings and embodied carbon, with relevant articles spread across different fields and disciplines.

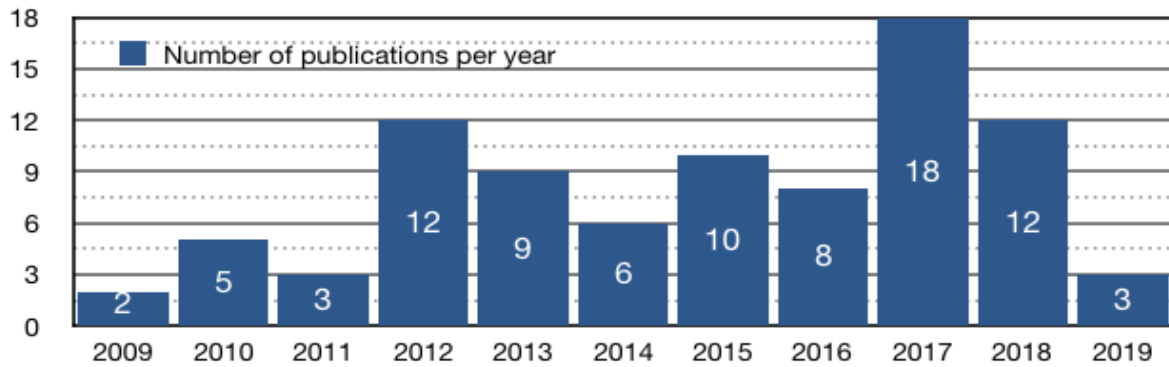


Figure 5. Publications per year during review period.

3.2. System Boundaries of LCA Studies

The system boundaries, data sources and scope of the 34 LCA studies were identified and are shown in Table 1 below. Many of these studies reference the ISO 1440 LCA standards and, in line with this, 88% had clear system boundaries [18,19], only 4 studies (12%) were deemed too unclear to categorise [20-23]. Figure 6 shows the different lifecycle stages. System boundary variation can mean the results of different studies are not directly comparable and as can be seen in Table 1 a range of lifecycle stages are included by different studies. 23% use cradle to grave (A1-C4), 23% cradle to site (A1-A4) and 12% cradle to gate (A1-A3). Cradle to grave is considered to provide the most comprehensive picture of lifecycle impacts, while studies with narrower boundaries are likely to underestimate the full impacts [11]. Studies used a number of different databases for materials' data, with several studies augmenting this with local data to provide a more accurate and contextual picture. For example, by considering the carbon intensity of a specific country's fuel mix [24] or the use of primary data where possible as in [25]. In other studies, however database information has been transposed to different national contexts, such as the use of UK average transport data in a Malaysian project [26], and this may reduce the accuracy of results. A broad variation of methods, system boundaries and data sources are therefore used in the LCA studies and this may reduce the accuracy and comparability of results.

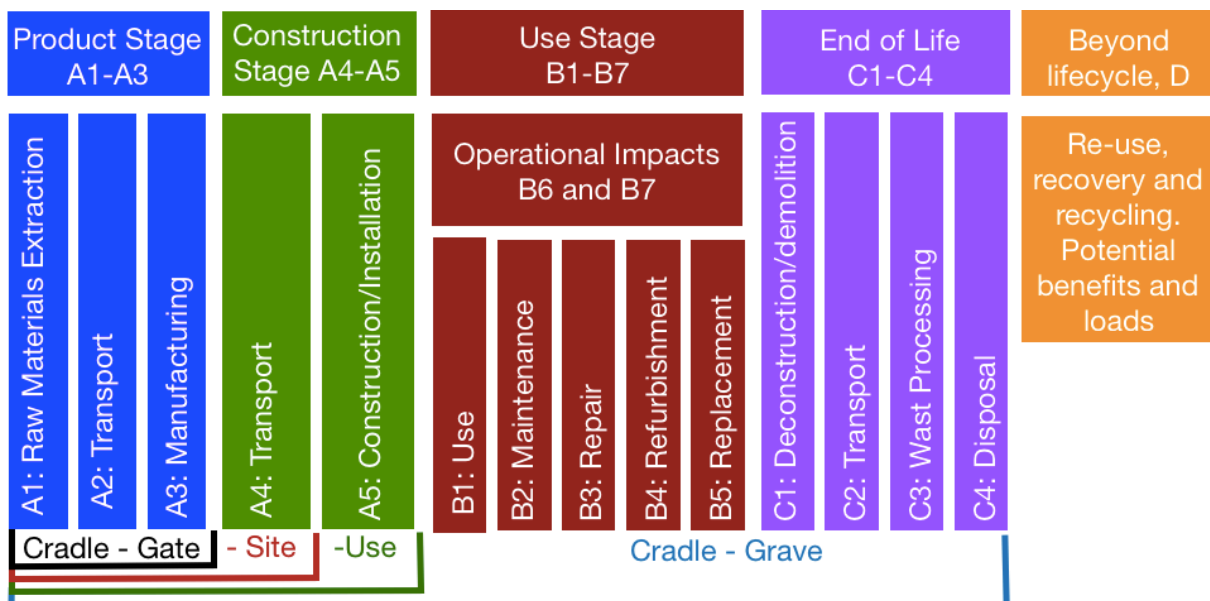


Figure 6: Lifecycle stages relating to buildings adapted from EN 15978 [27].

Table 1: System boundaries and scope of LCA studies.

Author	Lifecycle stages	LCA Database	Building type and scope. ie material, retrofit packages, repair options, etc.*
Almeida et al	Unclear	Multiple	EBs: 3 retrofit packages
Asdrubali et al	A1-B5	Eco-Invent	EB: 4 retrofit packages
Balleri and Marini	A1-A3	Bath	EB: Retrofit package + or - seismic strengthening
Bin Marsono and Balasbaneh	A1-A5	Unclear	RB: 7 wall material combinations
Brandão et al	A1-A3	Bath	M: Partition wall for HB
Burg and Fuglseth	A1-C4	Eco-Invent	HB: Retrofit package, demolish and replace
Chiang et al	A1-A4	Augmented database	EB: 32 internal finish options
D'Alessandro et al	A1-C4	Augmented database	M: straw bale building
Ding	A1-A4	Augmented database	HBs: Main construction materials
Ferreira et al	A1-A5	GaBi	HB: Retrofit package or demolish and replace
Franzoni et al	A1-A3	Eco-Invent	HB: 52 surface cleaning options
Gong et al	A1-C4	Unclear	M: 3 building frame structures
Hu	A1-C4	Athena	HB: complete building
Ip and Miller	A1-A5	Eco-Invent	M: Hemp line wall system
Iyer-Raniga and Wong	A1-C4	Eco-Invent	HBs: range of retrofit options
Kayan	A1-A4	Bath	HBs: 3 paint repair options
Kayan et al 2017 (a)	A1-A4	Bath	HB: 4 stone repair options
Kayan et al 2018, 2017, 2016, 2011	A1-A4	Bath	No specific building
Khorassani et al	A1-C4	Eco-Invent	HB: 1 retrofit package
Kyriakidis et al	A1-A3	Bath	M: 3 wall types, 1 traditional
Loussos et al	Unclear	NIBE	EB: 3 facade retrofits
Marique and Rossi	A, B6 -C4	Custom tool.	HB: Complete building
Mastali et al	A1-A3	Eco-Invent	M: Mortar
Pineda et al	A1-A5	Eco-Invent	HB: 6 grouts for stonework repair
Pomponi and D'Amico	A1-D	Multiple	RB: Timber double skinned facade
Pulselli et al	Unclear	Unclear	RB: complete buildings
Rodrigues and Freire	A1-B5	Unclear	HB: Insulation variants
Sharif and Hammad	Unclear	Multiple	EB: Retrofit package
Shen et al	A1-C4	Multiple	HBs: 4 whole buildings
Weiler et al	A1-C4	Eco-Invent	EB: 2 retrofit packages, demolish and replace
Zhang and Wang	A1-C4	Unclear	NB: complete building

***HB/s:** Heritage building/s, **EB/s:** Existing Building/s, **NB:** New Building, **RB:** Reference Building, **M:** Materials

3.3. Thematic Analysis

3.3.1 In lifecycle terms, preserving and retrofitting heritage buildings is better than their demolition and replacement with new energy efficient buildings (35 papers). Avoiding demolition waste and the embodied carbon investment of new build is frequently cited as a major benefit of preservation in heritage building adaptive re-use literature [28-31]. This is often stated with only limited detail but seems to be a widely accepted view [32-35]. A number of LCA studies, however, actually assess re-use and

retrofit versus demolition and rebuild. A Belgian heritage building study concluded that a retrofit package was 57% better in lifecycle carbon terms than demolish and rebuild [36]. [37] identified that a high level retrofit to a building constructed in 1975 was 15% better than a new construction built to 2016 German standards and [38] identified that re-use could be 4%-46% better in a Portuguese context. [38] identified 13% savings for their actual case study because of extensive structural support requirements due to seismic activity. 2 studies in this review [39, 40] suggested that the embodied carbon already extant in heritage buildings should be included in calculations as wastage if they are demolished, but most studies consider this a sunk cost and only include the embodied carbon required for demolition and new construction. An additional benefit of preservation identified in [41,42] is the temporal element to emissions. Carbon emissions must be reduced now to avoid climate change tipping points and uncontrollable feedback loops. Demolish and rebuild requires a large investment of embodied carbon in the present for future operational savings, which can have a highly negative impact, especially as energy mixes are expected to decarbonise in the future.

3.3.2 Traditional materials can perform better in lifecycle terms than highly manufactured modern solutions but research on more materials in diverse contexts is needed (25 papers). Studies in China and Malaysia assessed the lifecycle carbon of building frame materials, concluding that wood is significantly better than concrete and brick and slightly better than steel [43-44]. [19] examined hemp-lime walls in a UK context, concluding that these walls can have negative embodied carbon due to the potential for carbon sequestration. [33] also showed the carbon sequestration potential of hemp fibres in mortars with recycled aggregates but found that a maximum of 6% fibres was possible for structural applications. Other studies developed novel products; a low embodied carbon, wood and cork partition wall for Portuguese heritage buildings [45], or a double-skinned timber façade for a UK building [18]. Several of these LCA studies only measure initial embodied carbon and do not consider operational carbon or material lifespans [44-47]. As with studies that only look at operational carbon this is an issue because a full lifecycle picture is not developed, making assessments of benefits problematic. Considering the lifespan of different retrofit solutions is also important, to aid comparison of options. Other studies, [48- 51], identify the carbon benefits of traditional materials qualitatively, often in contrast to materials such as concrete, but do not provide any quantitative evidence for these benefits.

3.3.3 The embodied carbon of maintenance and repair should be included in the LCA of heritage buildings (12 papers). It is worth noting that 5 of these papers, by Kayan et al, are markedly similar in content, examining 4 options for stone repair in heritage buildings [26,52,53]. The authors' model identifies the importance of considering the durability and recurrent embodied carbon of different repair options as well as their initial embodied carbon and, in this context, identifies stone replacement as better than plastic repair or repointing. The importance of embodied carbon and the benefits of durability are noted by the same author in [54] when examining roof paint maintenance on Malaysian heritage buildings. A study from Hong Kong [24] explored the embodied carbon, financial cost and labour intensity of different internal finishes. A study of different grouting mortars in a Spanish heritage building [55] identified that hydrated lime grout is better than cement in embodied carbon and structural terms in a repair context. Finally, an LCA on 52 different surface cleaning products for use in Italian heritage buildings identified the high carbon impact of the cotton wool used in many cleaning processes [56]. There is a lack of studies on the maintenance of wooden components and elements such as windows which conservation organisations identify as having high heritage value [57]. This highlights that the durability and maintenance of retrofit options should be considered.

3.3.4 Lack of policy requirements to measure embodied carbon in heritage buildings (10 papers). This is seen as a key challenge to encouraging the calculation of embodied carbon. Two literature reviews identify the lack of, and need for, legislation on embodied energy in heritage buildings [58] and in buildings more generally [59]. [58] also specifically identifies the importance of comparing the lifecycle carbon of different retrofit options. Interviews with Australian building developers identify little

incentive for them to invest time and effort in calculating embodied carbon and the majority say they would not undertake this unless it was mandatory [60]. A study from Hong Kong also identified a lack of embodied impact consideration in practice and suggested that governments mandate for the routine availability of better-quality lifecycle data [61]. [62] cites a lack of embodied carbon policies in Australia, Spain and Europe. This lack of policy is particularly important for heritage buildings, where retrofits which affect heritage values must make lifecycle, not just operational, carbon savings.

3.3.5 Lack of tools and certification schemes that facilitate embodied carbon measurement in heritage buildings (12 papers). This is identified in numerous countries, particularly because key schemes such as LEED and BREEAM, which encourage the use of low carbon materials, are generally deemed poorly suited to a heritage building context [63,64]. Meanwhile the Portuguese ECS scheme and other similar decision support tools, often only consider operational carbon [65-68,60]. This is also identified in an Australian context [64,68] where the mandatory Green Star certification system was shown to not fully consider embodied carbon and to be poorly suited to heritage buildings [68]. Two studies [12,41] identify that some tools are being developed, such as a Swedish project covering lifecycle assessment and heritage values impacts and the EU's EFFESUS project. EFFESUS, completed in 2016, created a decision support tool assessing the lifecycle carbon and heritage impact of retrofits; however, the tool is not yet available as the business model is still in development.

3.3.6 Including embodied carbon in a lifecycle perspective significantly effects the most appropriate retrofit options and may be complementary to sensitive retrofit of heritage buildings (13 papers). A key finding is that smaller retrofit interventions are often better in lifecycle terms than more intrusive interventions [57]. An Australian study of different retrofits for eight heritage buildings identified that double glazing with ultra violet film actually increased the lifecycle energy by an average of 2% [62]. In contrast secondary glazing had average savings of 2%, while the addition of thermal curtains to the original windows led to average savings of 3% with a much lower impact on heritage values and reduced financial costs. This links to findings reported in [57], that curtains, shutters and secondary glazing had better lifecycle carbon than most double-glazing options in Scottish heritage buildings. An Italian study of retrofit packages to an 80-year old school identified that the cost optimal package, with smaller interventions, was significantly better in lifecycle carbon terms than retrofitting to government standards or as a nearly zero energy building [69]. [47] showed the low embodied carbon and significant thermal benefits of adding thermal lime plaster to a traditional adobe wall in southern Europe. [41] identified the benefits of smaller interventions and also noted that environmentally conscious user behaviour can significantly affect operational carbon in heritage buildings, with almost 50% less energy used in the case study than predicted by modelling. The effect of user behaviour was also considered in insulation retrofits to a Portuguese heritage building where different temperature set points were modelled [70]. A final study, a heritage complex in Spain, considered the project's social and economic impacts in addition to the lifecycle carbon, identifying these as broadly positive [71].

4. Conclusions

This study has identified a developing global interest in this topic, particularly in Europe, and shown that relevant articles are spread across a broad range of journals from different disciplines.

In response to the research question 'What academic research has been carried out into the embodied carbon and energy of heritage buildings to date and what are the main conclusions and gaps?' There are few LCA studies dealing with heritage buildings specifically. There is a broad diversity in system boundaries for the LCA studies and this, and the out of context use of LCA databases, reduces accuracy and makes comparisons challenging. Preserving heritage buildings has been shown by several authors to have lifecycle carbon benefits over demolition and rebuild, with temporal aspects of carbon emissions providing additional support for preservation. Some evidence was found for the carbon benefits of traditional materials and these would also help to preserve heritage values. The importance of including recurrent carbon from repair and maintenance activities was identified, as was the need to consider

retrofit lifespans. The literature showed a global lack of policy mandating for the calculation of embodied carbon and identified that the majority of practitioners are unlikely to undertake these measurements without regulation or incentives. A lack of support tools and certification schemes for embodied impacts in heritage buildings was also seen, although there appears to be some development in this area. Finally, the importance of considering the embodied and operational carbon of heritage building retrofits in a lifecycle perspective was identified and it was seen that this approach might be complementary to heritage sensitive retrofitting by providing support for lower impact interventions.

The literature therefore strongly suggests that embodied carbon affects the best retrofit choices for heritage buildings and should be considered in these projects. Embodied carbon influences whether to retrofit or replace and which materials and retrofit options are best in lifecycle terms. More evidence is needed to help build the case to policy makers that the calculation of lifecycle carbon should be included in regulation. Further research on the lifecycle performance of different retrofit options and traditional materials is required to reduce carbon from heritage buildings and help mitigate climate change.

References

- [1] Deliotte R E 2017 *Heritage Works: A toolkit of best practice in heritage regeneration* (Historic England)
- [2] Mazzarella L 2015 *Energy Build.* **95** 23–31
- [3] CADW 2011 *Criteria for assessing historic buildings for the purposes of grant assistance* (Welsh Government)
- [4] Pickles D and McCaig I 2017 *Energy Efficiency & Historic Buildings: Application of Part L of the Building Regulations to Historic & Traditional* (Historic England)
- [5] Global Alliance for Buildings and Construction 2017 *Global Status Report 2017* (UN Environment)
- [6] UK Green Building Council and Aldersgate Group 2017 *Energy efficiency in the UK's buildings: key priorities for the new government* (London)
- [7] Pracchi V 2014 *Hist. Environ. Policy Pract.* **5** 210–25
- [8] Cabeza L F, de Gracia A and Pisello A L 2018 *Energy Build.* **177** 96–111
- [9] Ascione F, Bianco N, De Masi R F, de' Rossi F and Vanoli G P 2015 *Energy Build.* **95** 172–83
- [10] May N and Griffiths N 2015 *Planning Responsible Retrofit* (Sustainable Traditional Buildings Alliance)
- [11] Birgisdottir H, Moncaster A, Houlihan Wiberg A, Chae C, Yokoyama K, Balouktsi M, Seo S, Oka T, Lützkendorf T and Malmqvist T 2017 *Energy Build.* **154** 72–80
- [12] Webb A L 2017 *Renew. Sustain. Energy Rev.* **77** 748–59
- [13] UK Green building Council 2015 *Tackling Embodied Carbon in Buildings* (London: UK Green Building Council)
- [14] Sawyer R K 2017 *Educ. Res. Rev.* **15**
- [15] Pomponi F and Moncaster A 2016 *J. Environ. Manage.* **181** 687–700
- [16] Braun V and Clarke V 2006 *Qual. Res. Psychol.* **3** 77–101
- [17] Moncaster A M and Symons K E 2013 *Energy Build.* **66** 514–23
- [18] Pomponi F and D'Amico B 2017 *Build. Environ.* **124** 42–56
- [19] Ip K and Miller A 2012 *Resour. Conserv. Recycl.* **69** 1–9
- [20] Almeida M, Ferreira M and Barbosa R 2018 *Buildings* **8** 103
- [21] Sharif S A and Hammad A 2019 *J. Build. Eng.* **21** 429–45
- [22] Loussos P, Konstantinou T, Van den Dobbelsteen A and Bokel R 2015 *Buildings* **5** 622–49
- [23] Pulselli R M, Niccolucci V and Marchettini N 2009 *Int. J. Des. Nat. Ecodynamics* **4** 11–5
- [24] Chiang Y H, Li J, Zhou L, Wong F K W and Lam P T I 2015 *J. Clean. Prod.* **109** 326–35
- [25] D'Alessandro F, Bianchi F, Baldinelli G, Rotili A and Schiavoni S 2017 *J. Build. Eng.* **11** 56–68
- [26] Kayan B A, Zaid N S M and Mahmud N S 2017 *J. Des. Built Environ.* **15**
- [27] European Committee for Standardization, 2012b. *EN 15978: Sustainability of construction*

works - Assessment of environmental performance of buildings - Calculation method

- [28] Allen A D 2012 *Transylv. Rev. Adm. Sci.* **8** 11–8
- [29] Thornton B J 2011 *J. Green Build.* **6** 1–7
- [30] Matthews J, Dyson K and Love P E D 2016 *Built Environ. Proj. Asset Manag.* **6** 44–57
- [31] Khalil A M R, Hammouda N Y and El-Deeb K F 2018 *Heritage* **1** 57–87
- [32] Throsby D 2016 *City Cult. Soc.* **7** 81–6
- [33] Ragheb G, Ragheb A A and Ragheb R A 2017 *Int. J. Curr. Eng. Technol.* **7** 8
- [34] Firzan M, Keumala N, Zawawi R and Ahmad A G 2015 *Built. Environ.* **12** 13
- [35] Craun Z 2012 *J. Int. Aff. N. Y.* **65** 157–XII
- [36] Marique A-F and Rossi B 2018 *J. Environ. Manage.* **224** 396–405
- [37] Weiler V, Harter H and Eicker U 2017 *Energy Build.* **134** 319–28
- [38] Ferreira J, Duarte Pinheiro M and de Brito J 2015 *J. Build. Eng.* **3** 114–26
- [39] Akande O K, Odeleye D and Coday A 2014 *Int. J. Sustain. Dev. Plan.* **9** 237–50
- [40] Merlino K R 2014 *Public Hist.* **36** 70–85
- [41] Berg F and Fuglseth M 2018 *J. Archit. Conserv.* **24** 152–67
- [42] Zhang X and Wang F 2017 *Energy Build.* **155** 404–13
- [43] Gong X, Nie Z, Wang Z, Cui S, Gao F and Zuo T 2012 *J. Ind. Ecol.* **16** 576–87
- [44] Bin Marsono A K and Balasbaneh A T 2015 *Constr. Build. Mater.* **85** 100–8
- [45] Brandão F J da S, Paio A, Sousa J P and Rato V 2016 *Gest. Tecnol. Proj* **11** 9–24
- [46] Mastali M, Abdollahnejad Z and Pacheco-Torgal F 2018 *Constr. Build. Mater.* **160** 48–56
- [47] Kyriakidis A, Michael A, Illampas R, Charmpis D C and Ioannou I 2018 *Energy* **161** 1016–27
- [48] Quagliarini E, Stazi A, Pasqualini E and Fratolocchi E 2010 *Sustainability* **2** 3291–308
- [49] Kolokotsa D, Maravelaki-Kalaitzaki P, Papantoniou S, Vangeloglou E, Saliari M, Karlessi T and Santamouris M 2012 *Sol. Energy* **86** 1648–59
- [50] Ede A N, Olofinnade O M, Edwin E-A and Bamigboye G 2017 *Int. J. Appl. Eng. Res.* **12** 7873–83
- [51] Keable R 2010 *Carbon Clim. Law Rev.* **2010** 357–63
- [52] Kayan B A, Halim, I A and Mahmud N S 2017 *Chem. Eng. Trans.* 337–342
- [53] Kayan B A, Banfill P F G and Forster A M 2016 *Smart Sustain. Built Environ.* **5** 143–64
- [54] Kayan B A 2017 *Int. J. Build. Pathol. Adapt.* **35** 63–89
- [55] Pineda P, García-Martínez A and Castizo-Morales D 2017 *Constr. Build. Mater.* **138** 528–47
- [56] Franzoni E, Volpi L, Bonoli A, Spinelli R and Gabrielli R 2018 *Energy Build.* **165** 92–105
- [57] Curtis R 2010 *J. Archit. Conserv.* **16** 7–27
- [58] Lidelöw S, Örn T, Luciani A and Rizzo A 2019 *Sustain. Cities Soc.* **45** 231–42
- [59] Zeng R and Chini A 2017 *Energy Build.* **155** 172–84
- [60] Wilkinson S J and Remoy H 2017 *Sustain. Build.* **2** 1–10
- [61] Langston C, Chan E H W and Yung E H K 2018 *Sustainability* **10** 3229
- [62] Iyer-Raniga U and Wong J P C 2012 *Build. Environ.* **47** 138–49
- [63] Loli A and Bertolin C 2018 *Buildings* **8** 22
- [64] Balderstone S 2012 *Hist. Environ.* **24** 6
- [65] Nunes P, Lerer M and Graça G C da 2013 *Energy Eng.* **110** 7–34
- [66] Ferreira J, Duarte Pinheiro M and de Brito J 2013 *Constr. Build. Mater.* **49** 425–47
- [67] Baker H, Moncaster A and Al Tabbaa A 2017 *Proc. Inst. Civ. Eng. - Forensic Eng.* **170** 144–56
- [68] Conejos S, Langston C, Chan E H W and Chew M Y L 2016 *Build. Res. Inf.* **44** 507–19
- [69] Asdrubali F, Ballarini I, Corrado V, Evangelisti L, Grazieschi G and Guattari C 2019 *Build. Environ.* **147** 461–72
- [70] Rodrigues C and Freire F 2017 *J. Clean. Prod.* **157** 94–105
- [71] Khorassani S M, Ferrari A M, Pini M, Blundo D S, Muiña F E G and García J F 2018 *Int. J. Life Cycle Assess.* 1–22