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Embodied carbon consideration for maintenance & repair appraisal in heritage building: a review

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Abstract. Reducing carbon emissions is critical to mitigating climate change, and the building sector is one of the largest contributors to carbon emissions, accounting for around 39%. Recent evidence has shown that accounting for embodied carbon in life cycle assessment (LCA) could help reduce carbon emissions during the maintenance and repair phase. This paper narratively examines the literature review of embodied carbon considerations in the life cycle assessment (LCA) of historic buildings during the maintenance and repair phase. The search for all previously published articles was conducted in various databases using specific keywords identified as relevant to this study. The results of the database search were summarized and synthesized after review to ensure that the research questions could be met. The results show that considering embodied carbon in the LCA is essential when selecting the maintenance or repair approach taking environmental aspects into account. In addition, this study also highlights the importance of maintenance durability on the amount of embodied carbon consumed during the maintenance and repair phase. Furthermore, the lack of policy and legislation on carbon consideration in heritage conservation is seen as a major challenge in this area. This finding also suggests that there is a lack of interest in this area among policymakers, so this area needs to be studied in depth to address this issue. The study recommends developing a procedure that incorporates embodied carbon consideration into the existing decision-making process for preserving historic buildings. The procedure is intended to help select the best maintenance and repair approach that not only preserves the value of the structure but also results in the lowest possible carbon consumption during the maintenance and repair phase. The developed procedure should be tested and evaluated in a heritage conservation project to convince policy makers that life cycle carbon calculations should be included in the regulations.

1. Introduction

Building or structures that are essential to the country's history and culture must be preserved and well maintained. The implementation of a good conservation approach would be the best to fulfil that need. Good conservation effort shall encompass both ongoing maintenance operation and work intended to maintain the building in its original state. Historic buildings are thought to be able to live longer through maintenance. It will be a disadvantage to the historic buildings when there are no proper and regular maintenance work being carried out. This condition will lead to various issues that will expose heritage buildings to problems such as become decay, become non-functional and uninhabitable [1]. Poor maintenance causes historic buildings to age, become unsafe, and become unsightly, endangering not just the public but also its occupants. Neglecting maintenance can also result in severe issues that impact the state, capabilities, functionality, and efficiency of a building [4]. Structures with emotional, cultural, and practical values that are a part of a nation's cultural heritage ought to be preserved. If ongoing conservation efforts are not made, this historic structure may go extinct. Obviously, as a priceless piece of national heritage, this historic building needs to be restored immediately. The nation may suffer large financial losses due to failure in managing and preserving the cultural heritage [40].

It is commonly acknowledged that maintenance is not only a crucial mechanism for protecting the cultural heritage, but also to preserve embodied capital value, including environmental considerations [18]. Lately, sustainability has become the focus and attention in the conservation of heritage buildings especially in maintenance works and repair [20,22]. To achieve sustainable repair for heritage buildings, good maintenance practises and efficient repair operations are required. The amount of carbon emissions caused by maintenance work will be considerably decreased by utilising proper maintenance practises and repair approach for heritage buildings [18]. Combating climate change through the carbon emission reduction is essential since the building sector accounts for about 39% of annual carbon emissions [35]. Several studies have proven that considering embodied carbon in Life Cycle Assessment of heritage building could assists in mitigating the carbon emissions expended during the maintenance phase [21,24].

This paper explores the literature on embodied carbon assessment in heritage buildings specifically during maintenance and repair phase and addresses the following research question:

1) How embodied carbon consideration in Life Cycle Assessment (LCA) could influence in carbon emission reduction during maintenance and repair phase of heritage building?
2) Do embodied carbon assessment being considered in current policy and regulation of heritage building conservation works?

This study will eventually propose an upcoming potential research project based on any research gaps identified.

2. Methodology

This paper is based on a narrative literature review of embodied carbon consideration in maintenance, as well as a detailed and systematic literature review with clear inclusion criteria relevant to the research questions raised in this study. Based on the study's findings, discussions were held, and a potential research gap was identified. Several steps were done in this study to conduct the literature search, and the process flow of the literature search can be summarised as follows.:

1) *Define the topic and research questions.*
   Some exploratory searching of the literature has been done to get a sense of scope, to determine whether to narrow or broaden the focus of this study. This is to ensure that there is enough data in the literature to meet the needs to conduct a review [13].
2) *Conduct a search.*
   Before conducting a search, it is vital to identify databases that provide the most relevant sources and also relevant keywords to be used while searching [10]. As for this study, several databases being selected to conduct the search are Emerald Insight, IEEE, ScienceDirect, IOPScience, Scopus and also Google Scholar. While conducting this research, numerous keywords been used on those electronic databases to search for the research papers that are pertinent with the study. This is to ensure all the related papers managed to be identified. Among the keywords that being used are such as “ Heritage Building Maintenance”, “Life Cycle Assessment” and “Embodied Carbon”. Combining those keywords with Boolean operators such as “AND”, “OR”, and “NOT” [13], was really helpful in this study as all related articles could be find and any unnecessary articles could be excluded.
3) *Review Abstracts and Articles*
   After the search is complete and all unnecessary papers are sorted out, then the abstracts of the remaining articles had been reviewed to ensure that those papers address the research question [10].

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4) *Document Results*
Findings from the articles are then summarized and synthesized. This is to not only summarise the relevant literature but to also analyse it, to provide a critical discussion of it, and to identify any knowledge gaps [13]. By doing this, this study managed to give a critical discussion based on findings from the literature review and subsequently identified the research gap.

3. Literature review

This section provides relevant studies focusing on definitions of terminologies of heritage building, conservation, maintenance, and life cycle assessment is presented.

3.1 Heritage building

Something is put into a place as a heritage because it is valued to be worth protected or the understanding of why the place is important and what about it that contributes to that importance [27]. Heritage is characterized as any noteworthy structure, building, or artifact with a unique history and cultural significance. It is also understood as knowledge that is defined within a social, political, and cultural context. A society's identity and cultural legacy are represented by its old and historic structures [5]. There is many aesthetic, archaeological, architectural, cultural, historic, documentary, social, political, and even spiritual or symbolic values associated with built heritage, which is widely acknowledged. Structural remnants or building ruins can also be considered as built heritage [27].

Exposing the youth with cultural identities for heritage buildings should be emphasised [32] so that the new generation will be more appreciative and sensitive to the development of the country's history. Heritage buildings provide character and tangible connection to the past; they connect the present generation to history and identity that are hard to be replaced [3]. Preservation of the past for the benefit of the present and future generations is referred to as heritage [5].

3.2 Heritage building conservation

Conservation can be describe as maintaining existing structures while preserving their character and details, even when repairs or adjustments are needed. It focuses on preserving as much of the original structure as possible while also identifying new additions and modifications. Conservation allows significant alteration as long as the modifications are of historically and architecturally significance. [6]. Based on the definitions stated, conservation is any necessary act that could benefit the heritage buildings in terms of protecting and maintaining the building's unique characteristics such as cultural, aesthetic, and historical values. The intervention process should retain the building's unique characteristics as much as possible without damaging or changing the existing building's characteristics.

3.3 Maintenance in the context of conservation

Being acknowledge as one of the works involved in the effort to conserve heritage buildings, maintenance should be given specific attention compared to other conservation works, especially in terms of its implementation. The implementation of maintenance needs to be done on schedule and systematically. Maintenance also needs to be carried out from time to time regularly to prevent any serious issues on the heritage building structures and not only to be carried out when there is an urgent need [30,38]. In the context of conservation, maintenance being adopted to retain as much as possible the original structure of historical buildings and to prevent any declination of the historical buildings' status and value [2]. Zolkafli et al., (2019) further added maintenance refers to all of the technical and practical works required to preserve heritage buildings and prevent their value from declining. The longevity of historic buildings depends on how excellent the maintenance works being carried out. The implementation of good maintenance works needs to be emphasized as this could prevent any unnecessary and troublesome repair works which might give negative impact on significance values of heritage buildings. Good maintenance work also necessary to ensure the heritage building's structure remain intact and still can be used according to building's function besides preserving the uniqueness of heritage buildings throughout the time. Therefore, without doubt, maintenance is essential for heritage buildings when it comes to protecting and preserving all the significant value's which make the heritage buildings worth to be conserved.

3.4 Life cycle assessment & embodied carbon

Life cycle assessment refers to a process that measures the environmental impact of a product during the whole life cycle. Assessing the environmental impact would require calculating the consumption of energy and materials as well as waste that is released into the environment [12]. A building's life cycle consists of several phases and each of those contributes to embodied emissions [7] which generally make up the environmental impact. Every stage of a building's life cycle involves a certain process which requires the use of energy to carry out the process. Due to this, the consumption of various types of energy is necessary such as fossil fuel, electric energy, and water, which results in the production of pollutant gases which could harm the environment especially carbon dioxide (CO_2) [28]. Life cycle stages of a building are shown in the table below.

Table 1. Life cycle stages of a building (Source: Baker & Moncaster, 2018)

Stage	Code	Sub-stage
Product Stage	A1	Raw Material Supply
	A2	Transport
	A3	Manufacturing
Construction Process Stage	A4	Transport
	A5	Construction Installation Process
Use Stage	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Refurbishment
	B5	Replacement
	B6	Operational energy use
	B7	Operational water use
End of Life Stage	C1	De-construction/demolition
	C2	Transport
	C3	Waste Processing
	C4	Disposal
Benefits and loads beyond the system boundary	D	Reuse, Recovery, and Recycling Potential

Embodied carbon includes all the CO_2 produced from various processes which take place inside the specific boundaries or phases of a product life cycle [14]. In practice, there are various definitions of embodied carbon, relying on the boundary of the studies and embodied carbon's different forms [33]. Based on the chosen system boundary, there are three common definitions: cradle-to-gate; cradle-to-site; and cradle-to-grave embodied carbon. There are two types of emissions that make up embodied carbon which are direct emissions and indirect emissions. Direct emissions are from the assembly activities while indirect emission incurred in the extraction of feedstock, the building material production and transportation of final building materials to the construction site. Moreover, it is also possible to define embodied carbon as the total of process-related and fuel-related carbon emissions released from manufacturing facilities and machinery.

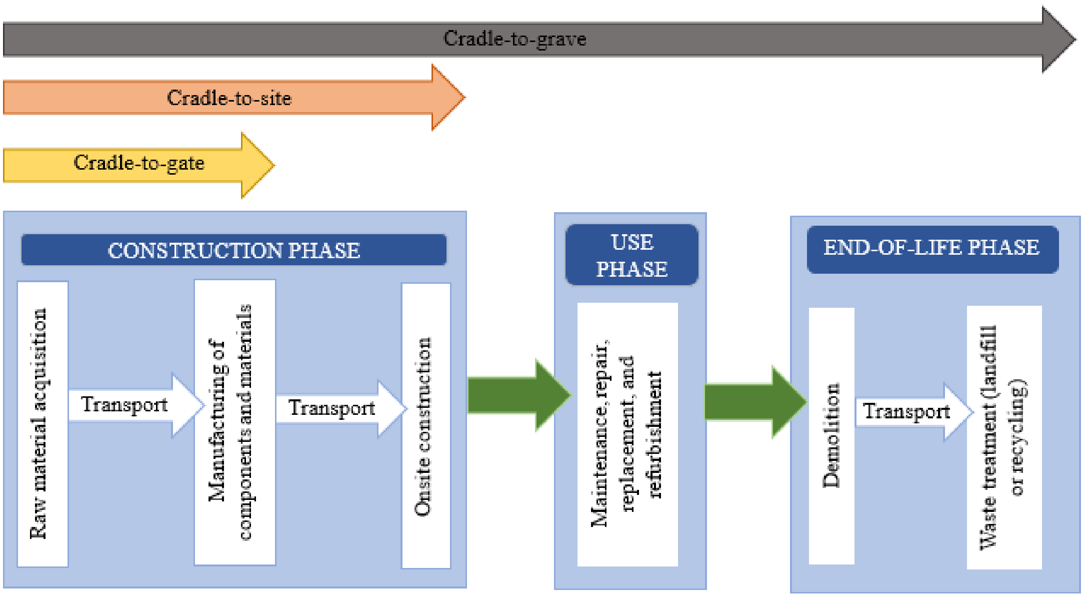

Figure 1. Building's lifecycle embodied carbon emissions (cradle-to-gate; cradle-to-site, and cradle-to-grave) (Source: Trinh, Doh & Hou, 2017)

4. Findings & discussion

This section will highlight the findings from the literature study which are relevant to the research questions identified in this study and subsequently will give a brief discussion regarding the findings.

4.1 The influence of carbon consideration in LCA to reduce carbon emissions of heritage buildings during maintenance and repair phase

This study through literature review has found that carbon emission reduction in heritage buildings during maintenance and repair could be achieved by quantifying the embodied carbon expended during that phase. Several studies [17,19,22,23] have shown the assessment could be done through the cradle-to-site analysis (raw material extraction, materials manufacturing, and transportation of material to construction site) in Life Cycle assessment (LCA). Thus, making it necessary for embodied carbon to be included in LCA when considering the maintenance or repair approach with environmental considerations. Through the Life Cycle Assessment (LCA), it is possible to determine the environmental impact during the maintenance phase of heritage buildings and enabling the examination of low carbon maintenance options. Based on the literature, durability of maintenance also influences the carbon consumed during the maintenance phase, as durable maintenance required minimal intervention and thus reduced carbon emissions during the maintenance phase compared to less durable maintenance. Embodied carbon assessment can contribute to reducing carbon emissions and help make the right decisions for the selection of maintenance and repair techniques in heritage buildings. This review has identified the repair materials that have been studied regarding the carbon embodied assessment in heritage building are laterite stone [19,22,23], stone masonry [17], paint [18], lime plaster [24], clay [21] and lime grout and cement [29]. Another heritage building material that have potential to be assess its embodied carbon in maintenance and repair is timber. In addition to that, according to Wise et al., (2019) there is a lack of studies on the maintenance of wooden components and elements such as windows which being regarded as high heritage value by conservation organisations. Table 2 summarizes the findings from the recent studies obtained through the literature review regarding embodied carbon consideration in maintenance and repair for heritage buildings.

Table 2. Summary of findings regarding the LCA of heritage buildings during maintenance and repair phase

No	Source	Findings
1	Kayan *et al*., (2017) (2018a) (2018b)	Highlights the importance of considering the durability and the embodied carbon of different repair options in selecting the best approach for maintenance when examining different options for stone repair in heritage building.
2	Kayan (2017)	Highlights the importance of embodied carbon assessment and the benefits of durability in maintenance when examining roof pain maintenance on Malaysian heritage buildings.
3	Kayan *et al.*, (2016)	Assessment of embodied carbon can play in reducing carbon emissions and underpins rational decision making for stone masonry wall repair techniques selection.
4	Kayan *et al*., (2021a)	Evaluation of the Environmental Maintenance Impact (EMI) within the selected boundaries of life cycle assessment (LCA) has been recognized in embodied carbon expenditure reduction in the form of CO2 emissions mitigation during maintenance phase when examining lime plaster repair for heritage buildings.
5	Kayan *et al*., (2021b)	Evaluation of the Environmental Maintenance Impact (EMI) within the selected boundaries of life cycle assessment (LCA) has been recognized in embodied carbon expenditure reduction in the form of CO2 emissions mitigation during maintenance phase when examining Singgora roof tile repair.
6	Chiang *et al*., (2015)	Explored the embodied carbon, financial cost, and labour intensity of different internal finishes in Hong Kong.
7	Pineda et al., (2017)	Identified that hydrated lime grout is better than cement in embodied carbon and structural terms in a repair context in a Spanish heritage building.
8	Franzoni et al., (2018)	Identified the high carbon impact of the cotton wool used in many cleaning processes through a life cycle assessment (LCA) that being carried out on 52 different surface cleaning products in Italian heritage buildings.

4.2 Carbon consideration in current policy and legislations of heritage building conservation works

This study found that there is a lack of policy and legislations globally to consider embodied carbon in Life Cycle Assessment (LCA) of heritage buildings and recent studies [36,25] show that the requirement for the legislations is necessary when making best decision for conservation approach with low carbon impact. This is seen as a boundary in promoting embodied carbon calculations among heritage conservation practitioners. This also shows that this area does not yet receive enough attention from policy makers and there is still no awareness of this matter. This literature also found out that the expert in building sector would only to consider embodied carbon in the project when there are legal requirements that oblige them to do so, and incentive also could be given as encouragement. A study [8] through the survey conducted with targeted group participant also found that embodied impacts are not part of policy yet is due to problems with its quantification and the methodology, including the choice of different life-cycle stages and data uncertainty. This is also implying that proper methodology or procedure is necessarily required to measure the embodied carbon in heritage buildings and the researchers shall take note in this matter.

Same paper also highlight that a lack of policy deemed to be the main reason for the absence of embodied impacts in decisions. Development of policy with regard of carbon emission in heritage building conservation works could also mitigate the environmental impact due to maintenance and repair works in heritage buildings. Table 3 summarizes the findings from the recent studies obtained through the literature review regarding embodied carbon consideration in policy and regulations for heritage building conservation.

Table 3. Summary of findings regarding the policy and regulations requirements for embodied carbon measurement in heritage buildings

No	Source	Findings
1	Lidelöwa *et al*., (2019)	Identified the lack of, and need for, legislation on embodied energy in heritage buildings.
2	Zheng & Chini, (2017)	Identified the lack of, and need for, legislation on embodied energy in buildings generally.
3	Wilkinson & Remoy, (2017)	Through the interviews with Australian building developers, it is being identified that little incentive is required to encourage them to invest time and effort in calculating embodied carbon and the majority of them say they would not undertake this unless it was mandatory.
4	Langston *et al*., (2018)	Identified a lack of embodied impact consideration in practice in Hong Kong and suggested that governments mandate the measurements of embodied carbon for better-quality lifecycle data.
5	Raniga & Wong, (2012)	Identified lack of embodied carbon policies in several countries include Australia, Spain, and European country as a whole.
6	Zaid *et al*., (2021)	It was identified that integration of carbon reduction requirement as a suitable environmental integration in improving existing Malaysian Heritage conservation legislation.
7	Baker *et al.*, (2021)	The calculation of embodied impacts needs to be included in regulation, and that demonstration of the reduction of whole life impacts should be a requirement before buildings are demolished.
8	Sesana et al., (2019)	Through the survey, the interviewees felt that having more legislation, regulations and guidelines would facilitate climate change mitigation in the cultural built heritage sector.

5. Conclusion & recommendations for future research

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

In response to the first research question mentioned earlier, there are few LCA studies dealing with embodied carbon expended during maintenance and repair phase in heritage buildings specifically. Those studies have shown that the environmental impact due to carbon expended during maintenance and repair phase can be measured through cradle-to-site analysis in LCA. Several authors have highlighted that it is necessary to put embodied carbon measurement into consideration in LCA when selecting the best maintenance and repair options for heritage buildings with lower environmental impact. This is also an approach that worth to be considered in mitigating the carbon emission in building sector. There is also clear evidence that showing the relation between the maintenance durability and the carbon expended where the durability of maintenance will influence how frequent the intervention will be thus have an effect on the carbon emission.

For the second research question, from the literature, there are lack of policy or legislations that consider embodied carbon as mandatory in heritage building conservation works. Besides from the literature also it is being identified that, majority of practitioners in building sector would only to consider the embodied carbon measurements when there are requirements by the policy and legislations. In addition to that few studies also emphasized that the policy and legislations on embodied carbon is necessary, and improvements shall be made in existing heritage conservation legislation and policy where carbon reduction requirement should be included. Recent studies have shown that embodied carbon consideration would be beneficial in reducing environmental impact from the heritage building maintenance and repair works. The researcher needs to give more focus in this area, as more evidence is needed to attract the attention of policy makers to include the calculation of embodied carbon in the regulations.

Given the lack of policies and regulations to account for embodied carbon emissions, it is likely that the existing historic preservation decision-making process does not include requirements to reduce carbon emissions. Therefore, this study proposes to develop a procedure that incorporates embodied carbon into the current decision-making process for the preservation of heritage buildings. The process should allow preservationists to choose maintenance and repair options that not only protect the building's historical significance but also reduce its environmental impact. Measuring embodied carbon in potential maintenance and repair approaches is one of the steps that must be taken when selecting the best maintenance and repair approach for heritage buildings. The procedure should be practical and applicable for conservation practitioners. The development of this procedure will also serve to address the issues raised by Baker et al., (2021) and quantify embodied carbon in heritage building. The development of this procedure significantly to support the carbon reduction strategy and also shows that the maintenance and repair of historic buildings can contribute to reducing carbon emissions. Supported by findings from recent studies, the procedure is expected to produce positive results for maintenance and repair works in heritage buildings. This could serve as evidence to attract the attention of policy makers so that consideration of embodied carbon becomes mandatory in policy and legislation.

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