GREEN MAINTENANCE MODELLING: MATHEMATICAL FRAMEWORK OF LIFE CYCLE ASSESSMENT APPROACH IN HISTORIC MASONRY BUILDINGS

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Abstract

The efficiency of maintenance interventions for historic masonry buildings can be assessed based on philosophical, economic and on increasingly, sustainability of built environment context. This paper establishes the concept of ‘Green Maintenance’ modelling for historic masonry buildings using mathematical framework of life cycle assessment (LCA) within ‘cradle-to-site’ boundary. This mathematical framework enabled assessment of embodied carbon expenditure expended from different stone masonry wall repair techniques for historic masonry buildings during maintenance phase. This paper also recognises the important role of ‘Green Maintenance’ model in reducing embodied carbon expenditure, thus minimising the Environmental Maintenance Impact (EMI) typically associated with the deterioration of external stone masonry walls. In addition, the model is not only aids in maintenance decisions making processes, but also contributes in substantiating the philosophical defensibility and sustainability of maintenance interventions. In the broader sense, the mathematical framework of the model is not simply confined to historic masonry buildings and will be of use to those entrusted with the repair of other type of buildings, elements and components.

Keywords

Green Maintenance, Historic Masonry Buildings, life cycle assessment (LCA), mathematical framework, Environmental Maintenance Impact (EMI)
1. Introduction

Maintenance of buildings is crucial in ensuring that the financial, economy and societal capital invested in their construction is holistically expended. There is emerging of ‘Green Maintenance’ model that becomes a shift of paradigm relating to maintenance and repair. The model is parallel with an increasing international focus on the sustainability of the built environment. This paper also envisaged the development of mathematical framework of life cycle assessment (LCA) approach of ‘Green Maintenance’ for historic masonry buildings repair within ‘cradle-to-site’ boundary during maintenance phase.


Protection of historic fabric through maintenance is not only undertaken from a cultural perspective, but also from an economic viewpoint. In Europe’s context, the importance of maintenance is reflected in the fact that 50% of its national wealth scale i.e. enclosed within existing built environment (Balaras et al., 2005; Forster et al., 2013). But, premature deterioration combined with lack of regular maintenance can extensively devalue these existing assets. In the United Kingdom’s total expenditure on construction context, an approximate of 50% of Gross Domestic Product (GDP) accounted on maintenance accounts (Balaras et al, 2005). In 2002, the UK’s built environment contains 450,000 listed and 10.6 million pre-1944 buildings (Maintain Our Heritage, 2004: 17) with the financial value of repair works £36 billion in (increment from calculated at £30 billion in 1995 prices [DTI, 2002:31; Arup, 2003:22].

Of the large and expanding market in repair works to the built environment, masonry contributes a significant cost. The Scottish Stone Liaison Group (UK) have estimated that the cost of masonry repairs required over a 20 year period as approximately £600 million (at 2010 prices) in Glasgow alone (SSLG, 2006). Comparatively, other major cities with a tradition of masonry construction in Scotland (such as Edinburgh) may also need similar levels of investment which benefits both local and international businesses. In addition to the cost perspective, this kind of investment not only provides significant advantage to the maintenance of the stone masonry walls of historic masonry buildings, but also can reduce the carbon expended in their repair.

Proportionately, the increment of aforementioned cost figure is slightly small considering that there is fluctuation on financial value over the years. Statistically however, maintenance has been consistently at greater financial cost, due to the usage of traditional materials for repairing the existing built environment. In addition, there is trend of market expansion for repair, i.e. economic cost is incurred for existing built environment maintenance in international context. By looking
ahead however, recognition of the contribution of maintenance should be expanded. Maintenance should not only appreciated in the protection of the historic fabric of buildings and economic costs of existing built environment (through repair), but also widely recognised on its ability to address sustainability of built environment based on Environmental Maintenance Impact (EMI).


The approach taken to evaluate maintenance needs in buildings is almost always confined within budgetary and cost constraints parameters. Simultaneously, the implementation of maintenance for masonry is highly influenced by buildings ethical (Foster, 2010a) and principle (Foster, 2010b) based philosophical framework. Forster (2010a:92) indicates that ‘repairs selected, based upon the ethical concepts and a combination of the principles should be defensible and should in theory lead to naturally ‘good’, well founded conservation interventions’. The tenets associated with building conservation philosophy include: least intervention; like for like material replacement; honesty and distinguishability; integrity; reversibility; respect for historic patina; and respect for traditional craft skills (Bell, 1997). The success of maintenance intervention for buildings (including historic masonry buildings) is therefore not only evaluated on the quality of the repair, but also conformity to aforementioned principles.

That being said, interventions that fit within the philosophical context, are generally high quality, have better compatibility with the fabric, highly defensible and have greater longevity than insensitive, often inappropriate repairs. Meanwhile, costs associated with maintaining a building can be contributed to retaining or increasing its value in economic context.

Adding to the complexity of prioritisation within the philosophical and economic context, a third and emerging factor in the evaluation of maintenance is environmental sustainability. The Venn diagram in Figure 1 represents the traditionally accepted model of sustainability with environmental, societal and economic factors, overlaid with the three factors that influence maintenance for historic buildings, namely; environment, cost and philosophy. Those interventions that intersect with all three contexts would potentially be considered as being the most sustainable.
The diagram also sets out a proposition to evaluate maintenance in terms of environmental considerations, particularly for historic masonry buildings repair. Tripartite approach based on parameters in Figure 1 draws parallels model of sustainable development and ‘green’ maintenance interventions.

To evaluate the long term maintenance requirements of historic masonry buildings in relation to the tripartite approach for ‘Green Maintenance’ model, it is necessary to understand the cumulative effect of routine their maintenance operations in terms of not only cost and philosophy, but also environmental impact. Using developed mathematical framework, this model has the potential to allow selection of maintenance options that provide a sustainable solution for historic masonry building repair.

4. ‘Green Maintenance’: The Concept and Methodology

Figure 2 overlays the embodied carbon expenditure (CO₂ emission) for each maintenance intervention on the service condition graph. Each maintenance intervention (repair) is characterised by its longevity and embodied carbon expenditure. The model distinguishes between ‘brown’ and ‘green’ maintenance:
namely, those repairs of high and low carbon impact respectively. The cumulative effect of ‘brown’ maintenance increases the total embodied carbon expended far more quickly than ‘green’ maintenance. Conversely, the former is synonymous with less efficient repairs, which have lower longevity and higher embodied carbon (more CO$_2$ emission) compared to the latter.

Principally, the higher the embodied carbon expenditure (more CO$_2$ emissions) is due to more frequent maintenance intervention. In the case of historic masonry building repair, however, various mechanisms may exist to attain total CO$_2$ emissions reduction. These include usage of locally sourced repair materials, engagement of regional companies to undertake the masonry repair work and selection low embodied carbon materials. Commonly, in order to attain low embodied carbon expenditure for stone masonry wall repair, preference is given to repair techniques with higher longevity. Theoretically, the higher the longevity of repair, the less number of maintenance intervention to be undertaken (lower embodied carbon expenditure and less CO$_2$ emissions). Comparatively, natural stone replacement is more ‘greener’ in terms of embodied carbon expenditure as opposed to plastic repair (lower longevity, high embodied carbon expenditure and more CO$_2$ emissions). It must be emphasised that the complexity of repair longevity, using either single or combined stone masonry wall repair techniques in different repair scenarios within the selected boundary of LCA and the maintenance period, requires an appropriate approach for determining ‘brown’ and ‘green’ maintenance in historic masonry buildings.

![Relationship between longevity of repair and embodied carbon expenditure](image)

Figure 2: Relationship between longevity of repair and embodied carbon expenditure Source: Forster, et al., 2011 and 2013; Kayan, 2013.
To fully appreciate the Environmental Maintenance Impact (EMI) of repair, the boundary of LCA and maintenance profile period must be set appropriately. If we can evaluate the efficiency of stone masonry wall repair in terms of its embodied carbon expenditure (CO₂ emissions), it could then be tailored to suit the Environmental Maintenance Impact (EMI) aspects rather than the longevity of repair alone. This practical approach will be positively welcomed as our society moves towards a low carbon economy and materials and ‘green’ procurement. The level of awareness in our society upon the importance of selection and prioritises low embodied carbon materials is increasing steadily. Additionally, as low carbon trading in building industry becomes more prevalent, ‘Green Maintenance’ model can be converted into a supplementary financial cost in maintenance decision making process.

Conceptually, the efficiency of single or combined stone masonry wall repair techniques undertaken in different repair scenarios can also be tested based on their Environmental Maintenance Impact (EMI). That said, as these model become more accurate, the evaluation of selected stone masonry wall repair techniques efficiency in terms of embodied carbon expenditure will have greater efficacy and compatibility.

Meanwhile, in the opinion of the authors, it is essential to understand the embodied carbon expenditure associated with maintenance and repair; therefore, a multi-criteria approach is required. Apparently, for the ‘Green Maintenance’ model to be of rational use, the embodied carbon expenditure of the repairs must be evaluated using comparable, reproducible methods.

In the case of historic masonry buildings, the frequency of their maintenance interventions obviously affects their embodied carbon expenditure. It must be emphasised however that the time between interventions is influenced by many variables; longevity of repair, resourcing and geographical location, technological development, mode of transportation, degree of wall exposure, building and wall detailing, quality of initial work and specification.

5. Green Maintenance Modelling: Mathematical Framework Development of Life Cycle Assessment Approach

Primarily, the development of mathematical framework of ‘Green Maintenance’ model in this paper is primarily to quantify the embodied carbon expenditure expended in historic buildings’ stone masonry wall repair. Using a set of unit processes and workflows from each stone masonry wall repair technique, calculation procedures were undertaken in different stages. The calculation focuses mainly on the embodied carbon expended in stone masonry wall repairs of historic masonry buildings, particularly during the maintenance phase (Figure 3).
5.1 Cumulative Embodied Carbon Expenditure

In this paper, recurring embodied carbon expended for repairing stone masonry walls calculated within ‘cradle-to-gate’ (for quarrying, mining, manufacturing and processing) and ‘gate-to-site’ (transportation to site). The efficiency of each repair technique in terms of embodied carbon expenditure (kgCO₂e/kg/m²) was calculated and compared in terms of Environmental Maintenance Impact (EMI).
Calculations procedures of developed mathematical framework for ‘Green Maintenance’ model in this paper is attempted to evaluate the embodied carbon association with maintenance interventions, i.e. stone masonry wall repair.

It must be emphasised that in the ‘Green Maintenance’ model, the efficiency of each stone masonry wall repair technique was compared in terms of its embodied carbon expenditure. This was based on maintenance intervention \( n \) and total repaired area of stone masonry wall \( m^2 \) within selected LCA boundaries and maintenance periods.

The calculations were based on the embodied carbon expenditure to repair \( 1m^2 \) wall for each stone masonry wall repair technique \( \text{kgCO}_2\text{e/kg} \), within the ‘cradle-to-site’ of LCA on a yearly basis, for the selected maintenance period. Cumulatively, the embodied carbon expended for each stone masonry wall repair technique was then calculated by multiplying the total area of wall repaired \( m^2 \) with the generated functional units (embodied carbon expended for repairing \( 1m^2 \) stone masonry wall, i.e. \( \text{kgCO}_2\text{e/kg/m}^2 \)). Overall total embodied carbon expenditure within selected maintenance periods were calculated based on the total combination of embodied carbon expended for stone masonry wall repair.

The ‘Green Maintenance’ model was then tested on its Environmental Maintenance Impact (EMI), either for single or a combination of stone masonry wall repair techniques in different repair scenarios to ascertained its practicality and compatibility. Primarily, the test was formed by evaluating the influences of longevity of repair within selected maintenance profiles.

The cumulative embodied carbon expenditure \( \text{kgCO}_2\text{e/kg/m}^2 \) can be generated by multiplying the total repaired stone masonry wall area \( m^2 \) with the embodied carbon expenditure for repairing \( 1m^2 \) wall for each repair technique within a selected maintenance period as. This can be expressed in Equation No. (1);

\[
\text{Carbon expenditure on maintenance} = \sum_{i=1}^{n} ce_i
\]

Equation No. (1)

where;
\( n \)=number of interventions
\( ce \)=embodied carbon expenditure for the \( i \)th maintenance intervention [evaluated within selected ‘cradle-to-site’ boundary of LCA]

The efficiency of one individual stone masonry wall repair technique in terms of embodied carbon expenditure \( \text{CO}_2 \text{e emission} \) per year would be a function of the
annual total of embodied carbon expenditure and the longevity of repair of undertaken stone masonry wall repair techniques.

In this case however, emphasis must be placed on the calculation procedures that it should be able to draw rational comparisons between individual and multiple cumulative maintenance interventions. It must be noted that formulaic expressions in Equation No. (1), could only be accurate if all the stone masonry wall repairs are carried out immediately after the life expectancy of the material used in each repair has concluded.

It must also emphasise that materials used in stone masonry wall repair (such as stone, cement, lime, sand, brick dust/fire clay/fly ash, steels dowels, epoxy resin, non-ferrous wire, etc.) were transported to site from different quarries or mining/resourcing locations. This contributed to differences in CO\textsubscript{2} emissions per mass kg of every transported repair material due to varying transportation distances. Additionally, the differences in CO\textsubscript{2} emitted in materials transportation were also dependant on the mode/vehicle of transport used.

It must be noted that the high value of embodied carbon coefficient of repair materials used in stone masonry wall repair (such as stone and lime) was due to the great use of energy, electricity and fuel combustion during the quarrying and processing process (‘cradle-to-gate’). Meanwhile, a high value of CO\textsubscript{2} emitted for imported repair materials (such as lime) transportation was due to the long distance between the resourcing location and building site.

Theoretically, organisation ‘A’ could repair a 1m\textsuperscript{2} area of deteriorated stone masonry wall structure of a historic masonry building using different types of repair techniques (either in single or a combination in different repair scenarios). Therefore, an evaluation of the embodied carbon expenditure could then be calculated for each of these repairs techniques within the selected boundary of LCA.

Using the formulaic expression formulated in Equation No. (2), the embodied carbon expenditure was evaluated in the form of kgCO\textsubscript{2}e/kg. This was completed by summing the embodied carbon expended in quarrying and processing (‘cradle-to-gate’) and CO\textsubscript{2} emitted in transporting repair materials to building sites (‘gate-to-site’) for all undertaken maintenance interventions within selected maintenance periods. It must be noted that the calculation based on Equation No. (2) does not include major refurbishment building.
Total embodied carbon + carbon expended for repair = \( CO_{2\text{op}} + \sum_{i=1}^{n} ce_i \)

Equation No. (2)

where;
\( CO_{2\text{op}} \) = embodied carbon expended for building operation
\( n \) = number of interventions
\( ce_i \) = embodied carbon expenditure for the \( i \)th maintenance intervention within ‘cradle-to-site’

For the purpose of this paper, however, only the total embodied carbon expenditure for the repair of deteriorated stone masonry during the maintenance phase (within the selected maintenance period) were considered for calculation within the ‘cradle-to-site’ of LCA. It must be noted that initial serviceability conditions and major refurbishments involving stone masonry walls of historic masonry buildings in the form of total embodied carbon were not calculated.

5.2 Total Approximate of Embodied Carbon Expenditure for Repairing 1 m² Stone Masonry Wall (kgCO₂e/kg/m²) Within ‘Cradle-to-Gate’

The total approximate embodied carbon (kgCO₂e/kg) of mass (kg) of repair materials expended in repairing every 1m² area of stone masonry wall for each selected technique within ‘cradle-to-gate’ could be calculated using Equation No. (3):

\[
\sum_{i=1}^{n} ECE_{\text{cradle-to-gate (m2)}}(m1 * ecc_1 + m_2 * ecc_2 \cdots m_n * ecc_n)
\]

Equation No. (3)

where;
\( m_n \) = mass (kg) of materials used in every 1m² stone masonry wall repaired
\( ecc_n \) = embodied carbon coefficient of the used materials type within ‘cradle-to-gate’ from Inventory of Carbon and Energy (ICE), Version 2.0, 2011 (Hammond and Jones 2011)

ECE = total approximate of embodied carbon expenditure in every 1m² stone masonry wall repaired within ‘cradle-to-gate’
5.3 Total Approximate of Embodied Carbon Expenditure for Transporting Repair Materials Used in Repairing 1m² Stone Masonry Wall Within ‘Gate-to-Site’

The total approximate embodied carbon (kgCO₂e/kg) for transportation of mass (kg) repair materials used in repairing every 1m² area of stone masonry wall from resourcing location to building site for each selected technique within ‘gate-to-site’ could be generated using Equation No. (4):

\[
\sum_{i=1}^{n} \text{ECE}_{\text{gate - to - site} (m2)}_i = m_1 \times e_{f_1} \times km_1 + m_2 \times e_{f_2} \times km_2 \cdots m_n \times e_{f_n} \times km_n
\]

Equation No. (4)

where;
- \(m_n\) = mass (kg) of materials used in every 1m² stone masonry wall repaired transported from resourcing location to building site
- \(e_{f_n}\) = emission factors per kg km for materials transportation (gate-to-site) @ 132 gm CO₂ emission factors per tonne km or 1.32 \times 10^{-4} kgCO₂ per kg km emission factors using updated 2008 CO₂ emission factors per tonne km for all HGVs road freight (based on UK average vehicle loads in 2005) (IFEU, 2008; Defra/DECC, 2009).
- \(km_n\) = approximate kilometre based on shortest/nearest road driving distance using land transportation (Google Maps)

5.4 Embodied Carbon Per m² Wall Repaired (‘Cradle-to-Gate’)

The total approximate embodied carbon (kgCO₂e/kg) expended in the processing and manufacturing of repair materials used in repairing stone masonry walls for each selected technique within ‘cradle-to-gate’ could be calculated using Equation No. (5):

\[
\sum_{i=1}^{n} \text{ECE}_{\text{cradle - to - gate} (m2)}_i = m^2_1 \times \text{ECE}_{\text{cradle - to - gate} (m2)}_1 + m^2_2 \times \text{ECE}_{\text{cradle - to - gate} (m2)}_2 \cdots m^2_n \times \text{ECE}_{\text{cradle - to - gate} (m2)}_n
\]

Equation No. (5)
where;
\( m^2_n \) = area (m\(^2\)) of stone masonry wall repaired using relevant repair techniques
\( ECE_{cradle-to-gate} (m^2)_n \) = embodied carbon expenditure value on every 1m\(^2\) of repaired stone masonry walls using relevant repair techniques within a ‘cradle-to-
gate’ boundary [generated from Equation No. (3)].

It must be emphasised that, there is distinction between Equation No. (5) and Equation No. (3). The former is formulated based on total area (m\(^2\)) of stone masonry wall repaired for different repair techniques. Conversely, the latter is developed mainly based on mass (kg) of materials used in repairing of 1 m\(^2\) of wall.

### 5.5 Embodied Carbon Per m\(^2\) Wall Repaired (‘Gate-to-Site’)

Total approximate embodied carbon (kgCO\(_2\)e/kg) expended in transporting repair materials used in every repaired area stone masonry wall for each selected technique within ‘gate-to-site’ could be calculated using Equation No. (6):

\[
\sum_{i=1}^{n} ECE_{gate-to-site} = m^2_1 \times ECE_{gate-to-site} + m^2_2 \times ECE_{gate-to-site} + \cdots + m^2_n \times ECE_{gate-to-site}
\]

Equation No. (6)

where;
\( m^2_n \) = area (m\(^2\)) of stone masonry wall repaired using relevant repair technique
\( ECE_{gate-to-site} (m^2)_n \) = embodied carbon expenditure value for transporting repair materials used in repairing stone masonry walls using relevant m\(^2\) repair techniques within gate-to-site boundary [generated from Equation No. (4)]

### 5.6 Total Embodied Carbon Per m\(^2\) (‘Cradle-to-Site’)

The total approximate embodied carbon (kgCO\(_2\)e/kg) expended from processing and manufacturing to transportation to historic masonry building sites of repair materials used in repairing stone masonry walls for each selected technique within ‘cradle-to-
site’ could be calculated using Equation No. (7):
Total approximate of embodied carbon expenditure (for total area of stone masonry wall repaired)

\[
\sum_{i=1}^{n} ECE_{\text{cradle} - \text{to} - \text{site}}_{i} = m^2_1 \times ECE_{\text{cradle} - \text{to} - \text{site}} (m^2)_1 + m^2_2 \times ECE_{\text{cradle} - \text{to} - \text{site}} (m^2)_2 + \ldots + m^2_n \times ECE_{\text{cradle} - \text{to} - \text{site}} (m^2)_n
\]

Equation No. (7)

where;
\( m^2_n \) = area (m\(^2\)) of stone masonry wall repaired using relevant repair technique

\( ECE_{\text{cradle-to-site}} (m^2)_n \) = embodied carbon expenditure value for transporting repair materials used in repairing stone masonry walls using relevant repair techniques within ‘gate-to-site’ boundary [generated from Equation No. (5) and Equation No. (6)]

5.7 Functional Units of Embodied Carbon Per m\(^2\) (kg\(\text{CO}_2\)e/kg/m\(^2\))

The total embodied carbon per m\(^2\) (kg\(\text{CO}_2\)e/kg/m\(^2\)) expended from quarrying/mining, processing and manufacturing to transportation to historic masonry building sites of repair materials (used in repairing 1m\(^2\) stone masonry wall) for each selected technique within ‘cradle-to-site’ could be calculated using Equation No. (8):

Total approximate of embodied carbon expenditure (per 1 m\(^2\) stone masonry wall repaired)

\[
= \sum ECE_{\text{cradle} - \text{to} - \text{gate}} (m^2)_n \times ECE_{\text{cradle} - \text{to} - \text{gate}} (m^2)_n + ECE_{\text{gate} - \text{to} - \text{site}} (m^2)_n
\]

Equation No. (8)

where;
\( ECE_{\text{cradle-to-gate}} (m^2)_n \) = embodied carbon expenditure value on every 1m\(^2\) of repaired stone masonry wall using relevant repair techniques within ‘cradle-to-gate’ boundary [generated from Equation No.(5)]

\( ECE_{\text{gate-to-site}} (m^2)_n \) = embodied carbon expenditure value for transporting repair materials used in repairing 1m\(^2\) stone masonry wall using relevant repair techniques within ‘gate-to-site’ boundary [generated from and Equation No. (6)]

5.8 Total Embodied Carbon Expenditure for Stone Masonry Wall Repair Within (‘Cradle-to-Gate’)

The total embodied carbon (kg\(\text{CO}_2\)e/kg) expended from the quarrying, mining, manufacturing and processing of repair materials used in repairing stone masonry
walls for each selected technique within ‘cradle-to-gate’ could be calculated using Equation No. (9):

\[
\sum_{t_l=1}^{n} ECE_{\text{cradle-to-gate} t_l} = m_{t_1}^2 * ECE_{\text{cradle-to-gate}} + m_{t_2}^2 * \ldots * m_{t_n}^2 * ECE_{\text{cradle-to-gate}}
\]

Equation No. (9)

where;

\( m_{t_n}^2 \) = area \( (m^2) \) of stone masonry wall repaired using relevant repair technique \( (t_n) \)

\( ECE_{\text{cradle-to-site}} = \) embodied carbon expenditure value for processing and manufacturing of repair materials used in repairing stone masonry walls using relevant repair techniques within ‘cradle-to-gate’ boundary [generated from Equation No. (5)]

5.9 Total Embodied Carbon Expenditure for Stone Masonry Wall Repair ('Gate-to-Site')

The total embodied carbon (kgCO\(_2\)e/kg) expended in the transportation of repair materials used to repair stone masonry walls of historic masonry buildings to site for each selected technique within ‘gate-to-site’ could be calculated using Equation No. (10):

\[
\sum_{t_l=1}^{n} ECE_{\text{gate-to-site} t_l} = m_{t_1}^2 * ECE_{\text{gate-to-site}} + m_{t_2}^2 * \ldots * m_{t_n}^2 * ECE_{\text{gate-to-site}}
\]

Equation No. (10)

where;

\( m_{t_n}^2 \) = area \( (m^2) \) of stone masonry wall repaired using relevant repair technique \( (t_n) \)

\( ECE_{\text{gate-to-site}} = \) embodied carbon expenditure value for transportation of repair materials used repairing stone masonry walls of historic masonry building site using relevant repair techniques within ‘gate-to-site’ boundary [generated from Equation No. (6)]
5.10 Total Embodied Carbon Expenditure for Stone Masonry Wall Repair Within ‘Cradle-to-Site’ and Selected Maintenance Periods

The overall total of embodied carbon expenditure of the number of interventions (n) and area of stone masonry walls within ‘cradle-to-site’ and selected maintenance periods could be calculated using Equation No. (11):

\[
\sum_{t=1}^{n} \text{ECE}_{\text{cradle-to-site}} = [\text{ECE}_{\text{cradle-to-gate}} + \text{ECE}_{\text{gate-to-site}}] + [\text{ECE}_{\text{cradle-to-gate}} + \text{ECE}_{\text{gate-to-site}}] + ... + [\text{ECE}_{\text{cradle-to-gate}} + \text{ECE}_{\text{gate-to-site}}]
\]

Equation No. (11)

where:

- \( t_n = \) relevant repair technique (tn)
- \( \text{ECE}_{\text{cradle-to-gate}} = \) total approximate embodied carbon expenditure for quarrying/mining, processing and manufacturing of repair materials used in repairing stone masonry walls using relevant repair techniques within ‘cradle-to-gate’ boundary [generated from Equation No. (9)]
- \( \text{ECE}_{\text{gate-to-site}} = \) total embodied carbon expenditure for transportation of repair materials used repairing stone masonry walls of historic masonry building sites using relevant repair techniques in ‘gate-to-site’ and selected maintenance periods [generated from Equation No. (10)]

5.11 Overall Total Embodied Carbon Expenditure for Selected Maintenance Profile Period Within ‘Cradle-to-Site’

The estimated overall total embodied carbon expenditure expended in association with undertaking a series of complete interventions within selected maintenance periods could be calculated using Equation No. (12):

\[
\sum_{t=1}^{n} \text{ECE}_{\text{cradle-to-site}} = \text{ECE}_{\text{cradle-to-site}}[t_1] + \text{ECE}_{\text{cradle-to-site}}[t_2] + ... + \text{ECE}_{\text{cradle-to-site}}[t_n]
\]

Equation No. (12)
where:

\[ t_n = \text{relevant repair technique (tn)} \]

\[ EC\text{E cradle-to-site}_n = \text{total embodied carbon expenditure for quarrying/mining, processing and manufacturing and transporting of repair materials used in repairing stone masonry walls of historic masonry buildings using relevant repair techniques within 'cradle-to-site' and selected maintenance periods [generated from Equation No. (11)]} \]

6. Findings

The initial question in this works aimed to evaluate whether a ‘Green Maintenance’ model for historic masonry buildings can be developed to evaluate the efficiency of historic masonry buildings in terms of embodied carbon expenditure? It has been successfully demonstrated that this has been achieved by formulation of mathematical framework of life cycle assessment approach. Formulated mathematical framework in this paper has shows its capability to represents the evaluation of the Environmental Maintenance Impact (EMI) of the materials used in repairing stone masonry walls of historic masonry buildings.

In addition, the model is not only act as maintenance decisions making processes tools, but also substantiating the philosophical defensibility and sustainability of maintenance and repair. The mathematical framework of ‘Green Maintenance’ is not restricted to historic masonry buildings and is universal in its nature.

7. Conclusion

It could be concluded that mathematical framework of life cycle assessment approach of ‘Green Maintenance’ model could be developed to achieve more rigorous analysis of the disparity between philosophy and cost of repair versus CO\(_2\) emissions. This will making initial difficult maintenance decisions easier to made and defend. Upon determination and understanding of the interrelationship of the longevity and the repair materials in terms of embodied carbon expenditure, the testing of this model could be discussed in greater depth.
8. References


