Green Maintenance for Historic Masonry Buildings: An Option Appraisal Approach

Abstract

Purpose – Sustainability is well understood to encapsulate economic, environmental and societal parameters. The efficiency of maintenance interventions for historic buildings is no exception and also conforms to these broad factors. Recently, environmental considerations for masonry repair have become increasingly important and this work supports this growing area. This paper gives insight on how an option appraisal approach of 'Green Maintenance' modelling for historic masonry buildings repair practically determine and ultimately substantiate the decision making process using a calculation procedures of life cycle assessment (LCA), within delineated boundaries.

Design/methodology/approach –Calculation procedures of the model enables an assessment of embodied carbon that is expended from different stone masonry wall repair techniques and scenarios for historic masonry buildings during the maintenance phase.

Findings – It recognises the importance roles 'Green Maintenance' model can play in reducing carbon emissions and underpins rational decision making for repair selection.

Practical Implications- It must be emphasised that the calculation procedures presented here, is not confined to historic masonry buildings and can be applied to any repair types and building form. The decisions made as a result of the utilisation of this model practically support environmentally focused conservation decisions.

Social Implications- The implementation of the model highlights the efficacy of repairs that may be adopted.

Originality/value- The paper is a rigorous application and testing of the 'Green Maintenance' model. The model relays the 'true' carbon cost of repairs contextualised within the longevity of the materials and its embodied carbon that consequently allows rational appraisal of repair and maintenance options.

Keywords Green Maintenance, Historic Masonry Buildings, life cycle assessment, calculation procedures, embodied carbon, Environmental Maintenance Impact (EMI)

Paper type Research paper

1. Introduction

Maintenance of buildings is crucial for ensuring that the financial, economic and societal capital invested in the fabric is retained. 'Green Maintenance' has the potential to refocus the traditional view of the repair of building, towards sustainability (Forster et al., 2011; Kayan, 2013; Kayan, 2015) and therefore go some way to satisfy legally binding sustainability targets. Bell (1997) and British Standards Institution (1998) also expounded that this has been embedded in the principal building conservation legislative frameworks and charters (Bell, 1997; British Standards Institution, 1998). It is clear that a main tenet of these frameworks is sustainability.

That said, protection of historic fabric through maintenance is not only undertaken from a cultural perspective, but also from an economic viewpoint that is reflected in the fact that 50% of Europe's national wealth is encapsulated within its existing built environment (Balaras et al., 2005; Forster et al., 2009; Forster et al., 2013). Premature deterioration associated with lack of regular maintenance can extensively devalue these existing assets. Specifically, with regards to the United Kingdom, as a proportion of Gross Domestic Product, maintenance accounts for nearly half of the total expenditure on construction nationally (Balaras et al., 2005). Moreover, the UK's built environment contains 450,000 listed and 10.6 million pre-1944 buildings (Maintain Our Heritage, 2004). In 2002, the financial value of repair works to the existing built environment was calculated at £30 billion (in 1995 prices), a figure that increased to £36 billion in 2002 (at 2002 prices) [DTI, 2002; Arup, 2003]. Remarkably, of the large and expanding market in repair works to the built environment, masonry contributes a significant cost. In Glasgow alone, 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) (SSLG, 2006). Apparently, other major cities with a tradition of masonry construction in Scotland (such as Edinburgh) may also need similar levels of investment (Kayan 2013; 2015). In the future, however, recognition of the contribution of maintenance should be expanded, not only to cover the protection of the historic fabric of buildings and economic costs of existing built environment but also to address the perspective of environmental impact.

Hammond and Jones (2008a) state that the "*UK construction industry consumes over 420 Mt of materials, 8Mt of oil and releases over 29 Mt of carbon dioxide annually, including a significant quantity of new materials disposed of as waste*" (Hammond and Jones, 2008a). For example, in order to meet global targets, the Scottish Government has outlined their commitment to reduce greenhouse gas emissions in Scotland by 80% (relative to 1990 levels) in 2050 (Scottish Government, 2009). Significantly, a substantial proportion of these carbon emissions have been attributed to the operations as well as the maintenance and repair of existing buildings i.e. including historic masonry buildings.

Today, the cost implications of repairs must be considered within the context of the associated carbon expenditure. These measures are increasing in prevalence and form a part of carbon reduction strategies. This work practically applies a mathematical modelling method developed by Forster et al., (2011), and reflects the growing importance of the meaningful determination of the carbon cost associated with repair interventions. Forster et al's (2011) work into Green Maintenance was developed from mid stage doctoral research undertaken by Kayan (2013). This was further developed and the work was published in 2013. This current paper is a logical and meaningful continuation of Kayan's (2013) doctoral research and practically applies the established theory.

For the purpose of historic maintenance records data collection for this paper, the selected samples of historic masonry buildings were determined to be owned and managed by collaborative partners (Historic Scotland, National Trust for Scotland) and The City of Edinburgh Council (CEC). These sample buildings were selected from different localities in Scotland, including the central and west, the Scottish Borders, Glasgow, Clyde and Ayrshire, Edinburgh and the Lothians, Fife, and Dumfries and Galloway. These all selected sample were varies in type including tenements, public and private houses, townhouses, guesthouses and etc. had large areas of exposed stone masonry wall elements. Additionally, the stone masonry wall elements of each selected sample building were different in terms of type of wall construction and stone used. They had different localities (different local climate) and dissimilar weathering effects (rate of deterioration) in their stone masonry. Apparently, this influenced the longevity of the repair techniques undertaken (the faster the rate of deterioration, the more frequently repair was required) and the total wall area repaired (the larger the deteriorated surface of a wall, the higher total area repaired) within selected maintenance periods.

The data utilised to test the model was derived from evaluation of historic maintenance records within several significant portfolio holders. These include, Historic Scotland (HS);

National Trust for Scotland (NTS) and, City of Edinburgh Council (CEC). These records were primarily composed of repair type, date of executing the works, cost, and specification information etc. The main requirements for the effective utilisation of the model were details of specification and sourcing of the materials; the longevity and duration between repeat interventions and the extent of the works undertaken.

2. Maintenance of Historic Masonry Buildings: Setting the Evaluation Parameters and Methods

The green maintenance model aims to better inform the evaluation of the long term maintenance requirements of historic masonry buildings, appropriately directing decisions on interventions. This requires a clear understanding of the cumulative effect of routine maintenance operations, and their environmental impact (Forster, et al., 2011). Conceptually, the service condition and expended embodied carbon (CO_2 emission) for each maintenance intervention (in y-axis) of the model are illustrated in Figure 1. On the other hand, each maintenance intervention (repair) is characterised by its longevity (*l*) (denoted by the saw-tooth profile) and embodied carbon (*Ce*) (denoted by the stepped dotted lines). The model distinguishes delineation between ‘brown’ and ‘green’ maintenance: namely, those repairs of high and low carbon impact respectively. Representatively, a ‘brown’ maintenance (steep saw-tooth gradient) denotes a repair with short life expectancy, such as pinning and consolidation, which can extend the service condition by 20 years. Comparatively, a ‘green’ maitenance (shallow saw-tooth gradient) equates to a durable long-lasting intervention such as masonry replacement lasting at least 100 years.

The cumulative effect of ‘brown’ maintenance increases the total embodied carbon expended far more quickly than ‘green’ maintenance and does not attain required longevity. Practically, brown maintenance interventions are associated with many factors but prevalent issues may include, inadequately specified, high carbon materials, that are poorly executed and that do not attain functional longevity. Conversely, green maintenance could be typified by a durable low carbon repair that suitably achieves the required broader set of design requirements. As emphasised by Forster et al., (2013) however, the complexity of lifespan and combinations of repair types suggest a whole life cycle approach is necessary in determining ‘brown’ from ‘green maintenance’ (Forster et al., 2013).

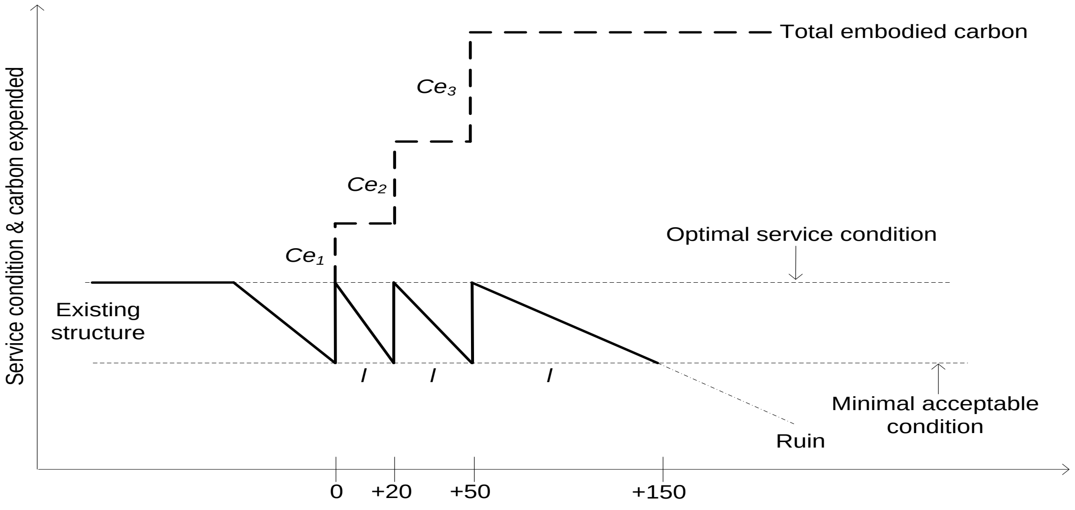

Figure 1: Relationship between longevity of repair and embodied carbon expenditure Source: Forster, et al., 2011.

Figure 1 illustrates the implications of undertaking maintenance interventions on the service condition of masonry over time. The downward sloping lines signify the steady decline in condition over the life of the masonry repairs. Each maintenance intervention brings the area of masonry back to optimal service condition (in this case, optimal service condition of masonry is defined as when it attained good condition and able to fulfil its elemental functions). It then deteriorates at a rate that depends on the repair type. Intervention is assumed to occur when the minimum acceptable condition is reached, and the saw-tooth profile results from successive interventions, each extending the life of the masonry.

Principally, the more frequent the maintenance intervention, the higher the embodied carbon expended (more CO_2 emissions). Generally, an almost zero impact repair (lowest CO_2 emissions) might be better even needed several times (example of repointing which highly influenced by minimal usage of materials on each intervention). It must be noted that, however, it is commonly frequently required for overall surface of wall to be repointed within maintenance phase (large wall areas will implicates consistently high overall total EMI within the life cycle of buildings).

Generally, in the case of historic masonry building repair, various mechanisms may exist to reduce the total CO_2 emitted (sometime referred as greenhouse gas emissions, GHG); local sourcing of masonry repair materials, using regional companies to undertake the masonry repair work and selecting low embodied carbon materials. To attain low embodied carbon expenditure for stone masonry wall repair within specified arbitrary maintenance period (such as in 100 years), preference is given to natural replacement (higher longevity, lower embodied carbon expenditure and less CO_2 emissions) as opposed to plastic repair (lower longevity, high embodied carbon expenditure and more CO_2 emissions). Due to complexity of repair longevity, using either single or combined repair techniques in different repair scenarios for stone masonry wall repair within the selected boundary of LCA and the maintenance profile period, therefore, an appropriate approach is essentially required in determining the impact in terms of overall EMI (CO_2 emissions).

It must be emphasise that every repair type has differences in term of durability [unpredictable of Estimated Service Life (ESL)] and longevity of repair. Therefore, it is not necessary for undertaking masonry repair only when reach the same level of optimal service condition. The time between interventions is influenced by many variables, including material durability, degree of exposure, building detailing, and quality of repair and specification. Undertaking repairs at frequent intervals increases the risk of mechanical damage to the masonry associated with scaffolding. Less regular masonry repair can reduce the risk of this damage and also aligns with the philosophical principle of least intervention.

Principally, higher embodied carbon (more CO_2 emissions) is associated with more frequent maintenance interventions. Clearly, ‘lock up’ of embodied carbon in stone masonry walling is a function of the longevity of the selected interventions. It is therefore desirable to attain low carbon, high durability repairs. For example, natural stone replacement can be considered as being ‘greener’ in terms of embodied carbon compared to plastic repair due to its relative longevity. Longevity of the individual repair is therefore inversely proportional to the number (‘n’) of repeat interventions required over a notional time frame. In reality ‘n’ is influenced by factors such as the materials specification; the quality of the executed works; the design and detailing of the structure; the exposure levels that the repair is exposed to and climatic conditions (Forster and Carter, 2011). In addition, there is leading professional body championing life-cycle data for historic fabric repair such as Royal Institution of Chartered Surveyor (RICS). It is highly recognised that RICS promotes sustainable development in property and construction sectors by advocating environmental assessment, i.e. through low carbon construction and materials. It must be noted that, life-cycle data for the different types of repairs materials can be derived from various authoritative sources. For the purpose of this paper, life-cycle data for repair materials for stone masonry wall are mainly derived based on RICS Building Cost Information System (BCIS) (BCIS, 2006).

Many masonry repair techniques are available to those entrusted with the sensitive and appropriate maintenance of historic structures. Whilst the permutations of the technical approaches are numerous four major repair types are most prevalent. These are repointing of mortar joints, plastic repair of deteriorating masonry faces, replacing natural stone; and pinning and consolidation of delaminating masonry faces (Forster, 2010; Ashurst and Ashurst, 1988). This view is shared by Torney et al., (2014:359) indicating that '*A number of repair options may be considered in cases of masonry deterioration, including; natural stone replacement (indenting), consolidation of existing masonry, or 'plastic' repair with mortars. Each of these repair approaches brings with it a number of benefits and drawbacks relating to both technical and philosophical aspects of masonry conservation'*. It must be emphasised that other techniques are commonly utilised by practitioners but they are outside the scope of this research.

The four repair types utilised for this study could be viewed in terms of relative levels of intrusion to the original fabric. For example, repointing deteriorated mortar joints would have a limited effect on adjacent masonry. Conversely, the removal of deteriorated natural stone and replacement with a new masonry unit logically requires the removal of greater quantities of original fabric (Hill, 1995). The environmental impact of these repair types also depend upon various factors.

Repeated repointing is synonymous with the removal of loose and friable mortar from the masonry joint. The prepared joint is then filled with a mortar which is principally composed of a binder (lime) and aggregate (well graded sand). For repeated repointing repair scenario, lime-based mortar was encouraged as it lets the wall breathe. In this repair scenario, the decayed mortar from the face of the stone masonry wall can then be cut by raking out to reach the good mortar that remains deep in the wall (two or three times the thickness of the original mortar joints on the surface of the wall). Commonly, the repair depth should be cleaned out to a minimum depth of 25mm (38–50mm for wide joints, such as those in a rubble wall, if necessary). Historically, repeated repointing intervention is commonly reapplied every twenty-five years (five times of intervention in a hundred selected specified periods) (Kayan, 2013).

Repeated plastic repair is a technique used to reface deteriorated masonry. The term 'plastic' refers to the plasticity or workability of the fresh mortar rather than a polymeric material. The mortar adopted for these surface repairs can vary greatly but as with repointing mortars are principally composed of a binder and an aggregate. Under this repair scenario, the decayed surface of the stone masonry wall was assumed to be cut back to a point at which a sound substrate was reached and lime-based mortar was used to resurface the stone. Then, the resurfacing of the stone used lime-based mortar (with aggregates) materials for a 1m^2 masonry wall plastic repair with a minimum of 3–12mm depth (depending upon the thickness of the joints) of undercut or cutback, with approximately 9mm thick layers (base coats) and 6mm finishes. For this repair scenario, a minimum depth of 40mm were commonly undercut or cutback with an approximately 9mm thick layer (base coats) and 4mm finish (http://www.lime-mortars.co.uk/calculators/plaster) for multi-layer patch. Normally, the intervention was reapplied every thirty years (3.33 times in the hundred-year study period) (Kayan, 2013).

N**atural stone replacement** is associated with partial or full integration of new stone masonry units, whether ashlar (squared cut blocks) or rubble (irregular shaped masonry). These units are built into the pockets that are formed by removing deteriorated stone. In the case of stone masonry wall, natural stone replacement was assumed to require the cutting back or indenting of approximately 100mm (0.1m) or 0.10m3 of volume (1m x 1m x 0.1m = 0.10m^3) of the defective material in natural stone. This this cutting back or indenting processes was then followed by building in a new section of stone with the approximate dimension of 1m x 1m x 0.1m of respective length (L) x height (H) x width (W). For this paper, the life expectancy was taken to be a hundred years and all of the replacement stone's EMI was attributed to the study period (only one intervention in a hundred selected arbitrary periods) (Kayan, 2013).

Pinning and consolidation, followed by natural stone replacement of natural stone is normally only required to those stones that are face bedded (hence perpendicular to the natural sedimentary deposited layers). The technique requires drilling holes through the debonded layers and connecting then with stainless steel or nylon dowels that are subsequently grouted, fixing them in position (Forster, 2010 a & b; Fielding, 1994). Generally, pinning and consolidation, followed by natural stone replacement repair scenarios for the stone masonry wall were assumed to require high-grade threaded stainless steel dowels, which should ensure the survival of the historic fabric of the stone masonry wall for an initial twenty-year period. In the case of this paper, high-grade threaded stainless steel dowels (grade 304), as specified by Institute of Stainless Steel Forum (ISSF), that were 100mm long and 6mm diameter, were used and inserted at an approximate minimum of 100mm spacing or one hundred pieces in $1m^2$ stone masonry wall with an average weight of 46g per piece (http://www.valbruna.co.uk/products/reval/dowel-bar-details). Historically, after a twenty-year period the repair may fail and require further intervention in the form of replacement of stone. As previously mentioned, this process requires the 'cutting out' of the defective masonry to a depth of approximately 100mm ($0.1m^3$) and the building in of a new section of stone. For this paper, the replacement stone will last beyond the hundred years and so only 0.8 of its EMI was attributed to the study period (Kayan, 2013).

It must be emphasised that certain combinations of stone masonry wall repair are more common than others. For example, pinning and consolidation would be done only once and followed by stone replacement, while a plastic repair is followed by stone replacement within a selected arbitrary period. By contrast, it would be highly unusual to pin and consolidate and then undertake a plastic repair within the same period (Foster et al., 2011 and Kayan, 2013).

The effective determination of cumulative carbon associated with any type of repair and its underlying sourcing to site are fundamental components of the model. Twinned with this is the durability or service life prediction for the repairs and the number of expected repeat interventions within a given timeframe. Collectively, these form the basis of the Environmental Maintenance Impact 'EMI'. For the purpose of this paper, testing on the 'Green Maintenance' model was undertaken by generating of EMI expended with either a single or combination of stone masonry wall repair techniques in different repair scenarios only, within selected maintenance profiles (in this case, over a hundred years). If we can evaluate the efficacy of stone masonry wall repair in terms of its embodied carbon expenditure (CO_2 emissions), it could then be tailored to suit the EMI aspects rather than the longevity of repair alone. It must be noted that the scope of LCA in this paper was defined by taking into account the EMI as the parameter in comparing embodied carbon expenditure (CO_2 emissions) from stone masonry wall repair (Kayan, 2013).

In practice however, LCA appears to be problematic as it commonly has many complications. Hammond and Jones (2008a) suggest that there are varies differences in LCA calculations including boundary conditions restriction and general incorrect assumptions. These differences carry a natural level of variation and methodological differences and relevant parameters. Previously, a significant number of studies have been conducted by researchers and organisations in order to identify variations of LCA. Ding (2004), as cited by Dixit et al. (2010), asserts that research studies have been undertaken that identify parameters responsible for variations in LCA (Dixit et al., 2010). It must be emphasised that, Dixit et al. (2010) has also revealed that there is 10 common parameters (system boundaries, analysis methods, geographic location, primary and delivered energy, age of data, completeness of data, manufacturing technology, feedstock energy consideration and temporal representation) that commonly influence the quality of embodied energy results, which could make differences on CO_2 emissions now or in the future. But, it must be noted that there is no clear indication has been provided by these previous LCA studies on how these relevance parameters causing variations in embodied carbon expenditure particularly for stone masonry wall repair in historic masonry buildings

To accurately and meaningfully determine the EMI of the repair, the boundary conditions of LCA and maintenance interventions must be established. For the evaluation of the EMI of this paper, no allowance was made for materials that last, for example, sixty years and then have an 'excess' service life of forty years from the point of stone masonry wall repair, over the designated hundred years. It must be emphasised that, if materials used in stone masonry wall repair are expected to fail before one hundred years and can be replaced without removing the rest of stone masonry wall element, then only the embodied carbon expenditure associated with the particular repair materials (such as lime mortar materials for re-pointing, pinning and consolidation, and lime plaster materials for plastic repair) will be considered for evaluation in LCA. Additionally, if other components or the entire stone masonry wall element must be replaced because of the shorter lived components (such as in natural stone replacement), then the embodied carbon expenditure within 'cradle-to-site' will be multiplied by the replacement, even if the materials removed have a potentially longer life expectancy or longevity of repair. Remarkably, in reality, it must be emphasised that natural stone replacement commonly outlived Predicted Life of one hundred years. Commonly, this is highly influenced by stone profiles as well as longevity of repair of for natural stone (Kayan, 2013).

Previously, several LCA studies have been undertaken to evaluate embodied carbon in different types of buildings. However, the focuses of these previous works are centred largely on embodied energy figures (rather than embodied carbon expenditure) for limited types of buildings, such as new residential (Treloar, 1997, 1998; Pullen, 2000a and 2000b; Dixit et al., 2010) and commercial buildings (Treloar, 1997; Yohanis and Norton, 2002; Dixit et al., 2010). Additionally, the focus of these previous LCA works do not specifically evaluate embodied carbon expended from stone masonry wall repairs during the maintenance phase.

Chronologically, few LCA studies in the public realm specifically investigate the carbon impacts of stone materials. Previous studies by Alshboul and Alzoubi (2008) and the University of Tennessee (2008a; 2008b; 2008c) on embodied carbon and energy values in Jordan and the United States respectively relating to natural stone. Moreover, Venkitachalam (2008) had evaluated the carbon footprint for stone in the Scottish context; highlighted the fact that a high proportion of the carbon footprint (within 'cradle-to-gate' LCA) for sandstone is contributed by transportation i.e. transportation emissions were between 31% and 90% of total represented embodied emissions associated with local and imported stone respectively (Venkitachalam, 2008). It must be noted that, despite its aim to quantify the carbon footprint for stone, however, this study's focus was restricted solely to sandstone and failed to take into account the proportion accrued in relation to other commonly used stones in the masonry walls of historic masonry buildings.

In 2010, Historic Scotland commissioned the Scottish Institute of Sustainable Technology (SISTech) and Heriot-Watt University undertaken a collaborative research project in order to understand embodied carbon in natural stone used in the construction and repair of Scotland's buildings. Methodologically, the results of this study were integrated using Sima Pro and Gabi4, leading to the publication of 'Embodied Carbon in Natural Building Stone in Scotland' by SISTech. Primarily, this study adopted the 'cradle-to-site' LCA approach to evaluate dimension stone as a building material, this study demonstrated the overwhelming significance of transport, which results in a vast difference in carbon emissions depending upon where the stone is sourced. Significantly, findings of this study revealed that imported stone has an enormous impact on the overall carbon footprint. This study found that a massive increment of 90% to 550% (over six times more) was noted in relation to transportation of stones imported mainly from China and India when compared to equivalent material sourced locally (see Crishna et al., 2011). It must be noted that, however, despite its primary aims to quantify a carbon footprint of locally-produced (within Scotland and the UK) natural stone, the scope of this research project extends only to sandstone, granite and slate; therefore, embodied carbon for the repair materials used in stone masonry wall repair were regrettably not quantified by this study.

Clearly, to attain rational use of Green Maintenance model, embodied carbon expenditure of the repairs would have to be evaluated using multi-criteria approach comparable, reproducible methods. As clearly shown in the model, there is clearly a relationship between the number, type and longevity of maintenance interventions undertaken, and the embodied energy (CO_2 emissions) in repairs. Comparatively, this model also shows that a durable repair requiring fewer repeat interventions may incur less energy over the lifespan of the building than a less durable alternative. It must be noted that, the parameters are influenced by many variables, such as; longevity of repair, resourcing and geographical location, and mode of transportation, degree of wall exposure, building and wall detailing, quality of initial work and specification etc. (Forster and Carter, 2011; Torney, et al., 2014; Torney, and Forster, 2012).

Whilst it is appreciated that these variables are complex and wide ranging in nature it is possible to establish embryonic or early stage data values that enable rational evaluation and determination to be made. Refinement of this will obviously occur as carbon accounting and LCA becomes more prevalent and a common understanding of boundaries is universally adopted, enabling the model to work with greater accuracy.

3. Green Maintenance Modelling: Calculation procedures Boundaries and Life Cycle Assessment

The development of the calculation procedures underpinning the ‘Green Maintenance’ model quantifies of the embodied carbon expended in historic fabric. This is correlated with the life expectancy of the repair. Using a set of unit processes and workflows from each stone masonry wall repair technique and potential repair scenario (see Figure 2), the embodied carbon calculation procedures were undertaken focusing upon ‘before’ use stages (encompassing the extraction and processing of raw materials as well as manufacturing processes) and ‘use’ stages (transportation and distribution) as defined by the Sustainable Building Alliance (2015).

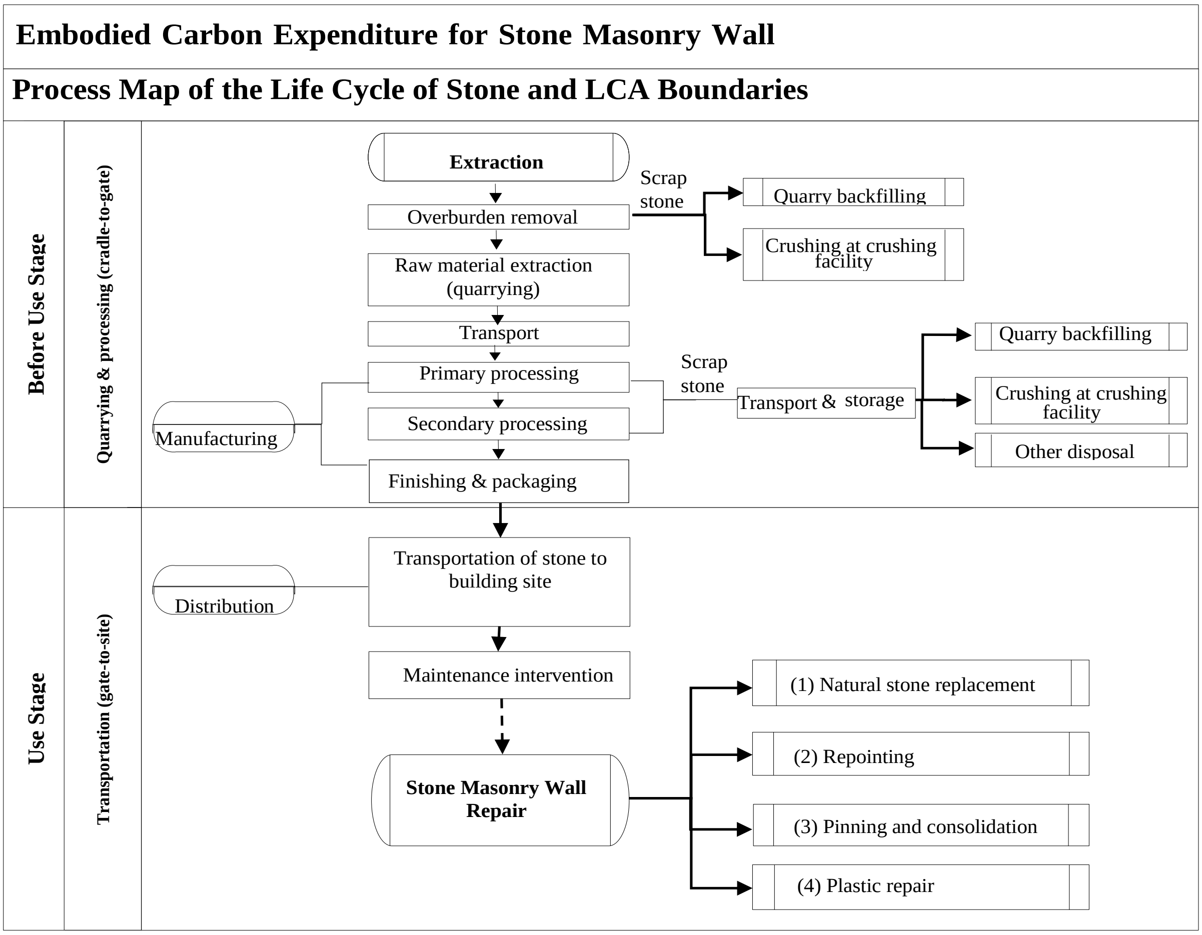

Figure 2: Process map of the life cycle of stone for historic buildings
Source: Kayan, 2013.

These stages are utilised to define the boundaries of LCA and therefore attain tangible values to be entered into the model.

Cumulative Embodied Carbon Expenditure

The embodied carbon for repairing stone masonry walls was calculated within ‘cradle-to-gate’ (for quarrying, mining, manufacturing and processing) and ‘gate-to-site’ (transportation to site). Green Maintenance model determined the efficiency in terms of Environmental Maintenance Impact (CO_2 emissions per kg of materials used) of each stone masonry wall repair technique by comparing the relative embodied carbon expenditure (*ce*). The fundamental components of the model were based upon the maintenance interventions (n) and the total area of repaired stone masonry wall (m^2) within selected maintenance periods.

The cumulative embodied carbon expenditure 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. This normalised the area to enable rational comparison. This is expressed in Equation No. (1);

$$\textit{Cumulative Carbon expenditure on maintenance} = \sum_{i=1}^{n} ce_i$$

Equation No. (1)

where;
n = number of interventions
ce_i = embodied carbon expenditure for the ith maintenance intervention [evaluated within selected ‘cradle-to-site’ boundary of LCA]

For the purpose of this paper, it must be noted that, however, this 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 (Forster et al., 2011; 2013 and Kayan 2013).

Functional Units of Embodied Carbon Per m^2 *(*$kgCO_2e/kg/m^2$*)*

The ‘Green Maintenance’ calculation procedures utilises the embodied carbon expenditure to repair 1m^2 of wall repair for each stone masonry technique. In this paper, a functional unit of $kgCO_2e/kg/m^2$ was used for the calculation purpose. It was defined in kilograms of carbon dioxide emissions, equivalent per kilogram of stone masonry wall repair materials or $kgCO_2e/kg$. These were all calculated within the ‘cradle-to-site’ of LCA on a yearly basis, for the selected maintenance period. To suit the purpose of this paper, the total embodied carbon per m^2 ($kgCO_2e/kg/m^2$) expended from quarrying, manufacturing and transportation to historic masonry building sites within cradle to site was calculated for each repair type (used in repairing 1m^2 stone masonry wall). The Functional Units of Embodied Carbon Per m^2 was expressed as $kgCO_2e/kg/m^2$.

Table 1 establishes the main embodied carbon for various repair scenarios; it is evident that stone replacement has the highest embodied carbon expenditure of all the interventions (either for single or a combination of repair techniques on one typical sample building, and in this case is in this case CEC4-22-30, Shandwick Place of Edinburgh) based on its relative embodied carbon expenditure associated with alternative repair scenarios undertaken on normalised 1m^2 of stone masonry wall (functional units of $kgCO_2e/kg/m^2$). However, when this is placed in context of a 100-year maintenance period, it has the lowest EMI due to the short life expectancy of the other interventions. For the purpose of calculation of EMI of this paper, longevity of repair for stone repair techniques is based on data derived from Ashurst and Ashurst, 1988, Ashurst, 1994a and 1994b, Ashurt and Dimes, 1998, McMillan et al., 1999, Historic Scotland 2003a, 2003b, 2007a, 2007b, 2007c and 2007d, Young et al., 2003, BCIS, 2006 and BRE 2010.

Table 1: Embodied carbon expenditure associated with alternative repair scenarios undertaken on normalised 1m^2 of stone masonry wall (functional units of kgCO_2e/kg/m^2)

		Scenario 1 Stone replacement	**Scenario 2** Repointing	**Scenario 3** Pinning and consolidation, then stone replacement	**Scenario 4** Plastic repair	**Scenario 5** Plastic repair, then stone replacement
Stone replacement	kgCO_2e/m^2	49.965	-	49.965	-	49.965
	Number of intervention (n)	1	-	0.8	-	0.7
	Total Average EMI	**49.965**		**39.972**		**34.976**
Repointing	kgCO_2e/m^2	-	1.641	-	-	-
	Number of intervention (n)	-	4	-	-	-
	Total Average EMI	**-**	**6.564**			
Pinning and consolidation	kgCO_2e/m^2	-		37.725		-
	Number of intervention (n)	-		1		-
	Total Average EMI			**37.725**		
Plastic repair	kgCO_2e/m^2	-		-	60.049	60.049
	Number of intervention (n)	-		-	3.33	1
	Total Average EMI			**-**	**199.963**	**60.049**
Overall Total Average EMI		**49.965**	**6.564**	**77.697**	**199.963**	**95.025**

Source: Kayan, 2013.

Note:

(a) Materials data are derived from Crishna et al., (2011) and Hammond and Jones, (2008a; 2008b and 2011); transport data are derived from the Department of Environment and Rural Affairs (DEFRA) and Department of Energy and Climate Change (DECC) (2009) and the Institute for Energy and Environmental Research (IFEU) (2008).

(b) Embodied carbon expenditure for materials transportation (gate-to-site) @ 132 gm CO_2 emission factors per tonne km or 1.32 x 10^{-4} kgCO_2 per kg km emission factors using updated 2008 CO_2 emission factors per tonne km for all HGV road freight (based on UK average vehicle loads in 2005) (IFEU, 2008; Defra/DECC, 2009) or mass (kg) * emission factors per kg km (for the purpose of this paper, 132 gm CO_2 emission factors or 1.32 x 10^{-4} kgCO_2 per kg km emission of HGV road freight were used to calculate embodied carbon expended in the transportation of stone masonry wall repair materials to building sites, within 'gate-site' boundary of LCA)* distance [shortest and most direct distance travelled for repair material transportation from resourcing location (quarrying or mining) to building site (in km)]. A tonne km (tkm) is the distance travelled multiplied by the weight of freight carried by the HGV. So, for example, an HGV carrying 5 tonnes freight over 100 km has a tkm value of 500 tkm. The CO_2 emissions are calculated from these factors by multiplying the number of tkm the user has for the distance and weight of the goods being moved by the CO_2 conversion factor for the relevant HGV class.

(c) HGV is heavy good vehicle (based on UK average vehicle loads in 2005, and defined by Defra/DECC, 2009).

(d) Sample taken from 22-30 Shandwick Place of Edinburgh.

Equation 2 was utilised to model the data.

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (per\ 1m2\ stone\ masonry\ wall\ repaired)$$
$$= \sum ECEcradle - to - site\ (m2)_{n=} ECEcradle - to - gate\ (m2)_{n}$$
$$+ ECEgate - to - site\ (m2)_{n}$$

Equation No. (2)

where;

ECEcradle-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 *ECEgate-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.

Total Embodied Carbon Expenditure for Selected Maintenance Period Within 'Cradle-to-Site'

The total embodied carbon expenditure within selected maintenance periods were calculated based on the total cumulative values for the stone masonry wall repair.

The total embodied carbon evaluates a series of complete interventions within selected maintenance periods. This was calculated using Equation No. (3):

$$Overall\ total\ \ of\ embodied\ carbon\ expenditure$$
$$= \sum_{ti=1}^{n} ECEcradle - to - site_{ti}\ = ECEcradle - to - site_{\ t1}$$
$$+\ ECEcradle - to - site_{\ t2} \ldots ECEcradle - to - site_{\ tn}$$

Equation No. (3)

where:

$_{tn}$ = relevant repair technique (tn)

$_{ti=1}$ represent first intervention which started initially with value of (n) is =1.

ECEcradle-to-site$_{tn}$ = total embodied carbon expenditure for quarrying, 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. (2)]

Comparative Embodied Carbon Expenditure Determined on Environmental Maintenance Impact (EMI)

Theoretically, an organisation could repair a 1m^2 area of deteriorated historic stone masonry using different types of repair techniques. Various repair permutations could be enlisted to undertake the works. For example, a single or a combination of alternative repair scenarios. Additionally, it must be placed on the calculation procedures of this paper, which should be able to draw rational comparisons between individual and multiple cumulative maintenance interventions. An evaluation of the embodied carbon expenditure could then be calculated for each of these repairs techniques within the selected boundary of LCA.

Table 2 represents the total Environmental Maintenance Impact (EMI) expended for 4 types of stone masonry wall repairs on different buildings. For examples, there are differences of EMI expended on repair for each building with different management and ownership. Comparatively, EMI (kgCO$_2$e/kg) for replacing natural stone was lower than the other three repair techniques within 'cradle-to-site' and 100-year maintenance profile periods with 170.969 $kgCO_2e/kg$, 189.114 $kgCO_2e/kg$ and 148.068 $kgCO_2e/kg$ for respective HS1, NTS1 and CEC1 (see note).

The typical results from HS1-Doune Castle show that the range of EMIs for natural stone replacement is 31.853-77.909 kgCO2e/kg. This is slightly higher than with repointing (11.312 kgCO2e/kg) and plastic repairs (20.147-376.130 kgCO2e/kg). However, it must be emphasised that the total embodied carbon expenditure for repointing is normally the highest. This is due to this technique being used for the largest total repaired area of delaminated surfaces of stone masonry walls; this trend occurred across selected sample properties. The trend is also similar with plastic repairs, due to the enormous usage of materials of a high embodied carbon coefficient value, such as secondary fixing materials, particularly for multi-layer patch. This is due to the higher longevity of repair this type requiring only one intervention within the same maintenance period. In general, natural stone replacement has the lowest total embodied carbon expenditure compared to re-pointing, pinning and consolidation and plastic repair. Despite the lowest initial EMI associated with lime mortar repointing, this repair technique is commonly subject to large total area of delaminated surface wall to be repaired.

Table 2: Total Environmental Maintenance Impact (EMI)

	Total Environmental Maintenance Impact (EMI) $\sum ECE_{cradle\text{-}to\text{-}site}$ **$kgCO_2e/kg$**		
	HS1	NTS1	CEC1
Replacement			
Indenting + lime grout mix	31.853	37.698	24.075
Indenting + dowels + lime grout mix	61.207	67.684	53.871
Dowels + epoxy resin	77.909	83.732	70.122
Total$_{100years}$	**170.969**	**189.114**	**148.068**
Repointing			
Lime mortar repointing	11.312	20.992	6.568
Total$_{100years}$	**11.312**	**20.992**	**6.568**
Pinning and consolidation			
Dowels + lime grout mix	146.130	148.775	147.005
Dowels + epoxy resin	230.280	230.170	231.115
Total$_{100years}$	**376.410**	**378.945**	**378.120**
Plastic repair			
Lime-based mortar + aggregates	20.147	24.212	21.955
Lime-based mortar (multi-layer plastic repair)	376.130	931.341	378.385
Total$_{100years}$	**396.277**	**955.553**	**400.340**

Source: Kayan, 2013.

Note:

HS1-Doune Castle,NTS1-Newhailes Estate, Stable Block and CEC1-15 Hillside Crescent and 30-32 Hillside Street, Edinburgh.

Testing

As expressed in Equation No. 3, the efficiency of embodied carbon expenditure (CO_2 emission) per year for one individual stone masonry wall repair technique would be a function of the annual total of embodied carbon expenditure and the longevity of repair undertaken.

The 'Green Maintenance' model can be tested on its Environmental Maintenance Impact (EMI), for either single or a combination of stone masonry wall repair techniques in different repair scenarios. This will ascertain repairs suitability based on longevity over the maintenance period. If a hypothetical 100 years is evaluated for stone masonry wall repair, the need to intervene will be a function of the life expectancy of the repair. Within this period, the values in Table 1 were entered into Equation No. (3). This equation determines the total Environmental Maintenance Impact (EMI) of either a single repair technique or a combination of them in different repair scenarios in the stone masonry wall structure for 100-year maintenance periods. Obviously, inconsistent data on the durability of product or materials makes the determination and benchmarking of component life difficult (Balaras et al., 2005) and leads to some estimated service life (ESL) predictions being quite unrealistic. It must be noted that, in the case of natural stone masonry, an average life expectancy of 100 years does not take account of a well-maintained building (Building Cost Information Service (BCIS, 2006) or the vast differences between stone types. There are many examples of stone still functioning satisfactorily in buildings that are several hundred years old. It must be emphasised, however, that the time between interventions is influenced by many variables, including material durability, degree of exposure, building detailing, and quality of repair and specification. For example, undertaking repairs at frequent intervals e.g. 50 or 200 years might or might not increases the risk of mechanical damage to the masonry associated with scaffolding. Practically, less regular masonry repair can reduce the risk of this damage and also aligns with the philosophical principle of least intervention.

For instance, Table 3 summarises the overall total EMI, evaluated in terms of embodied carbon expenditure, over the 100-year maintenance period for different repair scenarios at the same sample property (in this case CEC4-22-30, Shandwick Place of Edinburgh). It must be noted that, longevity of repair for stone repair techniques is based on data from Ashurst and Ashurst, 1988, Ashurst, 1994a and 1994b, Ashurt and Dimes, 1998, McMillan et al., 1999, Historic Scotland 2003a, 2003b, 2007a, 2007b, 2007c and 2007d, Young et al., 2003, BCIS, 2006 and BRE 2010.

Table 3: Embodied carbon expenditure associated with alternative repair scenarios.

		Scenario 1 Stone replacement	**Scenario 2** Repointing	**Scenario 3** Pinning and consolidation, then stone replacement	**Scenario 4** Plastic repair	**Scenario 5** Plastic repair, then stone replacement
Stone replacement						
(a) Indenting + lime grout mix	$kgCO_2e/m^2$	24.683	-	24.683	-	24.683
	Number of interventions (n)	1	-	0.8	-	0.7
	Total EMI	**24.683**		**19.746**		**17.278**
(b) Indenting + dowels + lime grout mix	$kgCO_2e/m^2$	54.481	-	54.481	-	54.481
	Number of interventions (n)	1	-	0.8	-	0.7
	Total EMI	**54.481**		**43.585**		**38.137**
(c) Dowels + epoxy resin	$kgCO_2e/m^2$	70.730		70.730	-	70.730
	Number of interventions (n)	1	-	0.8	-	0.7
	Total EMI	**70.730**		**56.584**		**49.511**
Repointing						
Lime mortar repointing	$kgCO_2e/m^2$	-	1.641	-	-	-
	Number of interventions (n)	-	4	-	-	-
	Total EMI	**-**	**6.564**			
Pinning and consolidation						
(a) Dowels + lime grout mix	$kgCO_2e/m^2$	-		29.402		-
	Number of interventions (n)	-		1		-
	Total EMI			**29.402**		
(b) Dowels + epoxy resin	$kgCO_2e/m^2$	-	-	46.047	-	-
	Number of interventions (n)	-	-	1	-	-
	Total EMI			**46.047**		
Plastic repair						
(a) Lime-based mortar + aggregates	$kgCO_2e/m^2$	-		-	6.489	6.489
	Number of interventions (n)	-		-	3.33	1
	Total EMI			**-**	**21.608**	**6.489**
(b) Lime-based mortar multi-layer plastic repair)	$kgCO_2e/m^2$	-	-	-	113.608	113.608
	Number of interventions (n)	-	-	-	3.33	1
	Total EMI	**-**	**-**		**378.315**	**113.608**
Overall Total EMI		**149.494**	**6.564**	**195.364**	**399.923**	**225.023**

Source: Kayan, 2013.

Note:

(a) Materials data are derived from Crishna et al., (2001) and Hammond and Jones, (2008a; 2008b and 2011); transport data are derived from the Department of Environment and Rural Affairs (DEFRA) and Department of Energy and Climate Change (DECC) (2009) and the Institute for Energy and Environmental Research (IFEU) (2008).

(b) Embodied carbon expenditure for materials transportation (gate-to-site) @ 132 gm CO_2 emission factors per tonne km or 1.32 x 10^{-4} $kgCO_2$ per kg km emission factors using updated 2008 CO_2 emission factors per tonne km for all HGV road freight (based on UK average vehicle loads in 2005) (IFEU, 2008; Defra/DECC, 2009) or mass (kg) * emission factors per kg km (for the purpose of this paper, 132 gm CO_2 emission factors or 1.32 x 10^{-4} $kgCO_2$ per kg km emission of HGV road freight were used to calculate embodied carbon expended in the transportation of stone masonry wall repair materials to building sites, within 'gate-site' boundary of LCA)* distance [shortest and most direct distance travelled for repair material transportation from resourcing location (quarrying or mining) to building site (in km)]. A tonne km (tkm) is the distance travelled multiplied by the weight of freight carried by the HGV. So, for example, an HGV carrying 5 tonnes freight over 100 km has a tkm value of 500 tkm. The CO_2 emissions are calculated from these factors by multiplying the number of tkm the user has for the distance and weight of the goods being moved by the CO_2 conversion factor for the relevant HGV class.

(c) HGV is heavy good vehicle (based on UK average vehicle loads in 2005, and defined by Defra/DECC, 2009).

(d) Sample taken from 22-30 Shandwick Place of Edinburgh.

From the data shown in Table 1 and Table 3, it is evident that stone replacement has the highest embodied carbon expenditure of all the individual interventions. However, when this is placed in context of a 100-year maintenance period, it has the lowest EMI due to the short life expectancy of the other interventions.

Testing results in Table 3 also revealed that on typical one sample building (in this case 22-30 Shandwick Place of Edinburgh) repeated plastic repair (Scenario 4) had a 300% higher EMI compared to replacement stone (Scenario 1) (nearly 40% higher over the same period as noted by Forster et al., 2011). In comparison, repeated repointing (Scenario 2) had an EMI that was nearly 87% lower than replacement stone over the same period. Comparatively, it must be emphasised that the lower EMI value of repeated repointing (Scenario 2) is influenced by the generally high number of interventions (n) and the large area (m^2) of delaminated stone masonry wall surface repaired. Despite the lower percentage of EMI for repeated repointing (Scenario 2) in this building sample, it must be noted that, the whole surface of the wall is essentially required for overall surface repointing works within the same arbitrary period. This intervention is commonly undertaken as a good conservation approach (planned maintenance) during the maintenance phase of the stone masonry wall. Consistently, based on this scenario, then the EMI for repointing could be higher than stone replacement (Scenario 1). Conversely, the latter which commonly undertaken on small surface areas of wall repair (based on pieces or block of stones), will implicates consistent small EMI as compared to the former.

It must be emphasised that, if deterioration has occurred to the substrate forming the base of the plastic repair, therefore, it is necessary to cut back the natural stone further. Importantly, this will prevent repeated plastic repairs due to build-up of excessive thickness. In this situation, the plastic repair and the decayed natural stone is assumed to be removed after 30 years and new stone built in to a depth of 100 mm. In accordance with scenario 2 the replacement stone will last beyond the 100-year maintenance period so only 0.7 of its EMI is attributed to the study period (single plastic repair, then stone replacement, in Scenario 5).

Importantly, the transport of materials has a major impact on the EMI results (as noted by Crishna et al., 2011). Comparatively, Kayan (2013) claim that transportation accounts contribute to similar trend of impact on EMI (given uncertainties, exclusion, inclusion, assumptions and limitation of LCA) for more than one-fifth (20%) (in all the Scenarios), as compared to one-quarter (25%) as noted by Forster et al., (2011). This work shows that the efficiency of stone masonry wall repair techniques can be evaluated in terms of embodied carbon expenditure as shown by the 'Green Maintenance' model test results of the Environmental Maintenance Impact (EMI). Practically implemented but geographically specific the range of EMIs for natural stone replacement is 31.853-77.909 $kgCO_2e/kg$. This is slightly higher than with repointing (11.312 $kgCO_2e/kg$) and plastic repairs (20.147-376.130 $kgCO_2e/kg$). Testing results are similar across other samples. However, it must be emphasised that the total embodied carbon expenditure for repointing is normally the highest. This is due to this technique being used for the largest total repaired area of delaminated surfaces of stone masonry walls; this trend occurred across selected sample properties. The trend is also similar with plastic repairs, due to the significant use of materials of a high embodied carbon coefficient value, such as secondary fixing materials, particularly associated for multi-layer patches. Also, it must be emphasised that certain combinations of stone masonry wall repair are more common than others and interchangeable, i.e. pinning and consolidation would be done only once and followed by stone replacement, while a plastic repair is followed by stone replacement within a selected arbitrary period. By contrast, it would be highly unusual to pin and consolidate and then undertake a plastic repair within the same period.

4. Discussion

The results show that all interventions have an associated carbon cost. This model utilised an arbitrary 100 years ($kgCO_2e/kg/m^2$) maintenance profile period for this test but any duration could be theoretically evaluated. Clearly, the longevity of the repair types and numbers of interventions are interrelated i.e. one natural stone versus 4 or 5 plastic repairs and repointing.

The results show that natural stone replacement has the lowest embodied carbon and energy expenditure within the 100-year maintenance profiles. Comparatively, within the selected maintenance period of historic masonry buildings, natural stone replacement commonly requires the lowest number of interventions (n) of all the techniques. The total area repaired using this technique is generally smaller than with the other repair techniques. These results suggest that the smallest repaired area of stone masonry wall has also contributed to the lowest total embodied carbon expenditure within the same maintenance periods.

Results also shows that variations in embodied carbon expenditure for stone masonry wall repair techniques is due to differences in the repair materials LCA profile and longevity. It has been established that the embodied carbon coefficient and quantity (mass in kg) of repair materials is largely associated with transportation CO_2 emission per tonne km and the multi-faceted issues surrounding material procurement and the influencing factors relating to the 'gate-to-site' boundaries. Importantly, differences in CO_2 emissions per mass kg of every repair material vary due to transportation distances and this adversely affects the environmental inputs. Additionally, the differences in CO_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 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'). Additionally, a high value of CO_2 emitted for transportation of imported repair materials (such as lime) was due to the long distance between the resourcing location and building site. In comparison, all types of lime materials used for repair on the selected sample buildings are mainly imported from St Astier in southwest France and the Canton of Jura in northwest Switzerland (Jura Kalk). Significantly, the long transportation distance for imported materials such as lime materials and Jura Kalk is commonly higher than that of locally sourced materials (stone, sand, cement, brick dust/fire clay/fly ash, aggregates and all secondary fixing materials). In some cases, transportation distance for the former was approximately 1400-2000km as compared to around 10-138km for the latter (Kayan, 2013). Moreover, high value of embodied carbon coefficient of lime used in stone masonry wall repair was due to the great use of energy, electricity and fuel combustion during the quarrying and processing process ('cradle-to-gate').

Apparently, the different source of power generation [as well as Green House Gas, (GHG)] contributes to different CO_2 emissions, particularly in product or materials manufacturing. It must be noted that embodied carbon coefficient values from foreign data were always influenced by national differences in fuel mixes and electricity generation. For example, Frischknecht (1998) has developed a life cycle inventory model on how different source of power generation influencing CO_2 emission in product manufacturing “national electricity mix” and “small scale gas-fired combined heat and power generation” (Frischknecht, 1998).

A significant number of previous works relating to LCA have attempted mainly to provide databases for the environmental impact and embodied carbon coefficient of building materials. But, most of the generated results have been incorporated into commercial software and handbooks that are widely used by academics and the industry alike. Generally, and inevitably, researchers studying LCA disagree about the selection of “best values” for the embodied carbon coefficient of materials. Consequently, the choice of “best value” for embodied carbon coefficient of a typical material largely relies upon careful analysis, data availability and the comprehensive boundaries of LCA (Dixit et al., 2010).

For the purpose of this paper, primary energy sources (such as coal and electricity) were only evaluated if relevant. However, this primary energy was only evaluated in order to attain a consistency measurement in terms of embodied carbon expenditure (CO_2 emissions) within ‘cradle-to-site’, i.e. for quarrying, processing and transporting repair materials used for repairing historic buildings stone masonry walls. In addition, all direct embodied carbon use from fuels and electricity at raw material extraction (embodied carbon co-efficient for quarrying, mining, manufacturing and processing) are included in calculations on embodied carbon expenditure of stone masonry wall repairs.

In line with PAS 2050, some sources of embodied carbon were excluded in LCA for this paper including embodied carbon expenditure (from direct consumption of fuels) in the quarrying, mining, manufacturing and processing procedure and maintenance of used machinery and vehicle, off-site transport, and electricity (either the sources purchased from the national or from another supply) (BSI, 2008). It must be emphasised that, there is varying value for embodied carbon coefficients of stone masonry wall repair materials (including additional materials such as cement, all lime, brick dust/fire and clay/fly ash) as a consequence of their different technology, fuels, electricity and energy used in within ‘cradle-to-site’ boundary of LCA. The number of interventions (n) and total area repaired (m^2) assessed is also critical.

Practically, the results will also be influenced by the specifiers philosophical attitude towards stone masonry wall repair and their broader repair strategies (Forster, 2010a and 2010b). The results show that by using the calculation procedures, the ‘Green Maintenance’ model can evaluate the efficiency of stone masonry wall repairs in terms of embodied carbon expenditure. Significantly, the model shows that there is correlation between test results and the efficiency of stone masonry wall repairs in terms of embodied carbon expenditure.

For the purpose of this paper, only the total embodied carbon expenditure for the repair of deteriorated stone masonry during the maintenance phase 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. Also, the data utilised in ‘Green Maintenance’ result testing should become more rigorous with time as LCA and life expectancy information of products or repair materials becomes more widely available.

5. Conclusions

The understanding of the interrelationship of the longevity of repair materials and their embodied carbon (within selected boundaries and maintenance period) was utilised to test the Green Maintenance Model. In this paper, different repair techniques and scenarios (either single or a combination) were utilising different material types and their efficiency in terms of Environmental Maintenance Impact (EMI). The calculation procedures of ‘Green Maintenance Model’ presented in this paper represents a meaningful and reproducible mechanism for the evaluation of the Environmental Maintenance Impact (EMI) of the materials used in repairing stone masonry walls of historic masonry buildings. Apparently, the model has shifted current paradigm of conventional frameworks to embodied energy expenditure evaluation by not only promoting the use of traditional materials, it also provides options to attain low carbon targets via repair interventions over the life cycle. This calculation procedure establishes and tangibly tests the ‘Green Maintenance’ model and supports its adoption for achieving more rigorous analysis of repair strategies. This allows rational appraisal of the different maintenance strategies and ultimately makes decisions easier to defend. Additionally, the model also promotes adoption of sustainable repair approach and can be adopted to evaluate of its impact on other repair options and building forms. Significantly, it could be of value to those making and support environmentally focused decisions.

Acknowledgements

The authors would like to thank the contribution made by the National Trust for Scotland, Historic Scotland and the City of Edinburgh Council for access to maintenance and repair data.

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