Green Maintenance for Historic Masonry Buildings: A Life Cycle Assessment Approach

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Abstract

This research establishes the concept of ‘Green Maintenance’ modelling for historic masonry buildings. It recognises the important role of maintenance and repair in reducing embodied carbon expenditure, thus minimising the Environmental Maintenance Impact (EMI) typically associated with the deterioration of external stone masonry walls. The model was developed using a mathematical framework, and it generated results described in terms of EMI. This model utilises life-cycle assessment (LCA) ‘cradle-to-site’ over a selected maintenance period.

The work evaluates embodied carbon expenditure from different stone masonry wall repair techniques for historic masonry buildings during their maintenance phase. It was discovered that embodied carbon expenditure for these repair techniques are highly influenced by the number of maintenance interventions, longevity of repairs, total wall surface repaired (m^2), the embodied carbon coefficient value (‘cradle-to-gate’) and kg/km emission factors (‘gate-to-site’) associated with materials and repair processes.

Based on the EMI in terms of embodied carbon expenditure generated from the results of ‘Green Maintenance’, the efficiency of stone masonry wall repair techniques can be determined. This not only aids in maintenance decisions making processes, but also contributes in substantiating the philosophical defensibility and sustainability of interventions. In the broader sense, this model is not simply confined to masonry and will be of use to those entrusted with the repair of other elements and components.

Dedication

I dedicate this work for my beloved family, parents, wife and children.

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Published Papers

The following papers have been published as a result of this research:

Forster, A.M., Carter, K., Banfill, P.F.G. and **Kayan, B.** (2011) Green maintenance for historic masonry buildings: an emerging concept, *Building Research & Information*, 39 (6): pp. 654-664.

Forster, A.M. and **Kayan, B.** (2009) Maintenance for historic buildings: a current perspective, *Structural Survey*, 27 (3): pp. 210-229.

Chapter 1: Introduction

This introductory chapter describes the structure of this research and explains the rationale and its broad aims which are to evaluate the embodied carbon expended when undertaking stone masonry wall repairs for historic masonry buildings. This chapter also introduces the research questions, objectives, problems and limitations that inform the parameters of the study.

1.1 Research Background

The survival of buildings is one that is essentially underpinned by maintenance. Maintenance and repair are crucial to the survival and in-service use of any building (Dann and Cantell, 2007); essentially this form of preservation protects the value embodied in the historic fabric of buildings by working to "stave off decay by daily care" (SPAB, 2008: 1) and prolonging the life of components (Bell, 1997; Maintain our Heritage, 2004). Maintenance reduces the need for many, often unnecessary costly repairs in the longer term (UWE, 2003). However, the importance of maintenance in terms of reducing embodied carbon expenditure generated during repair has been ignored by academia and industry alike.

In general, the approach to maintenance evaluation is not always straightforward: Historic Scotland (2008) indicate that *"there can be difficulties in identifying a generic hierarchy of maintenance interventions within historic buildings"* (Historic Scotland, 2008: 1). In regards to an evaluation of such repair, difficult decisions need to be taken into account to manage the relevant parameters. These include budgetary restraints and philosophical frameworks that include: reduced intervention; like for like material replacement; and, respect for traditional craft skills (Bell, 1997). However, consideration and evaluation of building maintenance through repair efficiency in relation to the embodied carbon expenditure remains unclear.

Generally, protection of historic fabric through maintenance is not only undertaken from a cultural perspective but also from an economic one. The scale of the importance of maintenance is reflected in the fact that 50% of Europe's national wealth is enclosed within its existing built environment (Balaras et al., 2005). A combination of premature deterioration and 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). In addition, the UK's built environment contains 450,000 listed and 10.6 million pre-1944 buildings (Maintain Our Heritage, 2004: 17). 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, 2002:31; Arup, 2003:22]. Statistics show that maintenance has been at greater financial cost, due to the usage of traditional materials for repairing the existing built environment. Meanwhile there is an expanding market for repair, i.e. economic cost is incurred for existing built environment maintenance in the national and international context. 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.

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). Other major cities with a tradition of masonry construction in Scotland (such as Edinburgh) may also need similar levels of investment, 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.

1.2 Maintenance Interventions and Embodied Carbon Expenditure

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 & Jones, 2008a**:** 96). It is inevitable that the resources in existing building construction are already becoming depleted. As echoed by The National Trust for Scotland (NTS), *‘the greenest building is the one that is already built’* (NTS, 2005: 1; NTS, 2012: 1). This statement is substantiated by the premise that an existing structure negates the necessity for the expenditure of further resources in constructing a replacement. Reducing embodied carbon expenditure for these existing structures is therefore essential for their sustained utility efficiency.

It must be recognised that existing buildings (including historic masonry buildings) bear *“a cost associated with their environmental impact”* (Historic Scotland, 2008: 25-26). These buildings clearly play an important role in reducing embodied carbon expenditure through maintenance and repair. Overall, the focus of efforts to reduce carbon emissions from existing buildings rests mainly on their improvement to reduce heat loss, conserve energy and utilise more renewable sources of energy (EU, 2010). However, SBSA (2007) articulates that ‘*For existing buildings, it is clear that we cannot make them completely net zero carbon, but the target is to reduce their carbon emissions steadily and consistently…’* (SBSA, 2007: 19). The realisation of this is vital for achieving the overall reduction in carbon emissions. 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). 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.

1.3 Embodied Carbon Expenditure in Historic Masonry Buildings

Traditionally, maintenance has been accepted as a cost commitment that is associated with a building (Wise, 1984). However, any maintenance intervention also entails a carbon obligation, and there is an increasing international focus on reducing carbon in the built environment (Stern, 2006). Fundamentally, maintenance contributes to the lifetime carbon emissions in a way that may be cumulatively significant. In reality however, this focus largely centres only on new build and upgrading works on existing buildings, and not on maintenance.

To date, an evaluation of carbon emissions from repair to stone masonry structures has attracted considerably less attention. It is interesting to note that legislation to control carbon emissions, particularly in buildings has been established in many countries. However, there is no specific guideline that targets reduced carbon emissions as a consequence of historic masonry buildings repair. Additionally, earlier studies that have attempted to evaluate embodied carbon expenditure for stone masonry wall repairs have been limited in scope.

Carbon emissions can be related to building maintenance in two distinct ways; firstly, the maintenance operation itself and the carbon emitted as a result; and secondly, the embodied carbon expended in the improvement or repair works, and its influence upon the reduced rate of degradation.

Very often, repair is undertaken to attain a simple objective i.e. to retain existing buildings in a serviceable condition. Theoretically, maintenance can be undertaken with primary aims being to retain the functional or operational state of a building. In reality however, maintenance aims to reduce the rapidity of degradation and does not necessarily set out to improve the operational performance of the building. Generally, maintenance has a complex relationship with carbon emissions as these are linked to subtle changes to the building fabric that can occur as a result of repair. However, very little previous work has focused on the embodied carbon expenditure as a consequence of repair processes, and more specifically the repair of stone masonry walls of historic masonry buildings. Indeed, the ability of maintenance to reduce embodied carbon expenditure following the repairs are largely disregarded by relevant organisations and industry alike.

Maintenance also has an environmental impact, with some interventions leading to higher embodied carbon expenditure (through CO_2 emissions) than others and vice versa (Historic Scotland, 2008). To date, the measurement of embodied carbon expenditure (CO_2 emissions) by Life Cycle Assessment (LCA) has mainly attempted to evaluate the environmental impacts of products, buildings or other services throughout their life span (ISO, 2006a and 2006b). Measurement includes an evaluation of processes encompassing the extraction and processing of raw materials and the life cycle (usage stage) of buildings; manufacturing; transportation and distribution; use; reuse; maintenance; recycling and final disposal (Consoli et al., 1993). In addition, Sustainable Building Alliance (2009) has developed a model, upon which to base building life cycle assessment, indicating 3 distinct life cycle stages; the 'Maintenance, repair and refurbishment' category of the 'Use' stage encapsulates all aspects of the 'Product'; and 'Construction' stages (SBA, 2009). To date however, there has been no prevalent development of a unifying model using LCA to evaluate the efficacy of repair during the maintenance phase in terms of the embodied carbon expenditure.

Ideally, measurement of carbon expended on maintenance would extend from the extraction of raw materials up to the end of the product's lifetime, also known as a 'Cradle-to-Grave' analysis. However, this measurement has been shown to have a high degree of inaccuracy and variability. This is commonly due to the large number of influencing variables in data collection of sources, the year of the original measurement, historical period of origin, geographical area and the representativeness of the technological level. It has therefore become common practice in LCA to specify the embodied carbon of individual materials using 'cradle-to-site' analysis (Hammond and Jones, 2008b). The specification includes all of the embodied carbon expended prior to the product or materials reaching the point of use (i.e. building site).

Certain aspects of the degradation of historic masonry buildings may relate to higher embodied carbon expenditure (such as the results of aging and the decay processes that occur with masonry): gaps in the masonry fabric lead to higher air volume changes and associated heat loss; dampness that may require dehumidification; saturated stone as a function of defective detailing and rainwater also leads to reduced thermal performance through the altered conductivity of the masonry materials. All the aforementioned degradation processes associated with masonry relate to a potentially higher embodied carbon expenditure. In this research, an evaluation of the selected repair techniques for stone masonry wall repairs in historic masonry buildings within a specified period will be used to determine the most efficient in terms of measuring and controlling the embodied carbon expenditure.

1.4 Embodied Carbon of Stone Masonry Wall Repair Materials and Techniques

Unlike the case with new construction materials, the guidelines and regulations for usage of traditional repair materials to achieve embodied carbon reduction are unclear. Additionally, the relative roles of historic masonry buildings in helping to attain this aim remain unclear. In addition, there has been a broad range of embodied carbon coefficient values for stone masonry wall repair materials, as generated by previous LCA guidelines. However, the most common estimated values are for new builds and materials for upgrading works, and not specifically for materials used in stone masonry wall repair. Currently, there is no well-established data describing the environmental impact of traditional materials as compared to modern materials.

In regard to stone masonry wall repair for historic masonry buildings, the evaluation of embodied carbon expenditure as a result of the usage of tradition materials, such as stone has been highly influenced by their production. In the case of stone, the production industry is in decline. In the Scottish context, there were 700 operational stone quarries in the 1850s and there are now approximately only 50 remaining (SISTech, 2010 and Scottish Government, 2012). This decline is due to a combination of the loss of relevant craft skills, a greater demand for alternative materials such as brick and concrete and the rise in imported building stone. These changes have had a significant impact, particularly on carbon emissions, as existing buildings, such as historic masonry buildings need to be regularly maintained. In addition, such buildings are to be repaired in accordance with best conservation practice (Forster 2010a and 2010b). The origin of the building fabric influences the procurement strategies with replacement materials needing to be ideally selected on a like for like basis. The total carbon expenditure within the maintenance and repair process is therefore dependent on procurement and availability. The applicability of traditional philosophical tenets for these works underpins the suitability and defensibility of the masonry repair. These philosophical parameters could be extended to more specifically encapsulate sustainability.

Each stone masonry wall repair technique has a different longevity and associated embodied carbon expenditure. A comparison can be made between carbon expended from the use of repair materials, by starting from the point of their procurement (such as in the quarrying and manufacturing process) through to the transportation and the building site construction phase stage.

The selection process for maintenance and repairs to natural stone in a stone masonry wall is clearly a function of characteristics of philosophical defensibility, cost, durability and environmental impact. Repair techniques applied to stone masonry walls can be selected to cater for preferences in one or more of the aforementioned requirements. In this research, the efficiency of stone masonry wall repair techniques have focused on the environmental impact. Maintenance that attempts to achieve embodied carbon reduction in historic masonry buildings, cannot be made solely, or rely upon, a single repair technique. Therefore, a unified model and methodology that has the ability to evaluate the efficiency of a single, or a combination of stone masonry wall repair techniques in different repair scenarios has been developed.

1.5 'Green Maintenance' Model: Concept and Methodology

There is a relationship between the quantity of maintenance intervention that takes place within an existing building and the embodied carbon expenditure. In general, a durable repair undertaken upon a building requires a lower number of repeat interventions. This is illustrated by natural stone replacement in historic masonry buildings which is significantly more durable than a plastic repair, but the initial embodied carbon associated with this intervention is higher. It is important therefore to recognise that a durable repair with better longevity may incur less embodied carbon expenditure over the life span of the building.

It must be emphasised that problems can arise because the evaluation of the longevity of a repair is often ill-defined and inconclusive (Ashworth, 1996 and Douglas, 1994). In addition, databases of information associated with the longevity of building components are prone to inaccuracy and inconsistency. This is due to discrepancies in Estimated Service Life (ESL). These issues have caused problems for those attempting to evaluate the longevity of repairs and their impacts on embodied carbon expenditure. Despite this problem, a comparison of the efficiency of repair techniques in terms of embodied carbon expenditure can be attained using approximate relative values.

As previously found, the maintenance of buildings can be evaluated through repair. Such an evaluation can be undertaken in reference to repair efficacy, longevity, ability to conform to building conservation philosophy and, finally, sustainability. The frequency of maintenance interventions, such as repair to the stone masonry walls of historic masonry wall buildings clearly affects the level of CO_2 emissions. The complexity of prioritisation within the context of philosophical, economic and sustainability has led to the emerging concept and methodology of ‘Green Maintenance’. The best techniques are associated with low CO_2 emissions, high longevity and philosophical adherence. In effect, the model determines “how green” and intervention type is.

For this research, the conceptual model for ‘Green Maintenance’ focuses on the stages of historic masonry building maintenance, in order to understand the potential for reducing embodied carbon expenditure (reduction of CO_2 emissions from stone masonry wall repair) based on ‘cradle-to-site’ of LCA.

The ‘Green Maintenance’ model in this research works in parallel with the generally accepted model of sustainable development (Brundtland, 1987) and offers a potentially useful framework for the evaluation of ‘sustainable’ or ‘green’ maintenance interventions. This research associates maintenance interventions i.e. repair to stone masonry wall of historic masonry buildings with a LCA that leads to the concept of ‘Green Maintenance’. This unifying concept can be seen as a tool for promoting good maintenance interventions in terms of embodied carbon expenditure with minimal environmental impact. It must be emphasised that as with any current carbon assessment, the concept of ‘Green Maintenance’ will become more accurate, in terms of data inputs and evaluation. It is hoped that this model will be adopted by those entrusted with the repair and maintenance of traditional stone masonry walling, and that the determination of expended embodied carbon will become a key performance indicator in the intervention strategies.

1.6 Research Question

Can a ‘Green Maintenance’ model for historic masonry buildings be developed and tested based on the evaluation of the efficiency of stone masonry wall repair techniques in terms of embodied carbon expenditure?

1.7 Research Aims

The aim of this research is to evaluate the environmental efficiency of stone masonry wall repair techniques for historic masonry buildings. Environmental efficiency is evaluated in terms of embodied carbon expenditure using a ‘Green Maintenance’ model within ‘cradle-to-site’ boundaries of Life Cycle Assessment (LCA).

1.8 Research Objectives

The aim of this research is to ascertain answers to the following specific objectives:

i. To review literature evaluating the importance of good maintenance interventions in achieving efficient, low carbon repairs;

ii. To evaluate the efficiency of selected stone masonry wall repair techniques for historic masonry buildings based upon how ‘green’ they are in terms of embodied carbon expenditure using ‘cradle-to-site’ of LCA; and

iii. To develop and test a ‘Green Maintenance’ model using embodied carbon expenditure and Environmental Maintenance Impact (EMI) expended in stone masonry wall repairs for historic masonry buildings.

1.9 Thesis Structure

This research has been divided into seven distinct chapters with content as shown in Table 1.1.

Table 1.1: Thesis structure and content

Thesis Structure	**Content**
Chapter 1: Introduction	Research background and the context of the whole thesis. Introduction to the importance and benefits of good maintenance interventions in terms of embodied carbon expenditure for historic masonry buildings, based on selected repair techniques for stone masonry walls. Insight into research questions, aims, objectives, methods, problems, limitations and research structures.
Chapter 2: Literature Review	Literature review on the maintenance of historic masonry buildings and their importance and beneficial impact through repair on embodied carbon expenditure. 'Green Maintenance' association and its influences upon the facilitation options for repair techniques for stone masonry walls and historic masonry buildings when achieving efficiency in terms of embodied carbon expenditure within 'cradle-to-site' of LCA.
Chapter 3:	Explanation of the underpinning concept of 'Green maintenance'. It establishes the underpinning rationale and the primary components required for the model to work, including principally, materials longevity and embodied carbon of the different repair techniques. This section also established the basic formulaic expressions used for large scale analysis in the later stages of the work.
Chapter 4: Research Methods	Methodology for the evaluation of the stone masonry wall repair techniques of historic masonry buildings; describing efficiency as based upon how 'green' they are in terms of embodied carbon expenditure within 'cradle-to-site' of LCA selected maintenance periods.
Chapter 5: Data Analysis-Results	Analysis of the results of embodied carbon expenditure expended for stone masonry wall repairs within 'cradle-to-site' of LCA and the selected maintenance period. Test the 'Green Maintenance' model, based on how 'green' selected repair techniques are using the Environmental Maintenance Impact (EMI).
Chapter 6: Discussion	Discussion of research findings and unification of results.
Chapter 7: Conclusions and Recommendations	Conclusions based on research findings. Recommendations for further research; expansion of the 'Green Maintenance' modelling and Environmental Maintenance Impact (EMI) results. Stimulation of creative thinking for good facilitation on appraisal options for maintenance and repair techniques, with regards to efficiency in terms of embodied carbon expenditure.
References	Provide useful sources and information for further reference.

Source: Author, 2012.

Chapter 2: Literature Review

2.1 Introduction

This chapter is comprised of a review of the relevant literature on the maintenance of historic masonry buildings, focusing on repair, and embodied carbon expenditure. This chapter also seeks to provide an insight into ‘Green Maintenance’ and its influence on the facilitation for decision making for repair options and techniques for the stone masonry walls of historic masonry buildings.

2.2 Historic Buildings and Maintenance

The definition of historic buildings and an overview of their association with maintenance are discussed in the following section.

2.2.1 What are Historic Buildings?

The definition of historic buildings is vary and very contextual in nature through either associative or intrinsic value. Historic buildings within a Scottish context are defined as any structure constructed pre 1919. This definition should however not be confused with the significance of a structure that may be considerably younger than this date but still invoke statutory protection through a listing system, due to contextual, associative or intrinsic value (Historic Scotland, SHEP document, 2009).

2.2.2 Historic Buildings Maintenance: An Overview

A diverse range of definitions of the word “maintenance” have been provided by scholars in relation to historic buildings. Generally, the purpose of maintenance is to “*retain an item or restore to acceptable standard*” (Dann, Worthing and Bond, 1999: 143). In terms of the survival of historic buildings, maintenance is “*all practical and technical measures to keep the building or site at a standard that permits enjoyment of their cultural significance and resources without damage”*. According to Feilden and Jokilehto, (1993:3) and the Burra Charter, (1999:2) it is the “*continuous protective care* *of the fabric, contents and setting of a place*". According to Hutton and Lloyd (1993), maintenance is a self-correcting balance that puts a building's structure, element and environment into its original condition within a philosophical framework.

Building conservation philosophy is an ethical and principle based framework that underpins practical decision making for fabric repairs to historic structures. The 'guiding' principles were primarily established by the Society for the Protection of Ancient Buildings (SPAB) in 1877 and included tenets such as; least or minimal intervention; reversibility; honesty; integrity and avoidance of conjecture. One important, yet not expressed concept incorporated into the framework was the undertaking of regular maintenance, as this was recognised as being pivotal for reduced rates of deterioration in building materials.

Due to decay and deterioration, regular intervention is paramount to the maintenance of historic buildings. Regular maintenance is a beneficial approach in *"arresting the rate of deterioration"* (UWE, 2003: 1), which provides *"the most sustainable and suitable way"* (Dann and Cantell, 2007: 185) to conserve a structure. Clearly, maintenance underpins a buildings' survival. Howard et al. (1999) assert that:

> "Whilst materials and components can be considered to have a lifetime from "cradle to grave", it is not possible to assign a life for certain materials (for example a pile of bricks or tonne of insulation). Building materials and components only have a true "life" when they are considered in the context in which they are used, such as wall, floor, roof etc. As in the context of their usage, they will have maintenance requirements and will have to be dismantled or demolished at the end of their role in building. Therefore, different materials and components can then be compared on a like-for-like basis, as components that fulfil the same or very similar functions." (Howard et al., 1999: 6).

Globally, maintenance is widely recognised as a vital system for retaining not only the cultural heritage of historic buildings but also to preserve the capital value embodied in a building's fabric, including financial, social and environmental considerations. This recognition is embedded within major building conservation legislative frameworks and charters (Bell, 1997; BS7913, 1998; Forster and Kayan, 2009: 212). From the perspective of historic building maintenance, the main tenet of these frameworks is sustainability in terms of prolonging the life of cultural assets (ICOMOS, 1993), as opposed simply to maintaining the structure itself. Nationally, English Heritage, as cited by Brereton (1995), accepted maintenance as *"the best means of ensuring the continued preservation of a building..."* (Brereton, 1995: 7). Meanwhile, under the umbrella of Planning Policy Guidance Note 15 PPG, Worthing, Dann and Bond (2002) assert that maintenance is "*key to the preservation of historic buildings*" (Worthing, Dann and Bond, 2002: 295). In addition, BS 7913 articulates that maintenance is "...*fundamental to good conservation*" (BS 7913, 1998: 8). Internationally, maintenance is regarded as *"essential to the conservation of monuments"* (Venice Charter, 1964: 1) and "*fundamental to conservation"* (The Burra Charter, 1999: 6). In four decades of work with the primary aim of preserving buildings of international importance, the UN member states of the 'World Heritage Convention' have promoted conservation of historic buildings and sites by adopting and extolling the virtues of building maintenance (UNESCO, 1972).

To date, various proactive historic building maintenance schemes (Monumentenwacht, 2000; Raadvad Bygningssyn, 2011) have been successfully implemented to achieve conservation objectives. For example, Italy's 'Merlioni laws' have been enforced since 1990 to implement maintenance activity (UWE, 2003: 29-30). Meanwhile, maintenance activity in Australia has been stimulated by the '*Heritage Incentives Program*' (Northern Territory Government, Australia, 2013). The '*funding allocation programme*' of the Malaysian government primarily targets funding towards early maintenance interventions (Kayan, 2006: 53). Underlying such schemes, laws and programmes, it is apparent that there is an increasing interest in existing buildings and their relative historic importance. However, in order to achieve aesthetic and satisfactory long term performance of these buildings through maintenance, their sustainability is of paramount important.

2.3 Historic Masonry Buildings Maintenance and Sustainability

"Sustainability" has been defined in many alternative ways to suit different needs, requirements or situations. In the "Brundtland Report" (1987), the World Commission on Environment and Development (WCED) defined sustainability as *"meeting the needs of the present without compromising the ability of future generations to meet their* *own needs"* (WCED, 1987: 24). Citing the same report, Banfill and Peacock (2007) suggested that sustainability is the duty on *"the present inhabitants of the world"* to *"pass it on to the next generation in a state which is no worse than now"* (Banfill & Peacock, 2007:426). However, complex prioritisation and parameters influence building maintenance and environmental sustainability. Bell (1997) highlighted influencing factors in building maintenance, such as least intervention, like for like material replacement and respect for traditional craft skills (Bell, 1997). The degree of success in maintenance of historic masonry buildings relies on conformity to these aforementioned factors. The most effective maintenance interventions in terms of environmental sustainability are those that most suitably accommodate all priorities, parameters and sustainable solutions. In addition to the complexity of prioritisation within the philosophical and economic contexts, a third and emerging factor in the evaluation of maintenance is environmental sustainability. This tripartite approach draws parallels with the generally accepted model of sustainable development (Brundtland, 1987) and offers a potentially useful framework for evaluation of 'sustainable' or 'green' maintenance interventions (Figure 2.1).

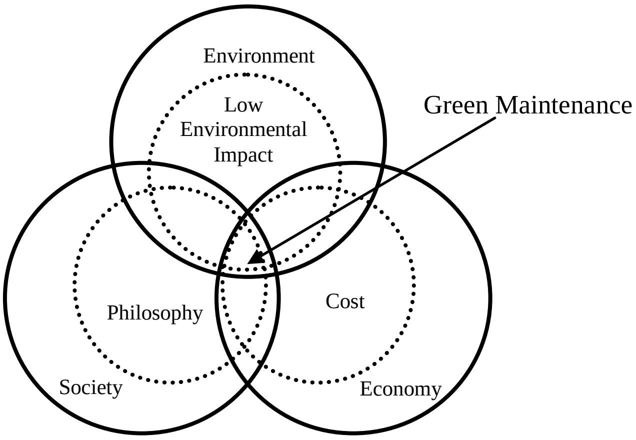


Figure 2.1: Parameters for evaluating maintenance interventions for buildings
Source: Adapted from Forster et al., 2011: 656.

The Venn diagram in Figure 2.1 represents the traditionally accepted model of sustainability with environmental, societal and economic factors, overlaid with the three factors that influence maintenance for buildings: namely, environment, cost and philosophy. Those interventions that intersect with all three aspects would potentially be considered to be the most sustainable. In regard to historic masonry buildings, in order to evaluate their long-term maintenance requirements in relation to the tripartite approach proposed for 'Green Maintenance', it is necessary to understand the cumulative effect of their routine maintenance operations in terms not only of cost and philosophy but also environmental impact. The aim of this research is to understand the cumulative effect of stone masonry wall repair in terms of embodied carbon expenditure. In this research, a framework will be established in order to evaluate expended embodied carbon expenditure with the potential to allow selection of maintenance options (in this case, stone masonry wall repair techniques and usage repair materials), which could provide a sustainable solution in terms of environmental impact.

2.4 Historic Masonry Buildings Maintenance from Environmental Perspective

Generally, maintenance of the stonework of historic masonry buildings is considered crucial to ensure that the worldwide financial and social capital invested in these structures is not wasted. Traditionally, maintenance has been recognised as a cost commitment associated with a building (Wise, 1984). However, maintenance interventions also have a carbon commitment and there is an increasing international focus on achieving low carbon in the built environment (Stern, 2006).

Regrettably, however, this commitment largely focuses on new build structures and upgrading works, while only a little attention is given to maintenance of existing buildings (including historic masonry buildings). From the environmental perspective, maintenance of historic masonry contributes to the lifetime embodied carbon expenditure (CO_2 emissions) in a way that may be cumulatively significant. In practical terms, maintenance is essentially a way of prolonging the life span of a building. Associating historic masonry buildings maintenance interventions with a life cycle carbon approach leads to the concept of ‘Green Maintenance’, which can be seen as maintenance with minimal environmental impact.

An important role is played by existing buildings (including historic masonry buildings) in lowering embodied carbon expenditure (CO_2 emissions). As construction of these buildings has significantly depleted previous resources, this will negate the need for further resources. In the UK’s primary energy usage, an estimated of 50% was used to service buildings while 8% was used to manufacture and transport building materials (or overall 350 GJ per year, representing about six tonnes of building material per capita (Hill, 2010).

Approximately, the energy used in construction is estimated at just 0.5% of the UK's national energy use, which can be compared to the small but significant proportion of annual national energy (5-6%) used to produce building materials (in this case for new buildings) (Howard et al., 1999: 8). In addition, Harris (1999) and Kofoworola and Gheewala (2008) suggest that minimising environmental impacts within life time span (Figure 2.2) can be achieved by addressing and evaluating the environmental impact in the long run (Harris, 1999; Kofoworola and Gheewala, 2008).

Harris (1999) claims that Building Research Establishment Environmental Assessment Method (BREEAM) evaluates the varying degree of requirements of buildings using "poor" to "excellent" scoring systems (Harris, 1999). There is however, no clear indication that this method is applicable to evaluate embodied carbon expenditure in historic masonry building repair. In reality, a different building's elements or components may last for different times as they have different efficiency and longevity of repair (see example from Harris, 1999).

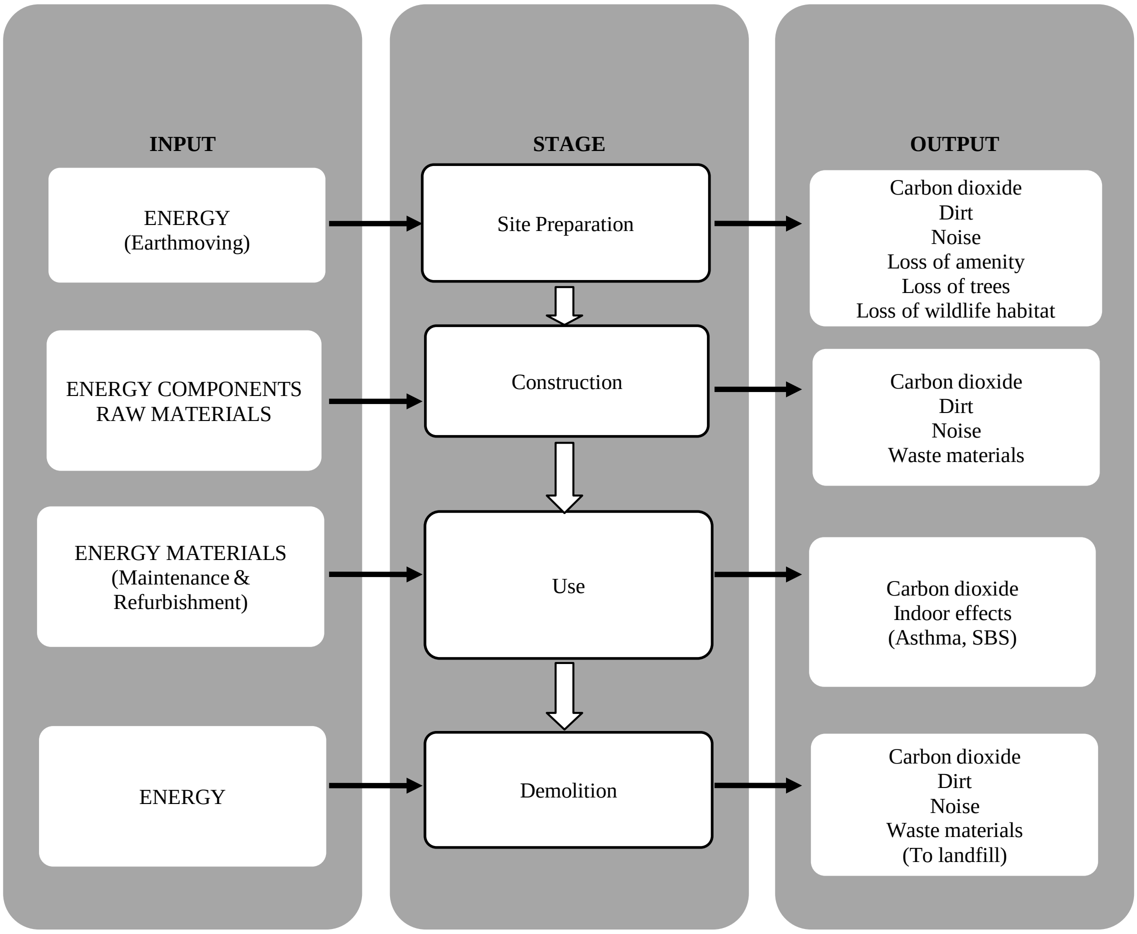


Figure 2.2: Environmental impact of a building within life time span

Source: Adapted from Harris, 1999: 752.

Lippiatt (1999) has introduced The Building for Environmental and Economic Sustainability (BEES) tool. This tool adopts national methodical techniques to select cost-effective “green” building products (Lippiatt, 1999). However, the applicability and practicality of this tool in evaluating embodied carbon and developing the ‘Green Maintenance’ model in historic masonry building repair remains doubtful.

It has been found that a sizeable proportion of embodied carbon expenditure in historic masonry buildings is attributed to their elements repair (Forster et al., 2011). Embodied carbon expended (including carbon emissions) associated with maintenance can be distinguished into, first, maintenance interventions and, second, operational energy use linked to improvement in performance or slowing the degradation of a building. As found previously, historic masonry buildings have an association with embodied carbon expenditure (carbon emissions). Through maintenance, these can be evaluated through stone masonry wall repair activities. This is vital for lowering embodied carbon expenditure (CO_2 emissions).

Regrettably, very little of the previous work undertaken has focused on the embodied carbon expenditure encompassed by historic masonry building maintenance processes. The focus of these previous works largely falls on one simple objective: to retain buildings in service condition. Previous LCA works attempts to facilitate options for repairs to the stone masonry walls of historic masonry buildings, in order to achieve efficiency in terms of embodied carbon expenditure within ‘cradle-to-site’, remain unconvincing.

2.5 What is Life Cycle Assessment (LCA)?

In general, a Life Cycle Assessment (LCA) is a technique to assess the environmental impacts associated with all the stages of a product's life. Selmes (2005) has raised concerns over the evaluation of (LCA) and highlights that there is *“confusing and puzzling likeness”* with the range of terms used for the different types of LCA (Selmes, 2005). This situation is illustrated in Table 2.1.

Table 2.1: Range of LCA terms and types

Terms and Type	
Cradle-to-Grave Analysis	Frequently used as a descriptive rather than definitive term in studies that focus on association of the whole life cycle and may or may not include impact and improvement assessment.
Ecobalance	Term of European origin (White, 1993; White et al., 1995).
Eco-Profile	Often made with a one-stage impact assessment and final judgments made by an expert (White, 1993; White et al., 1995).
Life Cycle Accounting	Financial accounting based on a life cycle perspective (Keoleian and Menerey, 1994).
Life Cycle Analysis (LCA)	Interchangeably used with Life Cycle Assessment in the early 1990s (Kirkpatrick, 1992). The term has also been used to refer to studies made using the inventory alone (White, 1993; White, et al., 1995).
Life Cycle Assessment (LCA)	Core framework for contemporary/modern life cycle studies, although some sources might say that life cycle assessment is only standardised by ISO.
Life Cycle Inventory Analysis (LCIA)	Term used to refer to studies made using analysis of a life cycle inventory alone.
Life Cycle Costing (LCC)	See Life Cycle Accounting (with which it is synonymous).
'Produktlinienanalyse' (PLA)	Essentially an LCA that includes "an appraisal of product utility" and includes assessment of social and economic impacts (Pfeifer, 1996).
Resource and Environmental Profile Analysis (REPA)	Term used for life cycle studies conducted in the US between 1970 and the early 1990s. Studies included those on impact assessment, frequently in the form of an environmental index (Hunt and Franklin, 1996).

Source: Adapted from Selmes (2005).

2.5.1 Chronological Development of Life Cycle Assessment in Brief

Chronologically, there is no clear indication of the origin and timeline of LCA. The beginning of LCA has been attributed by United States of America's defence industry to their "Life Cycle Accounting" or "Life Cycle Costing" evaluation of disused operation and maintenance equipments (LaGrega et al., 1994; Khasreen et al., 2009). LCA within the 'cradle-to-grave' boundary was initiated by Harry E. Teasley of Coca-Cola in 1969 (Hunt and Franklin, 1996; Khasreen et al., 2009).

Then, in 1972, the Midwest Research Institute (MRI), under instruction of the US Environmental Protection Agency (EPA), undertook a Resume and Environmental Profile Analysis (REPA), which lead to the '*Resource and Environmental Profile Analysis of Nine Beverage Beer Container Alternatives'* report (MRI, 1974). The aims of this study, however, focused mainly on solid waste reduction aspects (beer packaging), rather than on environmental emissions or energy use on buildings.

Between mid-1970 and the late 1980s, there was a significant increase in both the number of life cycle studies undertaken and public interest, with “a dramatic re-awakening” (Hunt and Franklin, 1996) and “significantly increment” (Curran, 1993) in emphasis on LCA. In 1979, in particular, the heavily referenced *‘Handbook of Industrial Energy Analysis’* co-authored by I. Boustead and G.F. Hancock (Boustead and Hancock, 1979) provided the UK’s first example of methodology for energy analysis from a life cycle perspective. During this period, however, most LCA studies were privately funded and, consequently, were rarely published and so were unknown to the public (Khasreen et al., 2009: 676). In mid 1990, a public forum held by The Conservation Foundation in Washington D.C. attempted to promote debate on LCA with regard to REPA’s environmental policy in the USA (Hunt and Franklin, 1996). In August of the same year, the Society of Environmental Toxicology and Chemistry (SETAC) held a workshop at Smugglers Notch, Vermont, USA, which lead to publication of ‘*A Technical Framework for Life Cycle Assessment’* (Fava et al., 1991).

A considerable number of LCA guidelines and manuals were developed during the 1990s. Such guidelines include *‘Dutch Guidelines’* (also called ‘*Environmental Life-Cycle Assessment of Products: Guide and Backgrounds’* from the Institute of Environmental Sciences (CML) of Leiden University, the Netherlands in 1992 (Heijungs et al., 1992); ‘*Life Cycle Assessment: Inventory Guidelines and Principles’* by Battelle of Franklin Associates Ltd and the US EPA Risk Reduction Engineering Laboratory in 1994 (Vigon et al., 1994); SETAC’s *‘Goal Definition and Scoping’* and ‘*A Conceptual Framework for Life-Cycle Impact Assessment’* manuals in 1993 (Selmes, 2005: 96); ‘*Life Cycle Design Guidance Manual: Environmental Requirements and the Product System’* and ‘*Design for the Environment: Product Life Cycle Design Guidance Manual’* in 1994 (Keoleian and Menery, 1994), and ‘*Z-760 Environmental Life-Cycle Assessment’* by the Canadian Standards Association, also in 1994 (Canadian Standards Association, 1994). Following these, other LCA guidelines have since been established, such as the ‘*Nordic Guidelines on Life-Cycle Assessment’* by Swedish, Finnish, Danish and Norwegian authors in 1995 (Lindfors, 1995); ‘*Life Cycle Assessment: What It Is and How to Do It’* by the United Nations Environment Programme in 1996 (United Nations Environment Programme (UNEP, 1996); *‘Life-Cycle Assessment Data Quality-A Conceptual Framework’* and *‘Guidelines for Life-Cycle Assessment: A ‘Code of Practice,’* (‘LCA Bible’*)*, both in 1996 (Jensen, 1996), and The European Environment

Agency's '*Life Cycle Assessment: A Guide to Approaches, Experiences and Information Sources'* in 1997 (Jensen et al., 1997).

Regrettably, the previous guidelines and manuals regarding LCA are largely based on life cycle philosophy and, therefore, their application and standardisation is not clearly justified. Consequently, the International Organization for Standardization (ISO) has published several standards of LCA since 1998 (ISO 1998; 2000a, 2000b; 2006a and 2006b). Publication of these standards has helped LCA to flourish, as more debate has taken place since on key issues such as 'holistic interpretation' (Selmes, 2005), wider 'areas allocation' (Ekvall and Finnveden, 2001), better 'impact assessment' (Klopffer, 2006; Guido and Sonia, 2007) and comprehensive 'operational guides' [such as CML's Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards (Guinée, 2002) and life cycle management (LCM) by UNEP-SETAC initiative (Udo de Haes et al., 2002)].

To date, however, there is little development in LCA works that attempt to evaluate the efficiency of maintenance based on repair to buildings. With regard to historic masonry buildings, there are no specific guidelines or supplementary manuals on LCA that offer specifically facilitated options for repair to stone masonry walls. Additionally, there is no well-developed LCA model with the aim of evaluating efficiency of repair to historic masonry buildings in terms of embodied carbon expenditure within selected boundaries and maintenance periods.

2.5.2 Life Cycle Assessment Establishment

Since 1989, SETAC became the first international body to act as an umbrella for the establishment of LCA covering European countries and the USA. Andersson et al. (1999) articulate that *"Under SETAC, the development of 'modern' LCA methodologies and applications started in the late eighties and early nineties in a number of European countries and the United States, quite soon leading to a dedicated and global discussion platform"* (Andersson et al., 1999: 175).

In 1996, the International Organization for Standardization (ISO) has published 14040 series-standards relating to LCA (ISO, 1996). From 1998, the ISO has also produced standardised LCA (such as 14001 series-Environmental Management Systems).

Consequently, ISO 14040-43 has also been appropriately tailored and adopted in the establishment of '*Sustainable Product Development'* and *'Environmental Performance Indicator and Product Declarations'*. Through production of these standards series, ISO is a primary example of an established organisation that facilitates the standardisation of LCA.

In 1999, under patronage of the Department of Technology, Industry and Economics (DTIE) based in Paris, UNEP's main focus was on the holistic adoption of LCA, particularly in developing nations. Through a series of user-friendly publications, such as '*Life Cycle Assessment: What It Is, and What To Do About It'* (UNEP, 1996) and '*Towards Global Use of Life Cycle Assessment*', UNEP also collaborated with the Environmental Protection Agency of the US (US-EPA) and the Institute of Environmental Sciences (CML) of the Netherlands (UNEP, 1999). Also in 1999, the Life Cycle Impact Assessment Working Group of SETAC-Europe and the Data Availability and Data Quality Working Group of the United Nations Environmental Program, Division of Technology, Industry and Economics (UNEP-DTIE) had attained a broader LCA framework in a more authoritative and reliable manner. In the same year, integrated LCA studies (largely in business activities) were established in many large corporations within the Nordic Region (including Sweden, Denmark, Norway, and Finland) (Hansen, 1999).

With the primary aims of developing a highly dependable and nationally available LCA database and methodology, the Ministry of International Trade and Industry (MITI) of Japan initiated, on a five-year basis and at an overall cost of 850 million yen (value at the time in 2000), the *'Development of Assessment Technology of Life Cycle Environmental Impacts of Products'* in the late 1990s (Yano et al., 2000).

In 2002, UNEP/SETAC established a combined initiative to identify best available practice in the field of LCA. Udo de Haes et al. (2002) claim that this initiative set the 'best practice' and 'extending scope and expansion' of life cycle assessment on an international level (Udo de Haes et al., 2002). Also in 2002, collaborative efforts between the Federal Ministry of Education and Research (BMBF) (funder) and The German Helmholtz Association (HGF) (researcher) established *'Quality Assurance and User-oriented Supply of a Life Cycle Inventory Data'* in Germany (Bauer et al., 2004). Under the guardianship of the Forschungszentrum Karlsruhe (FZK) (research centre), the aim of this establishment is to improve Germany's scientific and practical use of *'Network on Life Cycle Inventory Data'* in the international arena.

Both in the international and regional arenas, current establishments of LCA are very promising. However, establishment of LCA focusing on works that attempt to evaluate efficiency of maintenance based on repair to buildings remains unconvincing. In addition, there are no works specifically focusing on options facilitation for repair to the stone masonry walls of historic masonry buildings, either through individual or collaborative efforts. LCA establishment, it seems, is not paralleled by common methods to evaluate efficiency of repair to historic masonry buildings in terms of embodied carbon expenditure.

2.5.3 Common Life Cycle Assessment Methods

Suh and Huppes (2005) state that the common methods for LCA include process analysis (process flow diagrams and Life Cycle Inventory), input–output analysis, process-based matrix representation and hybrid analysis (Suh and Huppes, 2005). International Standards 14041 and various authors suggest two fundamental methods of LCA based on compilation: i.e. '*process analysis'* and '*input-output analysis*' (Consoli et al., 1993; Raynolds et al., 2000; Suh et al., 2004). Input-output analysis of LCA can be diagrammatically represented as shown in Figure 2.3. Under '*process analysis'*, comprehensive assessment has been undertaken using "process-flow diagrams" (Suh et al., 2004).

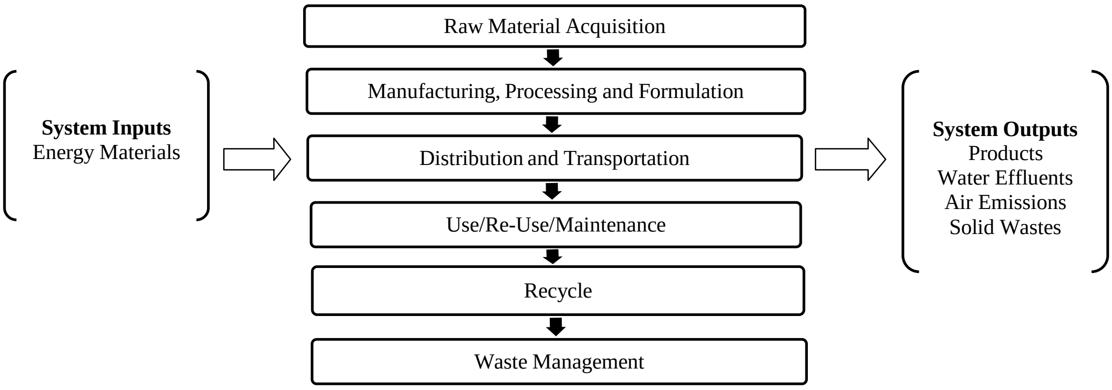


Figure 2.3: Diagrammatically representation of inputs/outputs of LCA
Source: Raynolds et al., 2000: 38

Life Cycle Inventories (LCI) (Figure 2.4), are however prone to inaccuracy issues. Khasreen et al., (2009) suggest that *"It is essentially important that the diagram of the process should be as complete as possible to get a high level of accuracy"* (Khasreen et al., 2009: 685).

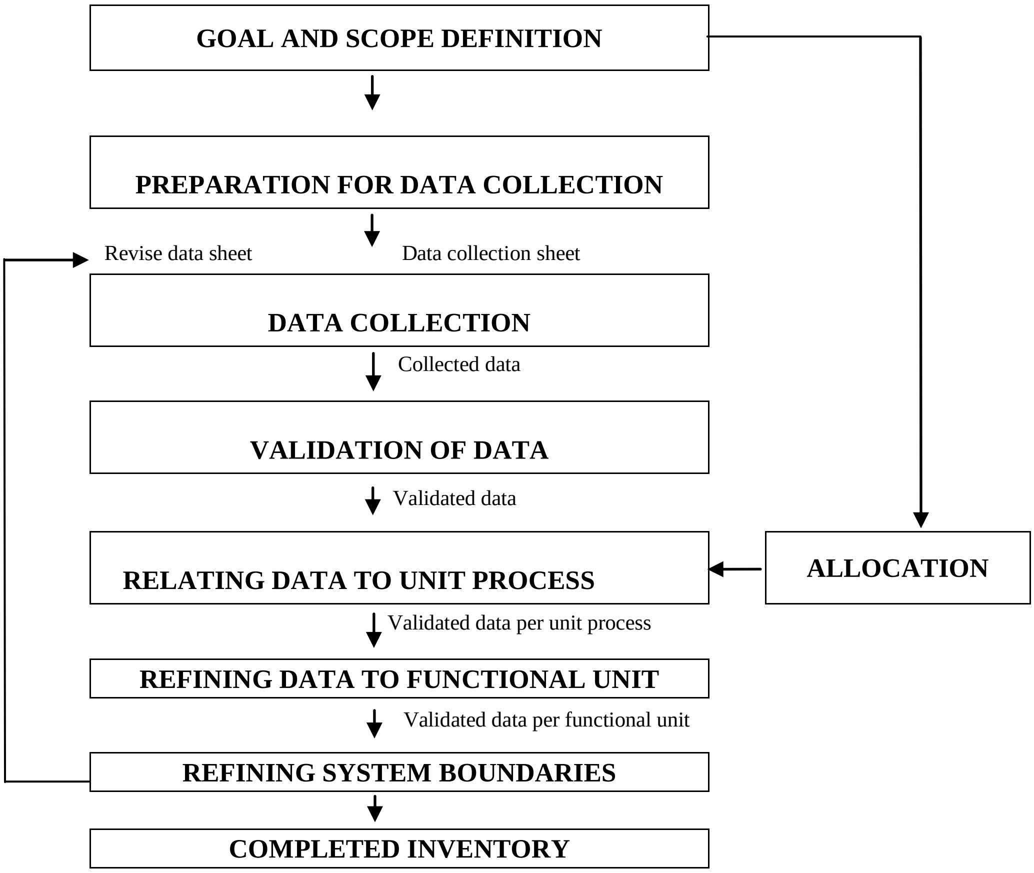


Figure 2.4: Simplified procedures for inventory analysis

Source: Adapted from Khasreen et al., 2009: 686.

According to Marheineke et al.(1999), Treloar et al. (2000), Munksgaard et al. (2001) and Nansai et al. (2001), hybrid approaches of LCA can be grouped into three different categories: namely, '*tiered hybrid analysis', 'input output-based hybrid analysis'* and *'integrated hybrid analysis'* (see also Table 2.2).

Table 2.2: Comparison between Hybrid Approaches of LCA

Approach	Strengths	Weaknesses	Methodological reference	Case studies
Tiered Hybrid	Easy to employ	Problem of double counting	Bullard et al. (1978)	Moriguchi et al. (1993) Marheineke et al. (1999) Hondo et al. (1996) Munksgaard et al. (2000 and 2001)
	Literature, databases and case studies are well documented	Recurring flows are not properly described by process flow diagram approach		
Input-output based hybrid	Avoid double counting	Only externally added to the main system at the end-of-life phase	Joshi (1999)	Joshi (1999)
	Process and input-output part are described in a consistent framework	Recurring process between the main system and use stage and end-of-life phase are not properly described		
		Need to be used jointly with other methods in situations where national economy is highly reliant on imports		
Integrated hybrid	Consistent mathematical framework for the whole life cycle	Relatively complex to use	Suh (2004)	Suh and Huppes (2000)
	Avoid double counting	High data and time requirements		Suh (2004)
	Easy to apply analytical tools			

Source: Suh et al., 2004: 662.

Since each LCA method is unique in terms of the calculation process and data types used, the procedure for evaluating embodied carbon expenditure for stone masonry repair of historic masonry buildings maintenance and repair remains unclear.

2.5.4 Previous Works on Life Cycle Assessment

In the late 1990s, several research outputs relating to Life Cycle Assessment have built on ideas from modelling, organisational theory, political analysis, toxicology, economy, medicine, anthropology, chemistry and engineering (Table 2.3). However, most do not specifically attempt to evaluate embodied carbon expenditure expended for building repair.

Table 2.3: Previous research efforts in LCA

Area of Studies	**Researcher/Year**	**Research Scope/Outcome**
LCI and allocation	Frischknecht, R. (1998)	LCI structure relations to decision-making using a theoretical approach to model "national electricity mix" and "small scale gas-fired combined heat and power generation"
Uncertainty and subjectivity in LCA	Finnveden, G. (1998)	Diverse aspects and limitations of LCA, new methods for landfill and the incineration of solid waste. Different LCI databases were compared to examine the uncertainties in common LCAs, and "rules of thumb" are recommended
	Hofstetter, P. (1998)	Provided one of the possible answers to the problems identified by Finnveden (1998) and Tukker (1999). Noted problems in the course of international standardisation of LCAs
	Tukker, A. (1999)	Political-philosophical of decision-making processes with regard to toxicity, using Substance Flow Analysis (SFA) and Risk Assessment (RA) within the Dutch chlorine and the Swedish PVC chain.
Nutrition & building sector	Cowell, S. (1998)	Focused on the establishment of LCA methodology for the assessment of agricultural systems
The application context of LCA	Jönsson, Å. (1998)	Demonstrating how LCAs may be applied to building products
	Baumann, H. (1998)	LCA practice focusing on improvements in LCA methodology
	Andersson, K. (1998)	Application of LCA to food products and production systems
	Lundie, S. (1999)	Under the guardianship of the Institute for Futures Studies and Technology Assessment (IZT), Berlin, Germany focuses on stakeholders' active participation in LCA and the practice-centred evaluation of impact assessment results to produce reliable recommendations (focusing on television sets)

Source: Andersson et al., 1999: 176-178.

2.5.4.1 Life Cycle Assessment Methods

Previously, considerable research effort has investigated a diverse array of Life Cycle Assessment method variations. In 1996, focusing on building materials used in New Zealand, Alcorn and Baird (1996) evaluated the incompleteness and unreliability of LCA *'process-based hybrid analysis',* using a computation programme (Alcorn and Baird, 1996). In 1998, Treloar (1998) undertook research into LCA using '*framework of measurement'*, which later recommended a new method to promote accuracy and completeness in LCA for building materials and components (Treloar, 1998; Dixit et al., 2010).

In 2000, Fay et al. (2000) evaluated LCA methods using '*life-cycle energy analysis'* by calculating embodied carbon increment over time using mathematical equations. To date, no specific LCA study has been undertaken in order to develop methods with the ability to evaluate embodied carbon expenditure from stone masonry wall repairs to historic masonry buildings. In 2001, Weeber et al. adopted *'Literature Based Discovery'* (LBD) to identify LCA's variations, particularly in embodied carbon expenditure (Weeber et al., 2001). Meanwhile, Paulsen & Borg undertook studies to evaluate the '*variation and inconsistency'* of LCA methods, focusing only on floor covering (Paulsen and Borg, 2003).

2.5.4.2 Environmental Databases and Embodied Carbon Coefficient

A significant number of previous works relating to LCA have attempted to provide databases for the environmental impact and embodied carbon coefficient of building materials. Most of the generated results have been incorporated into commercial software and handbooks that are widely used by academics and the industry alike. Researchers studying LCA generally, and inevitably, disagree about the selection of "best values" for the embodied carbon coefficient of materials. Therefore, 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: 1243).

In 1994, Buchanan and Honey (1994) used embodied carbon coefficient data (produced by Baird and Chan, 1983) to provide a complete list of carbon dioxide emission implications (Buchanan and Honey, 1994). However, the list provides carbon dioxide emission implications caused by construction activities only. In 2003, Junnila and Horvarth (2003) undertook an LCA that attempted to provide a database of environmental aspects relating to office buildings (Junnila and Horvath, 2003).

In 2009, the *'Green Guide to Specification and Tools'* provided by the Building Research Establishment (BRE) (Anderson, 2002; Anderson et al., 2009) and '*Environmental Profiles'* database (Anderson et al., 2009; www.greenbooklive.com) provided profiles for common materials. However, the coverage of these databases was mainly restricted to the UK regional context (Anderson et al., 2009).

Meanwhile, various researchers have undertaken works on inventory of embodied carbon coefficient. *'The Inventory of Carbon and Energy*' (ICE) (Hammond and Jones, 2008b and 2011) summarises embodied energy and CO_2 coefficients for building materials, using data collected from primary and secondary sources in the public domain. Under *'Carbon Vision Buildings Program'*, this inventory employs the 'cradle-to-gate', LCA analysis published by the University of Bath's Sustainable Energy Research Team (Hammond and Jones, 2008a; 2008b; 2011). In addition, there are differences between old and new embodied carbon coefficient data values (for example there is a different value for every Inventory of Carbon and Energy (ICE) 1.6a (2008) with 2.0 (January 2011) version). This is due to certain obsolete characteristics of both previous and recent inventories. For example, old and new vehicles used for transporting building stone masonry wall repair materials to site have different embodied carbon coefficient values. In general, the latter possess greater fuel efficiency and structure compared to the former and, therefore, produce lower embodied carbon expenditure for stone masonry wall repair materials transportation.

Comparatively, there are also initial publications on embodied carbon coefficients in other regional contexts. For example, the Buildings Research Association in New Zealand has undertaken its own LCA work in order to publish embodied carbon coefficients of building materials in their local context (Alcorn, 1998; 2001; 2003). In 1996, Alcorn and Baird of the Center for Building Performance and Research at Victoria University of Wellington, collaboration with the Buildings Research Association of New Zealand, evolved a coefficient of carbon emissions for building materials in the local context (Alcorn and Baird, 1996). As the development of this database is founded on the New Zealand regional basis, embodied carbon coefficient and CO_2 emissions are generated specifically for locally-sourced building materials.

2.5.4.3 Embodied Carbon in Buildings

Several LCA studies have been undertaken to evaluate embodied carbon in different types of buildings. The focus of these works are centred largely on embodied energy figures (rather than embodied carbon expenditure) for limited types of buildings, such as new residential and commercial buildings (Table 2.4).

Table 2.4: Previous LCA works on embodied energy figures

Embodied energy (GJ/M^2)	**Building Type**	**Source**
3.6	Residential	Hill (1978) (cited by Pullen, 2000a and 2000b)
3.9	Residential	Edwards et al. (1994) (cited by Dixit et al., 2010)
4.3-5.3	Residential	D’Cruz et al. (1990) (cited by Pullen, 2000a and 2000b)
4.9	Residential	Pullen (1995) (cited by Dixit et al., 2010)
5.0	Residential	Lawson (1996) (cited by Pullen, 2000a and 2000b)
5.9	Residential	Pullen (2000a and 2000b)
6.6	Residential	Ballantyne et al. (2000) (cited by Pullen, 2000a and 2000b)
6.8	Residential	Treloar (1998)
8.76	Residential	Treloar (1997)
3.4-6.5	Commercial	Honey and Buchanan (1992) (cited by Dixit et al., 2010)
4.3-5.1	Commercial	Cole and Kernan (1996) (cited by Dixit et al., 2010)
5.5	Commercial	Oppenheim and Treloar (1995) (cited by Dixit et al., 2010)
8.0-12.0	Commercial	Oka et al. (1993) (cited by Dixit et al., 2010)
8.2	Commercial	Tucker and Treloar (1994) (cited by Dixit et al., 2010)
10.5	Commercial	Yohanis and Norton (2002)
18.6	Commercial	Stein et al. (1976) (cited by Dixit et al., 2010)
19.0	Commercial	Tucker et al. (1993) (cited by Treloar, 1997)

Source: Dixit et al., 2010: 1242.

2.5.4.4 Life Cycle Assessment Variations

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) (Table 2.5). The literature by Dixit et al. (2010) as shown in Table 2.5 has revealed that there is 10 common parameters that commonly influence the quality of embodied energy results. Additionally, it represents a matrix of relevant parameters along with previous LCA studies that adopting them.

However, 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.

Table 2.5: Previous works on variation of matrix parameters of LCA

Author and year of study	**Parameters**									
	System boundaries	**Methods of EE analysis**	**Geographic location**	**Primary and delivered energy**	**Age of data**	**Data source**	**Completeness of data**	**Manufacturing technology**	**Feedstock energy consideration**	**Temporal representation**
Buchanan and Honey (1994)			✓		✓			✓		
Pears (1996)		✓		✓		✓		✓		
Pullen (1996)		✓	✓			✓	✓			
Alcorn and Wood (1998)			✓		✓	✓	✓			✓
Peereboom et al. (1998)			✓		✓	✓		✓		✓
Lippiatt (1999)			✓					✓		✓
Pullen (2000a)				✓						
Pullen (2000b)		✓	✓		✓			✓	✓	
Treloar et al. (2001)		✓	✓	✓				✓		
Miller (2001)	✓	✓								
Glover et al. (2002)	✓									
Junnila and Hovarth (2003)	✓		✓			✓				✓
Ding (2004)	✓		✓		✓	✓				
Horvarth (2004)	✓	✓								
Suh et al. (2004)	✓									
Crawford and Treloar (2005)		✓								
ISO 14040 (2006a)	✓		✓		✓		✓	✓	✓	✓
Lenzen (2006)	✓		✓		✓			✓		✓
Holtzhausen (2007)		✓	✓					✓		
Menzies et al. (2007)			✓		✓	✓	✓	✓		
Nassen et al. (2007)		✓								
Sartori and Hestnes (2007)			✓	✓		✓			✓	
Hammonds and Jones (2008a; 2008b)	✓	✓	✓		✓					
Peereboom et al. (1998)			✓		✓	✓		✓		✓

Source: Adapted from Dixit et al. 2010: 1243.

2.5.4.5 *Impact Assessment*

In regard to general buildings, the process of LCA impact assessment begins by selecting and defining categories of relevant impacts, such as global warming, acidification and toxicity as shown in Table 2.6.

Table 2.6: Commonly used impact categories in LCA.

Impact category	Abbreviation	Scale	Classification	Characterisation factor
Global warming	GW	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFC_S) Hydro chlorofluorocarbons ($HCFC_S$) Methyl Bromide (CH_3B_r)	Global warming potential
Acidification	A	Regional Local	Sulphur Oxides (SO_X) Nitrogen Oxides (NO_X) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)	Acidification potential
Eutrophication	E	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates, and Ammonia (NH_4)	Eutrophication potential
Ozone depletion	OD	Global	Chlorofluorocarbons (CFC_S) Hydro chlorofluorocarbons ($HCFC_S$) Halons, and Methyl Bromide (CH_3B_r)	Ozone depletion potential

Source: Khasreen et al., 2009: 689.

As cited by Adalberth (1996), Pullen (2000a and 200b), Lenzen et al. (2004) and Crawford and Treloar (2005), Dixit et al. (2010) assert that carbon dioxide emissions have "…noteworthy endeavours" in building materials (Dixit et al., 2010: 1241). However, studies rarely focus on investigating the recurring embodied carbon expended during maintenance phase for historic buildings. To date, there is no comprehensive statistical representation based on the specific aim of representing embodied carbon expenditure measurement for historic buildings maintenance, particularly relating to stone masonry wall repair.

It is clear that previous LCA studies have focused largely on documentation of the environmental impact and embodied coefficient of common materials used in building construction industry. There is an insufficient amount of LCA work completed on evaluation of embodied carbon coefficient of stone and stone masonry wall repair materials.

2.6 Life Cycle Assessment for Stone Materials

Few LCA studies in the public realm specifically investigate the carbon impacts of stone materials (Table 2.7). Studies by Alshboul and Alzoubi (2008) and the University of Tennessee (2008a; 2008b; 2008c) have been published on embodied carbon and energy values in Jordan and the United States respectively relating to natural stone.

In 2008, a preliminary study was been undertaken by Venkitachalam (2008) to evaluate the carbon footprint for stone in the Scottish context. This study highlighted the fact that a high proportion of the carbon footprint (within 'cradle-to-gate' LCA) for sandstone is contributed by transportation. This study found that transportation emissions were between 31% and 90% of total represented embodied emissions associated with local and imported stone respectively (Venkitachalam, 2008). 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 to undertake a collaborative research project in order to understand the carbon embodied in natural stone used in the construction and repair of Scotland's buildings. 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. By adopting 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. Findings revealed that imported stone has an enormous impact on the overall carbon footprint. 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). 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. Moreover, the focus of these previous

LCA works do not specifically evaluate embodied carbon expended from stone masonry wall repairs during the maintenance phase.

Table 2.7: Previous LCA studies on stone materials

Source Study	**Type of stone**	**Embodied Energy (MJ/kg)**	**Embodied Carbon Coefficient ($kgCO_2/kg$)**	**Boundaries**
Alcorn (2003)	General	0.656	n/a	Cradle-to-grave
Alshboul and Alzoubi (2008)	General	0.309	n/a	Cradle-to-site
Venkitachalam (2008)	Sandstone	0.122	0.0095	Cradle-to-site
University of Tennessee (2008a)	Granite	5.908	0.621	Cradle-to-gate
University of Tennessee (2008b)	Slate	0.208	0.028	Cradle-to-gate
University of Tennessee (2008c)	Limestone	0.964	0.105	Cradle-to-gate
University of Bath ICE (2008)	Granite	0.1 to 13.9	0.006-0.781	Cradle-to-gate
University of Bath ICE (2008)	Limestone	0.3	0.017	Cradle-to-gate

Source: SISTech, 2010.

2.7 Common Problems and Limitations of Life Cycle Assessment

There is a broad range of problems and limitations associated with goal and scope definitions, inventory analysis, impact assessment and interpretation phase (see Table 2.8). Other LCA problems include its own subjectivity characteristics, deficiencies in system boundary selection, and partial model and non-standardised databases. However, the impact of such problems and limitations on evaluation of embodied carbon expenditure in respect of repair, particularly for historic masonry buildings, remains to be ascertained.

Table 2.8: Problems and limitations by phase of LCA studies

Phase	Problems and limitations
Goal and scope definition	Functional unit definition[a] Boundary selection[a] Social and economic impacts[a] Alternative scenario considerations[a]
Life cycle inventory analysis	Allocation Negligible contribution ('cut-off') criteria Local technical uniqueness
Life cycle impact assessment	Impact category and methodology selection Spatial variation Local environmental uniqueness Dynamics of the environment Time horizons
Life cycle interpretation	Weighting and valuation[a] Uncertainty in the decision process
All	Data availability

Source: Reap et al., 2008: 291.

[a] One might reasonably consider these problems to be pivotal decisions. Unlike the others, their partial dependence on study goals limits the capacity to generate solutions via scientific and technical consensus building. However, their strong influence on a study's outcome increases the inaccuracies introduced by an inappropriate decision. It might, therefore, be more appropriate to think of these problems as problematic decisions.

2.7.1 Subjectivity Characteristics

Practically, LCA can often be very subjective. Therefore, they produce questionable and highly debatable results. Bauer et al., (2004) assert that the reliability of LCA results is highly dependent upon the availability and quality of LCI data (Bauer et al., 2004) (see also Table 2.9, which gives a common criteria matrix for assessing the quality of data for LCA).

Table 2.9: Data quality assessment matrix criteria for LCA

Indicator score	1 Excellent	2	3	4	5 Unreliable
Reliability	Verified data based purely on measurement	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representative-ness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years difference from year of study	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference from year of study
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Source: Khasreen et al., 2009: 683.

2.7.2 Deficiencies in System Boundary Selection

In general, all building materials and components can be considered to have a lifetime within a 'cradle-to-grave' boundary. Having said that, in making a 'cradle-to-grave' assessment, Howard et al., (1999) asserts that "a significant proportion of assumptions is essentially to be made for the use phase of the materials and products over timescales for buildings, which are typically very long" (Howard et al., 1999: 6).

The primary aims of LCA are science-based as it involves a considerable number of technical assumptions. These assumptions rely heavily on choices of values and are highly dependent upon the availability of relevant data within the selected boundary. Boundary selection problems have lead to erroneous LCA conclusions and decisions

(Suh et al., 2004). It has been suggested that LCA is *"only typically a steady-state, rather than a dynamic approach"* (Suh et al., 2004: 658). However, the extent of these problems in influencing LCA for embodied carbon expenditure from repair to the stone masonry walls of historic masonry buildings is yet to be ascertained.

2.7.3 Partial Model and Non-Standardised Databases

Previous research studies have commonly been built on ideas arising from LCA modelling. Such works are generally biased as most of these models failed to consider market mechanisms and technological developments in the building industry.

Undeniably, efforts to standardise LCA databases have developed and emerged in various countries (see Table 2.10). In practice, however, these databases are frequently either obsolete, outdated, incomparable, unmatched or of unknown quality**.** Additionally, extensive efforts are being made by various authors and researchers to complete LCA databases. However, none of these databases are able to model comprehensively the environmental impacts during an historic building's life-cycle on a uniform basis.

Table 2.10: Common and previous databases and tools adopted for LCA

Database	Country	Function	Type	Level	Software	Website
Athena	Canada	Database + Tool	Academic	whole building design decision	Eco Calculator	www.athenaSMI.ca
Bath data	UK	Database	Academic	product comparison	No	people.bath.ac.uk/cj219/
BEE	Finland	Tool	Academic	whole building design decision	BEE 1.0	-------------------------
BEES	USA	Tool	Commercial	whole building design decision	BEES	www.bfrl.nist.gov/oae/software/bees.html
BRE 3	UK	Database + Tool	Public	whole building assessment	No	www.bre.co.uk
Boustead	UK	Database + Tool	Academic	product comparison	Yes	www.boustead-consulting.co.uk
DBRI 4 Database	Denmark	Database	Public	product comparison	No	www.en.sbi.dk
Ecoinvent	SL	Database	Commercial	product comparison	No	www.pre.nl/ecoinvent
ECO-it	NL	Tool	Commercial	whole building design decision	ECO-it	www.pre.nl
ECO methods	France	Tool	Commercial	whole building design decision	Under development	www.ecomethods.com
Eco-Quantum	NL	Tool	Academic	whole building design decision	Eco-Quantum	www.ecoquantum.nl
Envest	UK	Tool	Commercial	whole building design decision	Envest	envestv2.bre.co.uk
Gabi	Germany	Database + Tool	Commercial	product comparison	Gabi 4	www.gabi-software.com
IO-database	Denmark	Database	Academic	product comparison	No	---------------------
IVAM	NL	Database	Commercial	product comparison	No	www.ivam.uva.nl
KCL-ECO	Finland	Tool	Commercial	product comparison	KCL-ECO 4.1	www.kcl.fi/eco
LCAiT	Sweden	Tool	Commercial	product comparison	LCAiT	www.ekologik.cit.chalmers.se
LISA	Australia	Tool	Public	whole building design decision	LISA	www.lisa.au.com
Optimize	Canada	Database + tool	---------	whole building design decision	Yes	----------------------
PEMS	UK	Tool	Public	product comparison	Web	----------------------
SEDA	Australia	Tool	Public	whole building assessment	SEDA	----------------------
Simapro	NL	Database + Tool	Commercial	product comparison	Simapro 7	www.pre.nl
Spin	Sweden	Database	Public	product Comparison	No	http://195.215.251.229/Dotnetnuke/
TEAM	France	Database + Tool	Commercial	product comparison	TEAM 3.0	www.ecobilan.com
Umberto	Germany	Database + Tool	Commercial	Product comparison	Umberto	www.umberto.de
US LCI data	USA	Database	Public	Product comparison	No	www.nrel.gov/lci

Source: Khasreen et al., 2009: 684.

2.7.4 Non-Reliable Inventories

A considerable number of inventories have been established to provide reliable databases for embodied carbon coefficient for construction materials. However, their application as a tool of reference for the embodied carbon coefficient of materials used in historic masonry buildings maintenance is not yet fully reliable. Therefore, their capacity as a means of reference for the embodied carbon coefficient of stone masonry wall repair materials remains doubtful. To date, various construction organisations in the UK have discussed the implications of using embodied carbon inventories for building materials. However, it remains unclear whether historic building maintenance in general, and stone masonry wall repair in particular, has any significant influence on this discussion.

2.7.5 Research Data Quality Requirements

Data quality requirements for this research have been specified, from general terms to the desirable characteristics. Data for the LCA of this research were maintained accordingly in order to recommended quality (see Weidema and Wesnaes, 1996: 167, 168). Independent data quality indicators have also been considered where applicable (only with sufficient numbers).

To achieve a high data quality, each collaborative partner selected for this research clearly specified their data sources for stone masonry wall repair materials (either based on official maintenance intervention records or estimations). For this research, source descriptions of the data were included if available. Additionally, verification processes (e.g. face-to-face interviews and expert opinions and judgements) were also undertaken to check the validity of the stone masonry wall repair data comprehensively.

Meanwhile, the reliability and applicability of LCA results for this research relied extensively upon the quality of original data (historic data records of stone masonry wall repair works on historic masonry buildings). At any stage in this research, adopted LCA were improved through consideration of the typical stone masonry wall repair data quality problems.

Low data quality of LCA for this research was minimised by using the most up-to-date and best embodied carbon coefficient values and CO_2 emissions factors per kg over per km of transport value for stone masonry wall repair materials. It must be noted that there is an increment of uncertainty and change with regard to the best value of embodied carbon coefficient in the Inventory of Carbon and Energy due to periodical updates. In parallel with the period of this research, the latest version of ICE (2.0; updated in January 2011) was used as a reference to calculate the embodied carbon expenditure for stone masonry wall repairs within 'cradle-to-gate'. Wherever applicable in this research, Inventory of Carbon and Energy (ICE) characteristics requirements that may influence LCA results were reported, including:

(a) acquisition methods (measurements, calculations and assumptions);
(b) verification methods;
(c) number of collection points, periods and representativeness;
(d) the age and year of the original measurement;
(e) the geographical area for representativeness; and
(f) the process technology, or technological level, and representativeness.

Additionally, the latest data, from 2008, of CO_2 emissions factors per tonne km for HGVs' road freight UK average, along with HGVs loads in 2005, were used as references to calculate embodied carbon expenditures within 'gate-to-site' (functional units used converted to CO_2 emissions factors per kg km) (IFEU, 2008; Defra/DECC, 2009). To suit the purpose this research, this functional units value was multiplied by the mass (kg) of materials transported (used in repairing every $1m^2$ stone masonry wall) and the respective transportation distance.

Realistically, embodied carbon coefficient and kg km emission factors values used for this research had differences in terms of their expression (metadata), uncertainty (spread and pattern of distribution), reliability (methods used for measurements, calculations, assumptions and quality control), completeness (number of collection points, periods and representativeness) and age (year of the original measurement). Therefore, the degree of uncertainty was minimised by clearly determining the impact of the following factors:

(a) absolute differences in data quality (e.g. verification and age of data);
(b) geographical and technological level used in quarrying and processing, and mode of transportation of stone masonry wall repair materials;
(c) importance of using comparable quality for different alternatives;
(d) gaps and lack of representativeness (e.g. worst-case estimates); and
(e) handling of missing information, dubious results and uncertainty.

2.7.6 Research Data Quality Indicators

Wherever applicable for this research, a ‘Pedigree matrix’ (see Table 2.11), which represents data quality indicators in LCA, was applied (Funtowicz and Ravetz, 1990, and introduced by Weidema and Wesnaes, 1996), in which indicators included:

(a) Reliability: including an assessment of the sampling methods and verification procedures (such as, in this case, collaboration efforts made with conservation organisations entrusted with maintenance of historic buildings in Scotland, namely Historic Scotland, National Trust for Scotland (NTS) and The City of Edinburgh Council (CEC);
(b) Completeness: independent of the data quality goals (including statistical representativeness of the data, number of measurements in the sample and time periods for data collection from previous LCA results), this was used as a reference in achieving good data quality, particularly with regard to embodied carbon coefficient and CO_2 emissions factors per tonne km (in this research converted to CO_2 emissions factors per kg km) for stone masonry wall repair materials; and
(c) Temporal, geographical and further technological correlations in preference for the UK context.

Throughout this research, other data quality indicators were also used in order to revise the data collection strategy and to improve the quality of LCA for stone masonry wall repair (see Weidema and Wesnaes, 1996: 168).

In this research, the relation and regression of data was made between embodied carbon expenditure and selected stone masonry wall repair techniques for historic masonry buildings, undertaken during a maintenance phase. The association of stone masonry wall repair undertaken in relation to historic masonry buildings with embodied carbon expenditure has been evaluated within the 'cradle-to-site' boundary of LCA over the period of 2001–10.

Table 2.11: 'Pedigree matrix' with data quality indicators.

Indicator Score	**1**	**2**	**3**	**4**	**5**
Reliability	Verified[a] data based on measurement[b]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years difference	Less than ten years difference	Less than fifteen years difference	Age of data unknown or more than fifteen years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Source: Weidema and Wesnaes, 1996: 169.

[a] Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources.

[b] Includes calculated data (e.g. emissions calculated from inputs to a process), when the basis inputs. If the calculation is based partly on assumptions, the score should be two or three, as calculation is a measurement (e.g. measured inputs). If the calculation is based partly on assumptions, the score should be two or three.

2.7.7 Research Variables, Parameters and Relevant Factors

Commonly, the accuracy of all LCA research results is highly influenced by relevant variables, parameters and factors. With regards to maintenance and repair of stone masonry wall, the time between their interventions is influenced by longevity of repair, resourcing and geographical location, technological development, mode of transportation used, degree of wall exposure, building and wall detailing as well as, quality of initial work and specification. This research is also subject to these issues however, it must emphasised that as the accuracy of LCA results are enhanced, so should the accuracy of the model.

2.7.7.1. Research Variables

In reality, external exposed stone masonry walls of historic masonry buildings deteriorate at variable rates. Deterioration of stone masonry wall rates are very much dependent upon wall construction, stone used, repair material quality, finishes, detailing and exposure, etc. In addition, the rate of deterioration of stone masonry walls is also very much dependent upon longevity of repair. For this research, it was assumed that longevity for natural stone replacement, re-pointing mortar joints, pinning and consolidation, and plastic repairs in stone masonry walls was one hundred, twenty-five, twenty and thirty years respectively (derived from Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurt and Dimes, 1998; McMillan et al., 1999; Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al., 2003; BCIS, 2006; BRE 2010).

2.7.7.2 Research Parameters

It must be emphasised that the scope of this research was defined by taking into account the parameters of LCA, in terms of the following:

(a) Geographical of Study

Wherever possible, embodied carbon coefficient data for this research was derived within the UK context, particularly with those in the Scottish region. However, it is not feasible to derive the best available data with regard to embodied carbon coefficient data only from UK. Therefore, data from foreign sources was also used as a point of reference (such as European and worldwide averages of embodied carbon coefficient values). It must be noted that embodied carbon coefficient values from foreign data were always influenced by national differences in fuel mixes and electricity generation.

(b) Primary and Delivered Energy

For this research, primary energy sources (such as coal and electricity) were only evaluated if relevant. However, this 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.

(c) Age of Data Sources

Preference was given in this research to up-to-date data of embodied carbon coefficients and CO_2 emissions factors, as they were more relevant and had a higher level of certainty. In the case of stone masonry wall repair materials for historic masonry buildings, it must be stated that there were constant changes in both data due the age of the sources.

(d) Data Sources and Origin

Ideally, the data sources for embodied carbon coefficients and CO_2 emissions factors in this research were obtained from previous LCA studies on embodied energy embodiment and carbon emissions. Whenever possible, they were also collected from inventories and databases of typical building maintenance markets in the UK.

(e) Completeness of Data

Where appropriate, this research also relies on secondary data as another means of sources. Due to the constant incompleteness of this, however (improper calculation frameworks, subjective system boundaries and restricted accessibility), consideration of their suitability was undertaken cautiously throughout. This issue was clearly explained whenever it occurred.

(f) Technology of Manufacturing Processes

Different technologies used for manufacturing building materials can reflect different embodied carbon and energy expenditure. Therefore, any dissimilar technology adopted to produce repair materials used in historic buildings stone masonry wall repairs was addressed accordingly.

(g) Feedstock Energy Consideration

Feedstocks energy was included in this research only if it represented a permanent loss of valuable resources (such as fossil fuel usage to operate machineries in quarries and stone yards in natural stone production). Feedstocks energy of petrochemicals (used in the production of additive/adhesive/sealant/plastics materials) were only taken into account if they had a great influence on embodied carbon for stone masonry wall repair.

(h) Temporal Representativeness

In either a newly developed, or mix of old and new, technology, temporal representativeness has a significant influence in embodied carbon expenditure. It can cause misleading results and confusion or distortion upon LCA. This causal parameter was explained as comprehensively as possible whenever it occurred in this research.

(i) Environmental Maintenance Impact

Environmental Maintenance Impacts (EMI) either for single or a combination of repair techniques for repairing stone masonry walls of historic masonry buildings in different scenarios was considered as the an additional parameter for this research.

2.7.7.3 Relevant Factors

Consideration was placed on any relevant factors that might have influenced the embodied carbon expenditure for stone masonry wall repair. This is explained in the following section:

(a) Influences of System Boundary Selection

The selection of a boundary system for this research depended on the aims and scope of the LCA, as well as data availability and quality. Additionally, this research also took into account the tracing back to the upstream level of production processes for materials used for stone masonry wall repair in historic masonry buildings (e.g. limestone mining, processing of natural gas, etc.) (see also Optis and Wild, 2010: 646).

(b) Consideration of Calculation Procedures

To suit the purpose of this research, relevant considerations in light of several calculation procedures from the previous studies were undertaken (for example, see Suh and Huppes, 2005: 687). This research also considered embodied carbon expended over the life cycle stage of historic masonry buildings, particularly during their use stage (maintenance phase).

(c) Data Sourcing

There are a significant number of building materials that need to be considered in any LCA study (dozens to hundreds). For examples, 19 materials have been considered in LCA of *'Embodied Energy and CO_2 Coefficient of NZ Building Materials'* (Alcorn, 1998; 2001 and 2003). Meanwhile, the University of Bath's Inventory of Carbon and Energy (ICE) database lists almost 200 different materials based on LCA study (Hammond and Jones, 2008a: 87). It is thus difficult to develop data sourcing for them. It must be noted that there are difficulties in retrieving data for every individual repair material used in repairing stone masonry walls of historic masonry buildings. This is due to limited data from previous LCA publications, which quantified embodied carbon coefficients and CO_2 emissions factors per tonne km for these materials in historic masonry buildings repair. Therefore, supplementary data was applied for this research.

(d) Modelling Data Uncertainty

Uncertainty LCA for this research was formed through identification and determination of their relevant issues and problems. For this research, this were completed based on common issues and problems highlighted by the Inventory of Carbon and Energy (ICE) and CO_2 emissions factors per kg km data sources. In addition, for materials used in repair to stone masonry walls of historic buildings, the laws of their respective mix, volume, mass and weight conversion were determined accordingly (see examples in SETAC in *Data Availability and Quality* (Selmes, 2005: 97) and data quality management (Weidema and Wesnaes, 1996: 167).

(e) Documentation in Condensed LCA Reports

Wherever applicable, LCA reports on historic buildings with reference to existing and traditional buildings from previous studies were also considered as a means of data sources. Technology Assessment for Radically Improving the Built Asset Base (TARBASE) and Energy Modelling In Traditional Scottish Houses (EMITSH) LCA reports were also referred to in this way (see EMITISH, 2008: 1; Historic Scotland, 2008: 1, 2; TARBASE, 2009: 1).

2.8 Environmental Impact and Embodied Carbon of Stone Masonry Walls

It is widely recognised that the stone masonry wall fabric in historic buildings has made a significant contribution to cultural heritage. Crishna et al. (2011) state that stone masonry (including wall fabric) “is characteristic of the built environment”. The prominence of stone masonry wall fabric in the existing built environment is very much associated with their production. Paradoxically, the Scottish stone industry is in decline (Scottish Executive, 2006). These changes have contributed to make a significant environmental impact, particularly in transportation carbon dioxide emissions. Clearly, stone continues to be required to maintain these buildings and indigenous, petrogaphically compatible and locally sourced materials would aid this process. Regular maintenance for stone masonry walls clearly contributes to the embodied carbon expenditure of the structure. These intervention types are clearly significantly influenced by the selection and specification of natural stone and lime, and the range of techniques at a practitioner’s disposal.

The environmental impact of stone masonry repair techniques have never been investigated and is clearly the premise of this research. It is clear that ashlar, rubble masonry, consolidation, plastic repair and lime repointing techniques will all expend varying degrees of carbon dioxide during construction and varied longevities.

The next section outlines some of the techniques available, discussing important background information that underpins the carbon inputs.

2.8.1 Stone Masonry Wall Construction

2.8.1.1 Rubble Walling

The term “rubble” encompasses many forms of stonework that are commonly categorised as different types: “common” or uncoursed (Figure 2.5), coursed (levelled every 300-600 mm to increase stability or to meet the level of dressed quoins, sills and etc); “squared rubble” (coursed in alternating units – 100, 200 and 300 mm deep – of consistent deep and shallow stones or “shoddie”); “uncoursed squared rubble” or “snecked rubble” (a simple pattern of deep through-stone “risers” combined with long flat “levellers”, which even up the coursing and “snecks” that fill in the gaps); and “block-in Course” (a rare type of Victorian walling in which the blocks were consistent in height, 10 mm joints and >400 mm deep, completed in hammer-finished) (Glasgow West Conservation Trust, 1999: 21). Rubble masonry has traditionally been considered a cheap method of construction when compared with ashlar techniques. Expended carbon for these types of repair must be based on the volume of natural stone, lime mortar transportation and sourcing.

Figure 2.5: Typical example of rubble masonry with lime mortar joints
Source: Historic Scotland, 2007d.

2.8.1.2 Ashlars Masonry Wall

Commonly, ashlar walling was the finest type of stonework (Figure 2.6) requiring the highest workmanship to manufacture and set squared and polished stone blocks (Historic Scotland, 2007a). These were usually cut with a flat bed of the outer six inches (150 mm) from the face, and thus was the most expensive element for stone tenement terraces, terraces and villas. Ashlar blocks of this type of wall were generally seven or eight inches (175-200 mm) thick, bedded in soft lime mortar at a lime : sand ratio of 1:3-4 and often left with ¾ inch (20 mm) deep lime putty pointed to an open joint. Header stones were normally placed on every course, commonly between 1.5-3.6m with actual placement depended on the location of window and door openings with "inbands". It must be emphasised that "pinned" or wedged beds of narrower dimension ashlar blocks have often resulted in chipping off due to uneven pressure (Glasgow West Conservation Trust, 1999: 18-19).

Figure 2.6: Typical example of ashlar masonry with ashlar mortar joints
Source: Historic Scotland, 2007a.

Although the stones used in this type of wall were commonly hewn to regular course height, the lengths of their "perpends" were relatively random and could vary from 10 inches (250 mm) to five feet (1.5 m) for their header, depending on the nature of the rough blocks extracted from the quarry. Thus, stones of varying lengths were generally laid in walls so that the "perpends" would be at least 6 inches (150 mm) apart to avoid "risband" or "racebond" of overlapping vertical joints, which would be structurally weak (Glasgow West Conservation Trust, 1999: 19). The gap between the inner and outer walls was filled with "packing", a grout lime mortar, and the "shivers" or chippings left by the stone hewers. Commonly, structural problems in this type of wall relate to separation of the two skins occurring over years due to inadequate bonding, often caused by hasty work on site. Such a failure of bulging and differential cracking in the bond between the ashlar wall and the rubble is due to an insufficient proportion of lime mortar (Glasgow West Conservation Trust, 1999: 19-20).

2.8.2 Stone Masonry Wall Exposure

Stone masonry wall exposure to the weather causes inevitable changes that impact on both its aesthetic and structure. This includes significant loss of its substance through decay processes such as salt crystallisation, attack by acid gases in the air and frost action (Honeyborne, 1998: 153 in Ashurst and Dimes, 1998). Stahl (1984) suggests that the deterioration rate of external walls in historic masonry buildings is faster than for internal walls due to the direct exposure to weathering factors, which include moisture, wind, chemical and pollutant causes (Stahl, 1984: 39-43). Commonly, the faster the degradation proceeds in stone masonry walls, the more maintenance intervention is needed to repair them. This also means that a greater quantity of repair materials are needed and, therefore, more embodied carbon expenditure is utilised for repair.

2.8.3 Stone Masonry Wall Finishes

2.8.3.1 Rubble Wall Finishes

In general, joints in rubble walls vary (10mm-50mm) and are either smoothly finished (“drafted”) or finished with parallel tooling marks (“droved or scabbed”). In addition, the faces of rubble stones depend upon their location in a building and are commonly dressed with “broaching” (narrow horizontal grooves), mason’s punch or point chisel for “pointed” (very fine variety) and “dabbed” work (common, coarser version) and “stugging” for a chiselled pattern. Comparatively, hammer-dressed stonework consists of a flush but roughened surface created by squaring off the block with a chisel-pointed hammer; it was sometimes used for back of tenements, but never for ashlar fronts due to the obvious problems of scaling (Glasgow West Conservation Trust, 1999: 23). Different quantities in mass (kg)/volume (m^3) for lime mortar/grout mix/lime plaster used in repairs contributes to diverse embodied carbon expenditure in rubble wall repair.

2.8.3.2 Ashlar Masonry Wall Finishes

The joints of ashlar masonry wall are commonly 3/16 inches (3mm), while the course heights rarely vary from 12 inches (300mm). The fineness of the joints was often emphasised by the use of white lime putty for the final pointing up of the ashlar blocks, while horizontal tooling (Figure 2.7) or “broaching” (Historic Scotland, 2003b) was also a popular way to articulate the base course, as was the “channelling” or rebating of the horizontal bed joints in a V-shaped or squared recess (Glasgow West Conservation Trust, 1999: 20). The most common surface treatment was rusticated base, usually with a rock-faced or “pinched” surface (Glasgow West Conservation Trust, 1999: 20). Another typical example of a tooling effect is illustrated in Figure 2.8. When indents or replacement stones are specified for ashlar walls, it is essential to ensure that the finish of the new block matches the original. In general, modern stone cutting techniques include the sawing of quarry blocks into dimension stones ready for installation on site. Unless the stones are smoothed by machine before leaving the yard, it is usually necessary that they are hand rubbed with carborundum and/or sandstone blocks in order to remove any tell-tale saw marks before setting them into the wall (Glasgow West Conservation Trust, 1999: 21). Different specifications, ornaments, decorative features, patterns, application and common problems of finishes in ashlar masonry walls are the main factors influencing the procurement of repair materials.

Figure 2.7: Tooling of ashlar masonry

Source: Historic Scotland, 2007c.

Figure 2.8: Typical example of stone tooling effects

Source: Historic Scotland, 2007c.

2.8.4 *Details of Mortar, Beds and Joints Pointing of Stone Masonry Walls*

Lime for mortar is produced from burning calcium carbonate ($CaCO_3$), usually in the form of shells, limestone or chalk (widely used), marble, shells, coral, marl and etc. (Historic Scotland, 2003a) (see Figure 2.9).

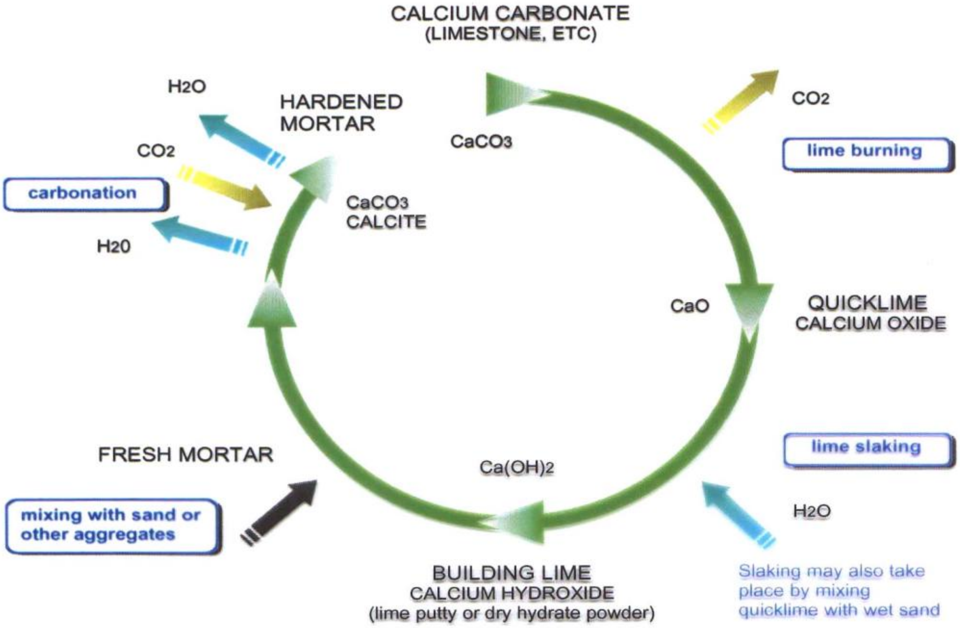


Figure 2.9: Simplified diagrammatic life cycle of lime

Source: Historic Scotland, 2003a.

Carbon dioxide is driven off during the burning process of these materials , leaving a white or tan-coloured mass of calcium oxide (malleable material) or “quicklime”, which is later converted to calcium hydroxide through the “slaking” process with water

(Historic Scotland, 2003a: 9; Glasgow West Conservation Trust, 1999: 23). The slaked lime will harden back into calcium carbonate when mixed with water and exposed to carbon dioxide in the atmosphere (commonly concerted using modern slaking); it is generally available as a dry powder, "hydrated lime" (Glasgow West Conservation Trust, 1999: 23), "hydraulic lime or water limes" (Historic Scotland, 2003a).

Prior to use on site, it must be noted that "hydrated lime" should be mixed with sand and clean water and allowed to soak for at least twenty-four hours in advance. Meanwhile, non-hydraulic lime (also known as fat limes, high calcium limes or air limes) produced from limestones which did do not contain clay or other reactive silicate and commonly use in favourable conditions and for working with soft sandstone (Historic Scotland, 2003a: 15).

Comparatively, hydraulic lime is produced from the burning of impure limestone. Its impurities provide greater resilience compared to hydrated lime (though it is more difficult to obtain and use). In general, the more hydraulic the lime the harder and more impermeable will be the resulting mortar, although these properties vary according to specific make of lime (Historic Scotland, 2003a; Banfill and Forster, 1999). Commonly available in powder form, hydraulic lime must be carefully transported and stored to avoid wetness. Hydraulic limes can be worked just as hydrated lime (Glasgow West Conservation Trust, 1999: 23).

Commonly, lime mortar not only acts as glue to hold masonry units together but also provides a cushion to keep them apart as the stone naturally expands and contracts. Additionally, mortar joints also act as the main conduit for moisture migrating through the wall in both directions as it is "breathable" materials (Banfill and Forster, 1999). Usually functioning as sacrificial product, good lime mortar is naturally weaker than the stone and will divert stresses of natural weathering agents, thereby protecting the stonework. Except for the finest ashlar, all stonework is commonly pointed up with approximately 1 portion of lime for every 3 to 4 portions of sand (Glasgow West Conservation Trust, 1999: 23).

Good lime mortar should rarely require pointing. It must be emphasise that, deterioration will occur in both extremes exposure and sheltered conditions. Comparatively, in the latter condition, the rate of degradation process is slower compared to the former (Historic Scotland 2007a; 2007b; 2007c and 2007d). In most buildings that are repaired in haste, it might occur that the mortar is not well mixed or properly set either too hard, too soft and loose (Historic Scotland, 1995: 35). In addition, mortar that is too lime-rich will set too rapidly and fail to adhere evenly to the stonework, while mortar with too much sand will be too soft and will not prove to be very durable. Comparatively, mortar mixed without clean, sharp sand will also fail over time, while any impurities, such as salts, clay or pyrites, that may weaken the bond and cause side-effects (such as iron staining or efflorescence) should be avoided. Additionally, a mono-granular aggregate also known as “builders’ sand” must also be avoided as they are poorly graded and lead to excessive drying shrinkage in the materials. In order to provide suitable mortar using sharp sand for a particular building, the colour should be selected appropriately (see example from Historic Scotland, 2006). To avoid any rouge pebbles or other debris that could damage fine ashlar joints, sharp sand should also be sieved before it is mixed with lime. To ensure the correct proportion of sand to lime and water, usage of dry sand is highly encouraged, as wet sand can retain a disproportionate amount of water, which can weaken mortar (Glasgow West Conservation Trust, 1999: 23).

The direction of the beds can usually be determined by the angle of mica flakes or other parallel bands of impurities in stone blocks. Commonly, all stone blocks used for walling (ashlar or rubble, or as indents) should be laid on their natural beds (except for “freestone”, in which there are no bedding planes and the stone can be worked in any direction). The process of laying walling blocks with the natural beds parallel to the face of the building is known as “building on cant” or the “face-bedding” position. It must be emphasised that this position exposes the stone’s inherent weaknesses, since moisture can get in between the bedding planes as well, denying the stone’s natural compressive strengths to cause scaling and delamination of the stone (Glasgow West Conservation Trust, 1999: 24). In the correct positioning the indents, the replacement stone blocks should be set so that the external face aligns evenly with the surrounding original face of the building (Historic Scotland, 2007b).

Not all stones within a wall must be laid on the natural bed. Commonly, arch stones should be placed with the natural bed at a right angle to the compressive “thrust” on the stone, parallel to the arch stone’s centre line and perpendicular to the soffit of the arch impurities. Meanwhile, stone for cornices and string courses must be carefully selected so that the mouldings are cut out of the block, which will be “edge-bedded” or placed with its natural bed vertically and at right angles to the face of the building (Historic Scotland, 2006). If naturally bedded, the moulded projections would erode and fall off. This also applied to all sills, lintels and blocking course stones (Glasgow West Conservation Trust, 1999: 25).

The quantity in mass (kg)/volume (m^3) of lime mortar/grout mix/lime plaster used for stone masonry wall repair is very much dependent upon details of mortar, width and length of wall beds and joints pointing. The quantity of materials used on mortar, stone bed laying and joints pointing subsequently affects embodied carbon expenditure. To date, however, the extent of these influencing factors on embodied carbon expenditure is yet to be evaluated in a comprehensive manner.

2.9 Environmental Profiles of Buildings Materials

With regard to the UK context, Hill (2010) suggests that there are common materials used in construction industry (Table 2.12). The environmental profiles for these materials vary, as they have different procurement processes. Differences in material procurement have a significant influence on their carbon emissions. However, the environmental profile for repair materials used in stone masonry walls remains non-comprehensive. To date, various ecotoxicology, indicators and weighing systems have been developed to identify environmental profiles for materials (example from Harris, 1999 and Table 2.13). The environmental profile of some building material have been researched by leading bodies, such as the Building Research Establishment (BRE) and the Construction Industry Research and Information Association, UK (CIRIA). However, there is no comprehensive agreement on a suitable variety of indicators of environmental profile for historic buildings materials, particularly the materials used in stone masonry wall repair. In addition, no specific benchmark has been established for the environmental profiling of materials using cradle-to-site boundaries LCA methods.

Table 2.12: Common materials and their environmental profiles (UK construction industry)

Materials	**Note**
Bricks	• Local raw material • Low firing temperature • Recoverable (used with lime mortars) • Recyclable • Long life ** the UK makes around 3 billion bricks annually but places about 1.5 billion into landfill (approximately 50%).*
Lime	• Burnt at 900-1100^{o} Celsius • Low grade fuel • Locally produced • Half as dense – 30-50% less energy • Reabsorbs some CO_2 • Recoverable • Recyclable **10% of global CO_2 production is from cement*
Cement	Burnt at 1200-1500^{o} Celsius (twice as high as lime)
Timber	• Flexible • Durable • Biodegradable • Non-toxic • Regenerates • Reusable • Adaptable • Recyclable **30% of global CO_2 emissions arise from tropical deforestation and the UK imported 80% of construction timber – World Wide Fund for Nature (WWF)*

Source: Adapted from Hill, 2010.

Table 2.13: Indicators and form of environmental impact of building materials

Indicator	**Environmental impact**
(1) Embodied energy	CO_2 emissions, other gaseous pollutants, NO_x, SO_x, quantifiable
(2) Raw materials consumption (Resource conservation)	Quarrying, which is a local nuisance due to noise and dust. Partially quantifiable
(3) Scarcity factor	Raw material expenditure. Are there any better options for use of the material? In part quantifiable
(4) Recycling potential	Difficult to quantify. Affects indicators l-3 above
(5) Effects on occupants (Toxic hazard)	Asthma, etc. Difficult to quantify (reactions vary between individuals)
(6) Potential for using recycled materials	Difficult to quantify
(7) Influence on energy consumption	CO, emissions, other gaseous pollutants, NO_x, SO_x. Possible to quantify but depends on location (i.e. climate)

Source: Adapted from Harris, 1999: 753.

2.9.1 Environmental Impact Indicators

Table 2.14 sets out the common list of relevant indicators for the environmental impact of building materials. Embodied carbon (CO_2 emissions) and pollutants and wastes are mainly released from materials used in repair. In general, however, there is no consensus of agreement on environmental impact indicators for buildings materials. Previous publications and LCA studies have weighted the environmental impact indicators of building materials against each other in terms of embodied carbon expenditure. With regard to historic masonry buildings, this led to the question "how can embodied carbon expenditure for materials usage in stone masonry wall repair be evaluated?". In addition, the selection process for common materials used in historic masonry buildings repair (such in stone masonry wall repair) must be scrutinised as their environmental profiles contribute to different embodied carbon expenditure.

Table 2.14: Common list of indicators used for environmental impact of building materials

Common indicators
Emission of carbon (for energy-in-use or global warming)
Extent of effect on the health of occupants of a building (e.g. asbestos materials)
Indoor air quality indicators
Embodied energy
Reduction of non-renewable resources
Reuse of recycled materials
Landfill

Source: Adapted from Harris, 1999: 754.

2.9.2 Low Carbon Materials and Recycling Options

There has been disagreement amongst previous researchers on the selection of 'best values' for embodied carbon of building materials. Conversely, it must emphasised that the usage of low carbon materials in historic masonry building repair is of paramount importance to achieve low embodied carbon expenditure. It is essential that these materials also be produced with minimal processing and that they are porous, hygroscopic in nature, flexible, locally sourced and renewable.

In practice, however, flexibility and compromise is required if locally available materials of similar durability are to be used while undertaking repair to historic buildings. According to Holtzhausen (2007), pitfalls in building design and consumers' unwillingness to compromise by using sustainable materials was normally caused by low understanding (Holtzhausen, 2007).

Recycling may seem to be an ideal solution to the scarcity of traditional materials. The sorting, cleaning and disposing of recyclable materials (such as recycling and reuse of brick dust/fire clay/fly ash or crushed limestone/gravel/chippings in stone masonry wall repair) will contribute additional embodied carbon expenditure. These additional processes also add substantial practical difficulties that may impair the historic masonry building's performance, i.e. the efficiency of stone masonry wall repair in terms of embodied carbon expenditure. This is also highly influenced by materials production, such as by the stone industry.

2.10. UK and Scottish Stone Industry Profile

2.10.1 UK Stone Industry

Two common markets for indigenous UK stone currently exist: namely, for new buildings and for repairing traditional buildings (including historic masonry buildings). High profile examples of the recent resurgence in the use of Scottish stone for new buildings include the Scottish Parliament, the Museum of Scotland and the Weston Link at the National Gallery of Scotland (SISTech, 2010). Comparatively, the usage of stone for Scotland's historic masonry buildings repair include castles, palaces, abbeys, cathedrals, mansions, houses, lodges and tenements.

The UK has become a major importer of building stone due in part to the low cost of labour from other countries, and the greater economies of scale in European operations compared to expensive domestic market. Commonly, slate and flagstones were mainly imported from Portugal; however, these have now been overtaken by imports from India and China as well. Meanwhile, granite and sandstone are also imported from India, China and, within Europe, from Spain and Italy (SISTech, 2010). Annual production, imports and exports in natural stone from the UK (in tonnes) are provided in Table 2.15.

Table 2.15: Annual production, imports and exports of building and dimension stone in the UK (in tonnes)

tonnes	**Imports**	**Exports**	**Production**
Marble and other calcareous stone	148443	6967	320000
Granite and other igneous rock	557878	8063	50000
Sandstone	322530	1081	419000
Other stone	133336	15950	1000
Paving stone and flagstone	297099	3716	*not available
Total	**1162187**	**32061**	**790000**

Source: SISTech, 2010.

2.10.2 Scottish Stone Industry

By and large, the natural variation in the geology of Scotland defines the distinct cultural identity throughout the land, both in terms of stone type used to construct and repair buildings as well as the construction methods employed (SISTech, 2010). Currently, there are two main markets for Scottish stone: stone for new buildings and stone for repairing Scotland's historic buildings. Regrettably, however, many of the stone types required for maintenance in Scottish stone are no longer available from their original source quarries.

There is a long history of stone usage in Scotland's construction industry, beginning with the earliest recorded settlements, peaking in the 19th century and subsequently declining during the 20th century (SISTech, 2010: 1). Natural stone plays an iconic role in Scotland's built environment and cultural heritage. As addressed by the Scottish Stone Liaison Group (SSLG), there is an issue with the procurement of such stone, which is mainly due to the diverse range of stone used in Scotland's built heritage (including imported stone), and the closure of most local stone quarry operations (such as the fact that Scottish slate, which has not been quarried since the 1950s) (SISTech, 2010: 2). To date, there are approximately 53 building stone quarries in Scotland (Table 2.16). However, the majority of these stone quarries produce building stone upon demand only for specific projects or for a few months each year.

Table 2.16: Distribution of active building stone quarries in the UK, March 2007.

	England	**Scotland**	**Wales**	**Northern Ireland**	**Isle of Man**	**Total**
Building sandstone	173	16	16	1	0	**208**
Building limestone, including chalk	118	5	10	2	2	**137**
Granite and other igneous rock	15	26	4	2	1	**48**
Slate and marble	18	1	15	0	4	**38**

Source: SISTech, 2010.

In addition, of those Scottish quarries that are still regularly producing building stone, output is variable. Generally, their operations range between 0.5 – 50 ha sites, with the smaller producers catering for local and niche markets with production rarely exceeding 500 tonnes. By comparison, larger producers operating a number of quarries have an average production of 5,000 – 10,000 tonnes per annum (Scottish Government, 2007). In 2010, SIStech outlined a more detailed description of the Scottish and UK stone industry (SISTech, 2010: 2). Scottish production tonnages of the principal rock types for all uses (including aggregate) are shown in Table 2.17.

Table 2.17: Scotland: Sales of building stone, 1990-2005

Year	Sandstone Total	Sandstone for building stone Total	Igneous rock Total	Igneous rock for building stone Total	Limestone Total	Limestone for building stone Total
						Thousand Tonnes
1990	1834	**10**	19280	**109**	1778	**-**
1991	1555	**na**	19588	**94**	2018	**-**
1992	1658	**9**	20064	**112**	1410	**-**
1993	1716	**30**	20806	**142**	1432	**-**
1994	1772	**22**	20672	**na**	1650	**-**
1995	2400	**15**	21731	**130**	1540	**na**
1996	2172	**11**	19933	**128**	1607	**-**
1997	1712	**8**	19863	**129**	1624	**-**
1998	2539	**17**	20500	**107**	1535	**na**
1999	1657	**14**	21761	**141**	1507	**na**
2000	1715	**na**	21455	**179**	1722	**na**
2001	1603	**18**	20034	**423**	1733	**na**
2002	1645	**na**	20543	**196**	1635	**1**
2003	1481	**63**	20920	**179**	1730	**na**
2004	1613	**28**	23724	**174**	1746	**na**
2005	1466	**33**	23052	**130**	1746	**na**

Source: Scottish Government, 2007.

Notes:

*na: not available

Some figures have had to be estimated because selected information is confidential. These figures should be treated with caution as they are believed to over-estimate production, particularly with respect to igneous rock. According to the Annual Minerals Raised Inquiry, there is slate production in Scotland. No figures are given for tonnage but returns have been received from West Central Scotland, Tayside and Fife and North East Scotland. It is possible that some flagstone products are being described as slate.

Meanwhile, the principal building stone resources in Scotland are listed in Table 2.18.

Table 2.18**:** Principal building stone resources in Scotland

Sandstones	**Principal producing counties**
Triassic (red & white)	Dumfries & Galloway, Fife and Moray
Permian (red)	Dumfries & Galloway
Carboniferous	Fife, Scottish Borders
Devonian (Old Red Sandstone - red purple sandstone; grey flagstone)	Caithness, Angus
Lower Palaeozoic (greywacke sandstone)	Scottish Borders and Dumfries & Galloway
Limestones	
Pre-Cambrian	Highland, Skye, Grampian
Slate	
Lower Palaeozoic (stone ‘slate’)	Dumfries & Galloway, Scottish Borders
Pre-Cambrian	Argyll & Bute, Aberdeenshire
Granites & other igneous rocks	Aberdeenshire, Argyll & Bute, Fife, Highland; Dumfries & Galloway

Source: Scottish Government, 2007.

However, limited studies have attempted to evaluate stone production implications for environmental impact, either in local or international contexts, with the exception of SISTech (2010), Alshboul and Alzoubi (2008), and the University of Tennessee (2008a, 2008b and 2008c). It must however be emphasised that the scope of these studies relates largely to specific types of stone and their production impacts within their regional context and are not comprehensively inclusive of varying type of stone. Therefore, research undertaken into investigating the influence of the stone industry on embodied carbon expenditure in stone masonry wall repair remains insufficient.

2.10.3 Foreign Stone Industry

Based on a report by SISTech 2010, the main countries importing stone to the UK were identified as Portugal, Spain, Italy and Poland from within the EU and Brazil, India and

China outwith the EU. Natural stone producing countries are scattered all over the world. Table 2.19 shows the top ten raw natural stone producers in the year of 2007.

Table 2.19: The world's ten largest raw natural stone producing countries in 2007

Country	**Production of raw natural stone (million tonnes) in 2007**
China	22.0
India	21.5
Iran	11.1
Italy	10.0
Turkey	9.5
Spain	8.0
Brazil	7.5
Egypt	3.5
Portugal	3.0
France	1.2

Source: SISTech, 2010.

2.11 Stone Masonry Wall Repair Materials Environmental Profiles

2.11.1 Stone

The processes used to extract and produce building stone are relatively uniform around the UK (SISTech, 2010: 2). The quarrying process for stone consists of removing large blocks of the building stone from its setting within a larger geological formation. In general, the process includes removal of any overlying rock and sediment to expose the desired bed. To achieve minimal damage to the rock, the use of heavy machinery is essential to remove and transport the stone to storage or processing facilities. Energy used at a dimensional stone quarry is mainly supplied by diesel and petrol for drills, excavators, front end loaders and dump trucks, while a limited amount of explosives are also used (SISTech, 2010: 3). Refer to Appendix A for the embodied carbon coefficient of stone materials.

In 2010, results of research undertaken by SISTech showed that the carbon footprint of UK sandstone and granite are lower than those of other building materials (64 and 93

$kgCO_2e$ per tonne respectively) but the carbon embodied in UK slate is significantly higher (232 $kgCO_2e$ per tonne stone) (SISTech, 2010). This research by SISTech reveals that stone processing (including quarrying, dressing etc.) and transportation (within the processing and building site) are the most significant contributors to the overall footprint (embodied carbon expenditure).

In general, however, the ease of quarrying/extraction processes depends mainly on the nature and structure of the geology of the area and the physical properties of the stone itself. The quarrying process also varies between stone types. Comparatively, quarrying a thin-layered, largely linear structure stone (such as slate) requires a different method of breaking the bed (along just one plane) to that used for quarrying larger-bedded stone (such as sandstone or granite). Subsequently, embodied carbon expenditure for stone production (within cradle-to-gate) is very much dependent upon the aforementioned variables. To date, however, existing information on the carbon impact of dimensional stone used for the repair of traditional buildings and construction of new buildings remains insufficient (SISTech, 2010: 1).

Stone masonry wall construction and repair uses stone of different bulk density (ratio of its density to the density of water or 1.00×10^3 kg/m^3). In general, the higher the value of bulk density, the stronger and heavier the stones are. Commonly, more carbon emissions are expended (kg km emission factors of road freight) in transporting the heavier stones (HGV restricted pay load and trip frequency) to site during stone masonry wall repair. To date, however, there is little information available on the implication of stone bulk density (kg/m^3) value upon embodied carbon expenditure in stone masonry wall repair.

2.11.2 Cement

Embodied carbon coefficient used for cement materials in stone masonry wall repair is mainly derived from the value of weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. According to Hammond and Jones's (2011) Inventory of Carbon & Energy (ICE) Version 2.0 (see also Appendix A), this data has been estimated from the Mineral Products Association (MPA) factsheets [see also embodied CO_2 of UK cement, additions and cementitious material, fact sheet 18 (P1) by Clear et al. (2009)]. In general, Hammond and Jones (2011) highlighted that an average of 23% cementitious additions have been added in cement materials (Hammond and Jones, 2011).

It must emphasised that there is a high value for embodied carbon coefficients in cements. This is due to the fact that the embodied carbon in cement production is highly dependent upon the clinker, its content, manufacturing technology and additions materials, such as fly ash and slag. Additionally, there are a wide range of cement types, which vary greatly in terms of their embodied carbon, but the typical cement (general category above) has been used for reference purposes (in the absence of knowing the type of cement to be used in a specific case) as it provides a reasonable embodied carbon coefficients value. The typical embodied carbon coefficient value for this type of cement is also consistent with the relevant database statistics and modern sources of data for inventory of carbon and energy. However, the extent of the influence of the embodied carbon coefficient value of cement in embodied carbon expenditure for stone masonry wall repair is yet to be evaluated.

2.11.3 Lime

There are wide range of embodied carbon coefficients in lime, dependent upon the manufacturing technology used (for example, for lime putty, hydraulic lime, non-hydraulic lime and jura-kalk) (see also Appendix A). The embodied carbon coefficient for embodied carbon in lime used for stone masonry wall repair is commonly that for general lime.

There is wide range of embodied carbon coefficient value for lime as they are commonly dependent upon manufacturing technology. Although the embodied energy for lime was commonly higher than for cement, the UK lime industry mix of fuels were cleaner than cement, and as such its embodied carbon was lower. Based on observation of 39 data records, Hammond and Jones suggest that lime is often chosen as an environmentally friendly material (Hammond and Jones, 2008a and 2008b; 2011). It was therefore surprising to learn that the embodied carbon of lime is slightly higher than that of cement. The former is fired in the kiln to a lower temperature than the latter, which is often misconceived as proof of a lower embodied energy. Hammond and Jones (2011) suggested that yield, density, and time in the kiln are all vital parameters to total energy consumption and that firing temperature may not be used as a proxy for embodied energy for lime. This is presented as a possibility for its higher embodied energy. However, it should be noted that the embodied carbon value for lime does not discredit its environmental credentials. Comparatively, it has a lower embodied carbon compared to cement due to a more favourable fuel mix and slightly lower number of production processes-related carbon dioxide emissions. An additional benefit of using lime-based mortar is its increased ability for deconstruction, as opposed to demolition. Commonly, the re-carbonation process that occurs during the lifetime of both lime and cement-based mortars (when exposed to air) reduce their embodied carbon impact. It is understood that this process is not undesirable for lime, unlike cement. Therefore, evaluation of embodied carbon expenditure for lime materials, particularly in stone masonry wall repair within 'cradle-to-site' LCA, is of paramount importance.

2.11.4 Sand

The embodied carbon coefficient for sand is mainly derived from the UK context (Hammond and Jones, 2008a and 2008b) (see also Appendix A). It must be emphasised that mining and transportation of sand is a significant contributor to their embodied carbon expenditure. To date, however, little research has been undertaken to evaluate embodied carbon expenditure expended in usage of sand materials in stone masonry wall repair, particularly within the LCA 'cradle-to-site' boundary and selected maintenance period.

2.11.5 Brick Dust/Fire Clay/Fly Ash

The embodied carbon coefficient used for this research is mainly the value estimated for general simple baked clay products (Hammond and Jones, 2008a and 2008b) (see also Appendix A). In general, the clay products release process causes carbon dioxide emissions during processing and manufacturing. This is, however, dependent upon the type of clay product. It must be emphasised that there is a large data range associated with all ceramic and brick products. Therefore, the embodied carbon coefficient for brick dust, fire clay and fly ash used in lime mortar/grout/plaster mix for stone masonry wall repair in historic masonry buildings is considered to be similar to general simple baked clay products. However, the embodied carbon expenditure expended from usage of these materials in stone masonry wall repair remains to be ascertained.

2.11.6 Aggregates

According to Hammond and Jones, data on embodied carbon coefficient for aggregates in the UK context is commonly based on estimated values from local data (Hammond and Jones, 2008a and 2008b) (see also Appendix A). It should be noted, however, that the data necessary to select a 'best' value embodied carbon coefficient for aggregates may not be achievable due to inconclusive LCA boundary conditions. However, no previous comprehensive research study has specifically attempted to evaluate influences of aggregates during stone masonry wall repair within the 'cradle-to-site' boundary of LCA.

2.11.7 Crushed Limestone and Limestone Gravel

In 2008, the University of Tennessee's *'Limestone Quarrying and Processing: A Life-Cycle Inventory'* generated embodied carbon coefficient values for limestone within the 'cradle-to-gate' boundary (University of Tennessee, 2008c). It must be noted that this estimation does not include values for 'gate-to-site' in transporting these materials from their respective resourcing location to the building site. In addition, the embodied carbon coefficient of these materials is commonly assumed to be similar to stone materials (Refer Appendix A).

2.11.8 Stainless Steel Dowels

Similarly, the embodied carbon coefficient value for stainless steel dowels is similar to stainless steel. It must be emphasised that this value is for CO_2 emissions only during the production process for steel within the 'cradle-to-gate' boundary. According to Hammond and Jones, the most common embodied carbon coefficient value for stainless steel was derived from world average data published by the Institute of Stainless Steel Forum (ISSF) for the most popular grade (304) stainless steel (Hammond and Jones, 2011) (see also Appendix A).

The majority of current embodied carbon coefficients data for stainless steel (including stainless steel dowels/rod) has been derived from the World Steel Association (formerly the International Iron & Steel Institute [IISI]) life cycle inventory (LCI) (www.worldsteel.org). It must be emphasised, though, that some of the IISI embodied carbon coefficients data has been modified to fit within the ICE framework and methodology (for example, by being converted to Gross Calorific Value) and is a purely 100% hypothetical of ‘primary steel’. In the UK, the typical embodied carbon coefficient for stainless steel was estimated from its 42.7% recycled content. In addition, most previous authors providing carbon and inventories for LCA have not estimated this breakdown, largely because the steel industry is complicated in terms of production (Hammond and Jones, 2008a, 2008b and 2011).

It must be noted that stainless steel does not have separate primary and recycled material production routes. Prior to using the embodied carbon coefficients for stainless steel, guidance on end-of-life issues for steel and recycling methodology must be read as supplementary data. To date, embodied carbon data for stainless steel value is provided largely within the ‘cradle-to-gate’ boundary only. Comparatively, their embodied carbon coefficients towards the end-of-life stage are commonly excluded in LCA.

2.11.9 Lime Grout Mix

The total embodied carbon expenditure for the usage of lime grout mix materials in repair is very much dependent upon their proportions within the mixture (ratio). With regard to stone masonry wall repair, the embodied carbon expenditure for lime grout mix materials is largely expended during their procurement processes, starting with production to transportation (‘cradle-to-site’). To date, however, there is no sufficient research providing an evaluation of embodied carbon expenditure for usage of these materials in stone masonry wall repair, particularly during the maintenance phase for historic masonry buildings.

2.11.10 Epoxy Resin

Commonly, the source for the embodied carbon coefficient value for epoxy resin is the PlasticEurope Organisation (see www.plasticseurope.org). Despite being categorised with sealants and adhesives materials, the embodied carbon coefficient data of epoxy resin is very limited. Currently, CO_2 emissions data for epoxy resin materials is available largely for the production stage within the ‘cradle-to-gate’ boundary only, while the same data for transportation within ‘gate-to-site’ remains insufficient.

Therefore, the embodied carbon expenditure arising from the usage of epoxy resin in stone masonry wall repair (common in natural stone replacement, pinning and consolidation techniques) remains to be ascertained.

2.11.11 Non-Ferrous Tying Wire

In general, the embodied carbon coefficient value for non-ferrous tying wire is similar to stainless steel (refer to Appendix A). It can be summarised that the embodied carbon expended in processing (‘cradle-to-gate’) the former (which is commonly used for tying up dowels/rods in natural stone replacement and for pinning and consolidation in stone masonry wall repair) is parallel to the latter’s production. It must be emphasised, however, that the embodied carbon coefficient value for both materials is solely for CO_2 emissions during the production process within the ‘cradle-to-gate’ boundary and does not include transportation (‘gate-to-site’).

2.12 Stone Masonry Wall Repair Techniques and Embodied Carbon Expenditure

A diverse array of variants are associated with stone masonry wall repair. The scale and quantity of materials used in repair may contribute to different results in embodied carbon expenditure (see the example of embodied carbon in a stone and brick production provided by Kennedy, (2010) and Jenkins, (2010). As historic buildings become more carbon compliant, the considerations of philosophical framework and sustainability must also be addressed. It is clear that the selection process for maintenance of, and repairs to, stone masonry walls is a function of philosophical defensibility, cost, durability and embodied carbon expenditure. Repair techniques can be selected to cater for preferences in one or more of these requirements.

Studies undertaken by the Australian CSIRO (Scientific and Industrial Research Organization) have concluded that there is a relationship between CO_2 emissions and the embodied carbon expended in the building materials manufacturing process (an average of 0.098 tonnes of CO_2 per GJ of embodied energy) (Holtzhausen, 2007). Yet, the focus of these studies remains exclusive to general building materials and does not include an embodied carbon expenditure evaluation for stone masonry wall repair materials.

2.12.1 Natural Stone Replacement

Natural stone replacement stones can be considered to be very durable when a suitably matched stone is used (BCIS, 2006), which is compatible with the underlying substrate (Hyslop, 2004). The philosophical defensibility of this technique is generally good as it enables the continuity of aesthetic integrity to be achieved, while simultaneously sustaining a workforce of traditionally-trained, craft-based operatives (Forster, 2010a; 2010b). That said, replacing natural stone can, in many cases, be considered as an unnecessarily intrusive approach as the preparation requires the removal of potentially sound stone, 'cut back' to approximately 75-100 mm (in normal cases 0.1 m) in depth and followed by an indenting process (Forster, 2010a; 2010b; Forster et al., 2011; Glasgow West Conservation Trust, 1999).

Good repairs of this nature use a lime mortar (Figure 2.10) and grouting techniques to 'fix' the stone in position for additional stability. This technique also uses secondary fixings materials (attached between the new stone and secure backing material, or several adjacent blocks tied together), mainly in the forms of stainless steels, phosphor bronze cramps or dowels set in lime mortar or epoxy grout. In most cases this can undertaken by 'building in' the stone without cramps (Forster, 2010b) (see Figure 2.11) It must be noted that the quantity of secondary fixing materials is relatively dependent upon number of block and walling area to be indented (Glasgow West Conservation Trust, 1999: 34; Historic Scotland 2007b).

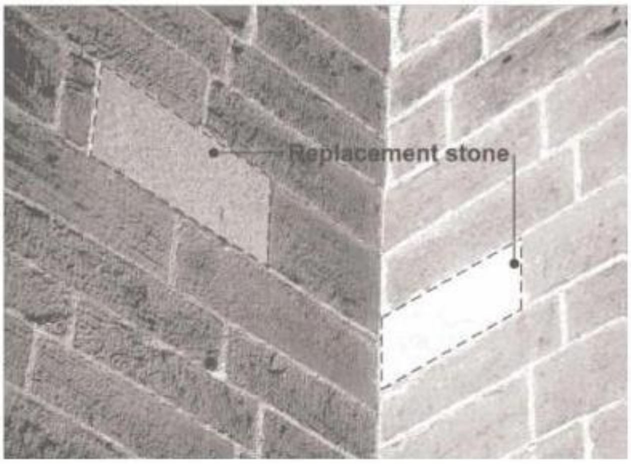


Figure 2.10: Typical example of stone replacement

Source: Forster et al., 2011.

Figure 2.11: Replacing natural stone and built in without cramps

Source: Forster, 2010b.

The embodied carbon expended in natural stone replacement repair techniques is considerable, as ‘cradle-to-site’ embodied carbon expenditure is high as a result of quarry extraction, processing and transportation. However, it must be recognised that the life expectancy of these repairs techniques is normally good, with one hundred years being a minimal value before the next replacement is required.

2.12.2 Repointing

In order to minimise the need for repointing mortar joints in stone repair contracts, a general rule of thumb is that, if a joint requires a power tool to remove mortar, it does not actually need repointing (Glasgow West Conservation Trust, 1999: 44). Repointing should only be undertaken where mortar has weathered or washed out, leaving open or deeply recessed joints vulnerable to water penetration, or where the mortar is very soft or start to become decayed or loose (Figure 2.12) from the joints and risks falling out of place (Historic Scotland 1995; 2007c; 2007d) (Figure 2.13). With regard to historic masonry buildings, lime-based mortar is the most appropriate and effective choice for stone masonry wall repointing work as it allows the wall to breathe.

Preparation of lime mortar for wall joints repointing is undertaken by 'batch' – the volume of lime and sand must be recorded accurately so that successive mixes can follow the same proportions. The successive mix can be achieved by understanding the behaviour of lime mortar and how it sets for appropriate use – by gaining this understanding and recognising that regional variations exist, the appearance of the finished work can match the original.

Figure 2.12: Loose joint of rubble stonework
Source: Historic Scotland, 2007d.

Figure 2.13: Deteriorated mortar that has ultimately led to the loosening and collapse of rubble masonry.

Source: Historic Scotland, 2007d.

This repair technique is an option for the repair of loose, open, soft, crumbly and washed-out bedding and jointing mortar in stone masonry walls (Glasgow West Conservation Trust, 1999: 44; INFORM of Historic Scotland, 2007d; Masonry Advisory Council, 2012). Using ‘cutting out’, any decayed mortar can be removed from the face of the stone masonry wall by raking to reach the position of sound mortar remains in the depth of the wall. The most common depth of decayed joints to be raked out is about two or three times the thickness or width of the original mortar joints on the surface of the wall (minimum depth of 25mm, never less than width of the joints itself and, if necessary, 38-50mm for rubble walls).

Deep joints should be filled with lime mortar tamped to a depth of 25mm from the arris and later pointed and flushed in a separate operation (Glasgow West Conservation Trust, 1999: 44; Historic Scotland, 2007d). This process starts with tamping (pushing new mortar back into the heart/core of the stone masonry wall), followed by pointing (pointing decayed mortar joints) (Figure 2.14), and may also include the pinning of loose stone (in the case of rubble stonework).

Figure 2.14: Repointing process rubble stonework
Source: Historic Scotland, 2007d.

For ashlar masonry, whatever system is employed it is important to ensure that an adequate depth of mortar is inserted into the joint and bed. Normally a minimum of 30 to 40mm would be anticipated from the raking out (Historic Scotland, 2007c).

In the case of ashlar masonry, care will essential when raking out the joints and beds, decayed mortar jointing should be removed by carefully picking it out with a thin steel hook or by easing the redundant material out by means of a hand hand-held hacksaw blade inserted into the joint and gently pulled forward. The use of chisels or power tools for raking out is generally not encouraged as they caused risk of damage to the stone (Historic Scotland, 2007c).

In the case of ashlar masonry, as the mortar starts to cure it should be tamped back with the tip of a bristle brush to eliminate any shrinkage cracks. Once it has firmed up sufficiently the mortar surface can be finished if required by lightly scraping it with a small wooden spatula or similar instrument. Where protective tape has been used this should only be removed once the mortar is sufficiently dry and before it becomes hard. In this way any disruption to the mortar caused by the removal of the tape can be pressed back into place.

The repointing of ashlar masonry with extremely narrow joints, filled with screened lime putty (Figure 2.15). It must be emphasised that this repointing requires the skilled use of specialist techniques.

Figure 2.15: Ashlar masonry lime repointing
Source: Historic Scotland, 2007c.

Comparatively, the efficiency of this repair technique in terms of embodied carbon expenditure is much less when compared to the natural stone replacement technique. Regrettably, however, the longevity of this repair technique is in the region of 25 years only (Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurt and Dimes, 1998; McMillan et al., 1999; Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al., 2003; BCIS, 2006; BRE 2010).

2.12.3 Pinning and Consolidation

Pinning and consolidation are techniques used to stabilise deteriorating masonry and are highly philosophically defensible, given that they retain the maximum amount of existing stone. In normal cases, nylon rods or stainless steel dowels are inserted into holes drilled (Figure 2.16) into delaminating layers (Figure 2.17) or detached sections of masonry, which are then fixed with modified lime grout mix (Figure 2.18). This technique can also be undertaken by filling open stress fractures and structural cracks using epoxies (Glasgow West Conservation Trust, 1999: 36).

Using this technique, the original fabric is saved and the aesthetic integrity and historic patina are retained. These repairs do not utilise a great deal of embodied carbon within the LCA ‘cradle-to-site’ boundary when compared to natural stone replacement; on the other hand, their life expectancy may be low. In addition, the quantity of stainless steel dowels and lime grout/epoxies used to repair every metre square (m^2) of wall may vary as the drilled and insertion position is significantly influenced by the delaminated wall surface. However, it must be emphasised that the usage of secondary fixing materials for this technique contributes to a high and varying embodied coefficient value. Comparatively, this repair technique has a longevity of repair in the region of 20 years. Due to its low longevity, this technique requires more maintenance intervention within the maintenance profile. Therefore, more embodied carbon is expended using this technique over a set period when compared to other repair techniques, such as natural stone replacement (which has the highest longevity of repair, 100 years or more). Additionally, this technique can be quite costly to execute due to the labour intensive nature of the process.

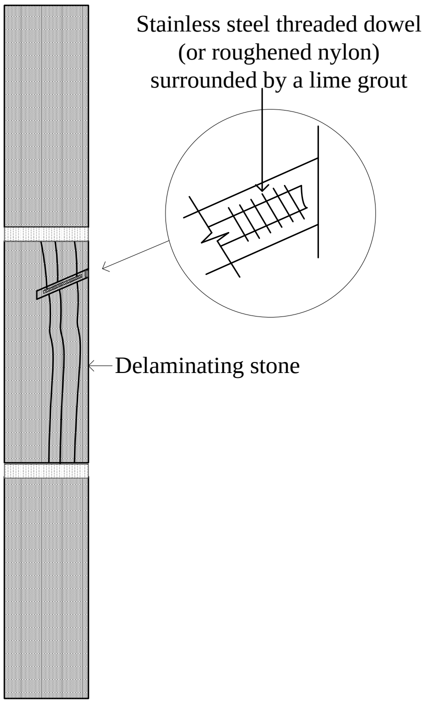


Figure 2.16: Diagrammatic representation of consolidation technique
Source: Forster, 2010b.

Figure 2.17: Delaminating argillaceous (clay rich) sandstone, Doune Castle

Source: Forster, 2010b.

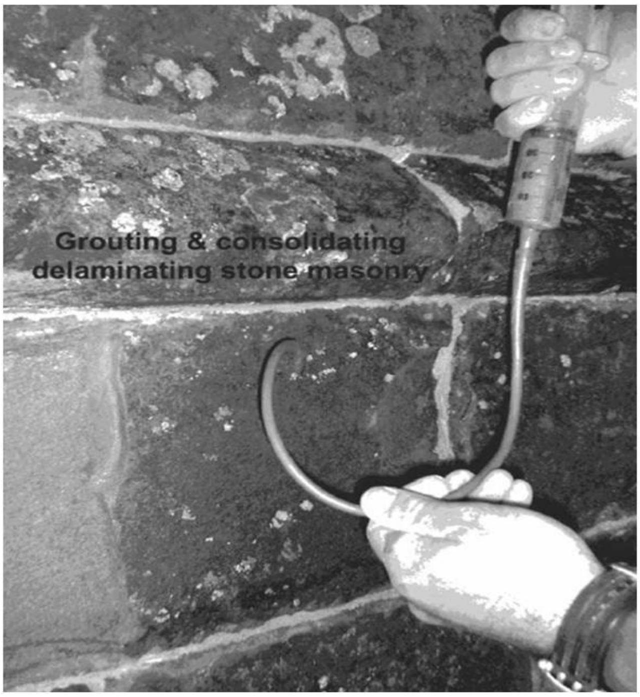


Figure 2.18: Pinning and consolidation of stone masonry

Source: Forster et al., 2011.

2.12.4 Plastic Repair

Commonly, plastic repairs are an alternative option for stone masonry walls and are characterised as a surface repair to deteriorated masonry faces (Figure 2.19). It must be emphasised that the term ‘plastic’ relates to the plasticity of the materials in application, rather than implying that they contain polymers (Ashurst and Ashurst, 1988). Using this technique, deteriorated and friable stone is ‘cut-back’ (minimum 15 mm) until a sound surface is achieved, upon which lime mortars are used to resurface the stone.

Figure 2.19: Execution of plastic repair to ashlar façade, Edinburgh.
Source: Forster, 2010b.

Comparatively, multi-layer plastic repair stonework repairs adopting these techniques, often use non-ferrous reinforcement (e.g. stainless steel dowels) set in epoxy resin or lime grout that form an armature support system (Figure 2.20).

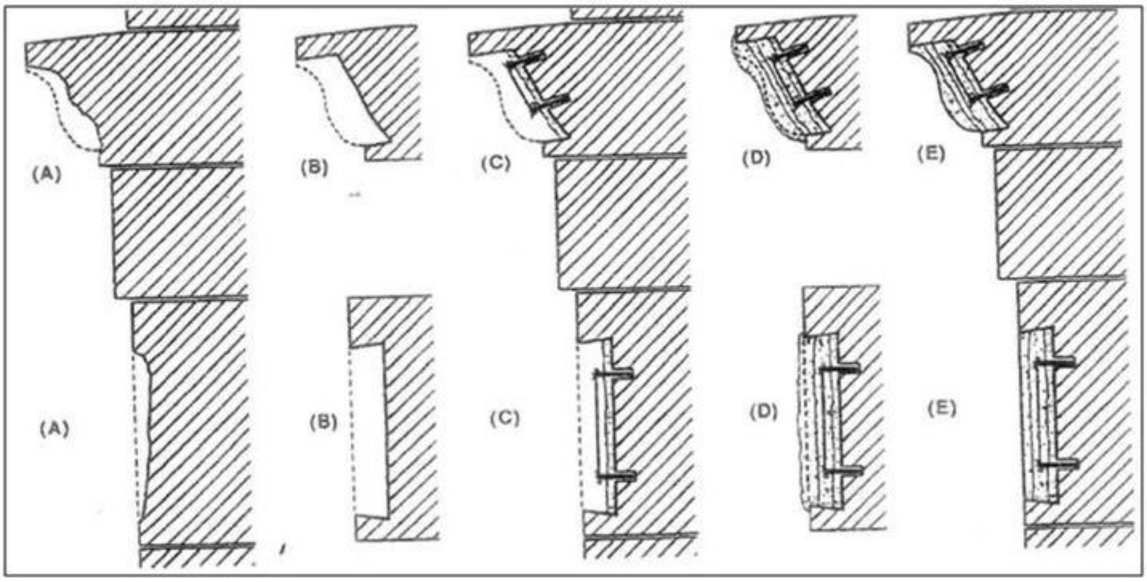


Figure 2.20: Multi-layer plastic repair using insertion of a non-ferrous armature support (metal dowels and tying wire) i.e. non-ferrous wire ties to deteriorated masonry substrate

Source: Glasgow West Conservation Trust, 1999

Note:

Firstly, the surface decay (A) should be 'cut back' until sound substrate is reached (B) with slight undercuts made top and bottom. Holes are drilled into the stone to take the threaded stainless steel dowel set in epoxy resin (C). Before the non-ferrous wire is wrapped around the dowels, the first scratch coats of lime based mortar are applied. The patch should be built up in layers no thicker than 10mm, each one scratched to form a key, and taken proud of the original surface (D). Finally, the outer layer is carefully dressed back to the original profile for a smooth surface after curing (E). Alternatively, it may be possible to run a template across the outer layer in a similar manner to the running of a plaster cornice.

During surface preparation, the cavity is to be wetted thoroughly before the preliminary undercoat is applied. Non-ferrous wire is wrapped around stainless steels dowels forming a framework that mechanically attaches the first scratch coat of lime mortar. Several layers of lime mortar (each 9 mm minimum or no thicker than 10 mm) are applied, allowing each to set partially before scoring for a key. For keying in, 6 mm holes are drilled to take the non-ferrous reinforcement [stainless pin/dowels support the multi-layer patch and are set in lime grout/epoxy resin if necessary] at approximate 50 – 100 mm centres.

The final coat may be either flush with stone surface and finished to suit (covered with clean damp fibrous fill) or brought proud of the stone edge and dressed back after setting (Glasgow West Conservation Trust, 1999: 43). It must be emphasised, however, that the quantity of secondary fixing materials used to repair every metre square (m^2) of wall may vary. The drilled and insertion position of stainless dowels and the length/quantity of tying wire are very much dependent upon the undercut decayed stone masonry wall surface/area.

Philosophically, it can be argued that these repairs techniques are highly defensible, as they enable the maximum amount of existing natural stone to be retained and are, in most cases, distinguishable from the surrounding host masonry. The ability to distinguish these repairs can also be viewed as being honest: no confusion will prevail when attempts are made to determine old from new fabric. Plastic repairs undertaken with lime as a binder, with a well-graded aggregate, have various advantages over inappropriate cement-based repairs, such as flexibility, breathability and compatibility with substrate (Banfill and Forster, 1999). Additionally, lime mortars are well known for their ability to sequester carbon to ensure their set propagation. This capability gives the material better environmental credentials when evaluated, compared to Ordinary Portland Cement counterparts. The life expectancy of these repairs are generally in the region of 30 years and so the embodied carbon expended in these repairs within the same boundary and maintenance period is commonly higher.

2.13 Operational Embodied Carbon Use

Generally, maintenance has a complex relationship with embodied carbon expenditure (CO_2 emissions). The first area that links these two is the embodied carbon expended in operational building. The second area is the subtle changes to the building fabric that occur as a result of maintenance. The primary aim of maintenance is to retain the functional state of a building; it does not necessarily intend to improve the performance of the building. However, certain aspects of the degradation of a building can relate to higher embodied carbon requirements. With regard to historic masonry buildings, this is mainly due to the ageing results and deterioration processes in stone masonry wall: gaps in the building's fabric (loose joints and pointing) lead to higher air changes and associated heat loss; wall dampness may require dehumidification; stone may be saturated as a result of defective detailing and rainwater goods, leading to reduced thermal performance through altered conductivity of the stone masonry wall materials.

Maintenance interventions can reduce or retard the rising embodied carbon expenditure. The measurement of these complicated issues adds further to the difficulty in evaluating the embodied carbon associated with maintenance. It is interesting to note that legislation to control carbon emissions and encourage the use of low carbon materials has been established in many countries. Nevertheless, they are not specifically directly targeted to reduce embodied carbon expenditure and carbon emissions in historic masonry buildings, particularly in stone masonry wall repair. Due to these setbacks, the 'Green Maintenance' model becomes more prevalent in evaluating the efficiency of repair techniques.

2.14 Summary

The literature review was a critical and comprehensive evaluation of current thinking into the primary tenets for this research. The interrelationship between maintenance, carbon accounting and materials have formed the basis of the study. It has been shown that maintenance is clearly essential for the long term sustained upkeep and conservation of historic buildings. The literature suggests that irregularities exist in the current protocols for determining embodied carbon in materials and their associated technologies. However, the long term improvement of input required will ensure greater accuracy.

Significant reductions in embodied carbon expenditure can be achieved over the lifetime of buildings. Using the maintenance records of historic masonry buildings, stone masonry wall repair efficiency can be evaluated as to how "green" it is in terms of embodied carbon expenditure. Within the selected LCA boundary and maintenance profile period, the efficiency of stone masonry wall repair in terms of embodied carbon expenditure and the Environmental Maintenance Impacts (EMI) (either singly or combined in different repair scenarios) can be evaluated and tested using the innovate concept of the 'Green Maintenance' model. The development of this new model and its testing will be discussed in greater depth in Chapter 3, but essentially it relies upon determination and understanding of the interrelationship of the longevity and the repair materials embodied carbon.

Chapter 3: Green Maintenance: A Conceptual Model

This chapter explains the underpinning concept of 'Green maintenance'. It establishes underpinning rationale and the primary components required for the model to work, including principally, materials longevity and embodied carbon of the different repair techniques. This section also established the basic formulaic expressions used for large scale analysis in the later stages of the work.

3.1 Green maintenance Model Development

Figure 3.1 illustrates the typical approximate maximum life expectancy (longevity of repair) of different repair techniques for stone masonry walls. It reveals that different stone masonry wall repair techniques have different life expectancies and, therefore, contribute to different embodied carbon expenditure.

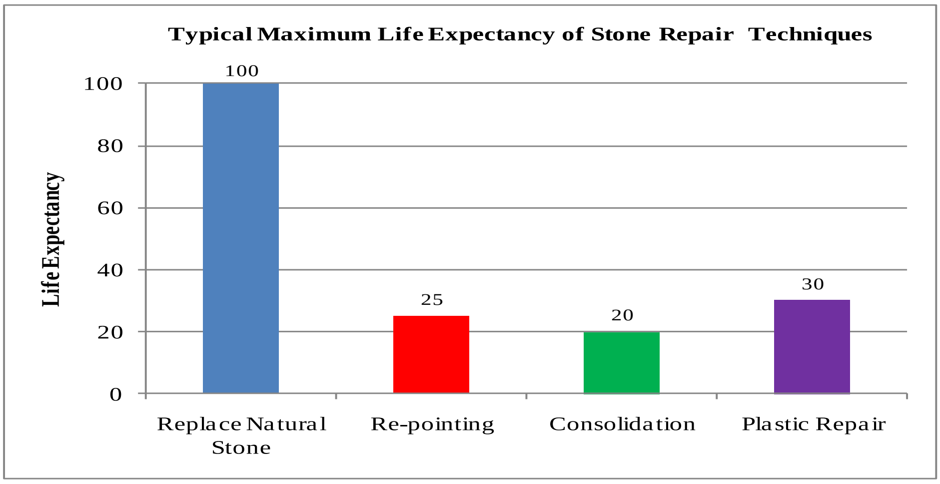


Figure 3.1: Typical approximate maximum life expectancy of different stone masonry wall repair techniques

Source: Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurt and Dimes, 1998; McMillan et al., 1999; Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al., 2003; BCIS, 2006; BRE 2010.

Note: See also http://www.maconline.org/tech/maintenance/point1/point1.html for typical re-pointing life expectancy

Figure 3.2 shows that there are implications for undertaking maintenance interventions on the service condition of buildings over time. Over the longevity of repair, the downward sloping lines signify the steady decline in building condition. Each maintenance intervention is undertaken largely to bring the building's existing structure back to its optimal service condition. However, the deterioration rate depends mainly on the repair techniques undertaken. Maintenance intervention is assumed to occur when the minimum acceptable condition for the building is reached; the saw tooth profile results from successive interventions, each extending the life of the existing structure.

With regard to historic masonry buildings, a steep gradient denotes a repair technique with a short life expectancy (lower longevity of repair, such for pinning and consolidation techniques in stone masonry wall), which can lengthen the service condition by 20 years. Comparatively, a shallow gradient equates to a durable long lasting intervention (higher longevity of repair), such as the natural stone replacement repair technique, which lasts for at least 100 years.

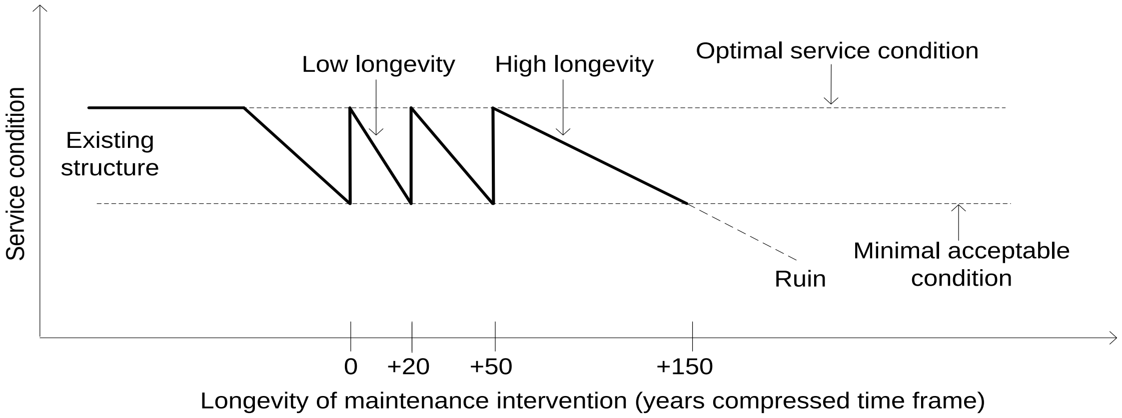


Figure 3.2: Impact of maintenance interventions on the service condition over the whole life of a buildings.

Source: Adopted from Forster, et al., 2011.

The longevity of building materials is evaluated by 'service life' predictions. 'Service life' may be defined as '*a period of time, post installation, during which all products or materials fail, achieve, or exceed the minimum acceptable performance*' (Balaras et al., 2005: 516). Commonly, the evaluation of longevity of building components appears to be ill-defined and inconclusive (Ashworth, 1996; Douglas, 1994). In general, inaccurate service life predictions are largely caused by inconsistent data pertaining to the durability of products or materials (Balaras et al., 2005). Some Estimated Service Life (ESL) predictions are unrealistic due to discrepancies in their assessment methods and process. These issues cause problems for those attempting to evaluate longevity of repairs and their influence on efficiency of repair in terms of embodied carbon expenditure.

Hammond and Jones (2008a) state that the "*UK construction industry consumes over 420 Mt of materials, 8 Mt of oil and releases over 29 Mt of carbon dioxide annually, including a significant quantity of new materials disposed of as waste*". In the UK, the amount of CO_2 emissions that construction sector can influence is significant i.e. accounting for almost 47% of total CO_2 emissions with over 80% CO_2 emissions contributed by in-use building (BSI, 2010). Considering the large stock of existing buildings in the UK (see Maintain Our Heritage, 2004), a sizeable proportion of this embodied carbon expenditure (CO_2 emissions) is attributed to maintenance interventions in existing buildings (including historic masonry buildings). According to UKGBC (2013), the construction and maintenance of buildings is responsible for around 50% of UK CO_2 emissions (UKGBC, 2013). Logically, a durable repair with higher longevity, requiring fewer repeat maintenance interventions, may incur less embodied carbon expenditure over the life span of the building than a less durable alternative.

Theoretically, the higher the value of longevity of repair, the better the technique in terms of the embodied carbon expenditure of stone masonry wall repair. Fewer interventions undertaken in repairing stone masonry walls within a selected arbitrary period contribute to lower embodied carbon expenditure. Obviously, the embodied carbon expenditure of the repairs must be evaluated using comparable, reproducible methods for this concept if they are to be of rational use. As previously discussed, maintenance attempting to achieve a reduction in embodied carbon expenditure cannot be undertaken solely on the basis of a single source of input.

In 2007, the Scottish Building Standards Agency (SBSA) adopted a mechanism to evaluate the release of embodied carbon (CO_2 emissions) within maintenance in the 'cradle-to-grave' boundary of LCA (SBSA, 2007). It could be surmised that reactive repair works will negatively impact upon the embodied carbon and energy expenditure, due to the potential for a higher degree of neglect and deterioration between maintenance interventions. In contrast, regular maintenance intervention will have a beneficial effect.

Figure 3.3 overlays the embodied carbon expenditure (CO_2 emission) for each maintenance intervention on the service condition graph. Each 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. The former is synonymous with less efficient repairs, which have lower longevity and higher embodied carbon (more CO_2 emission).

In principle, the more frequent the maintenance intervention, the higher the embodied carbon expended (more CO_2 emissions). In the case of historic masonry building repair, however, various mechanisms may exist to reduce the total CO_2 emitted. These include local sourcing of masonry repair materials, using regional companies to undertake the masonry repair work and selecting low embodied carbon materials. In order to attain low embodied carbon expenditure for stone masonry wall repair, 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). However 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 profile period, requires that an appropriate approach is taken in determining 'brown' from 'green' maintenance in historic masonry buildings.

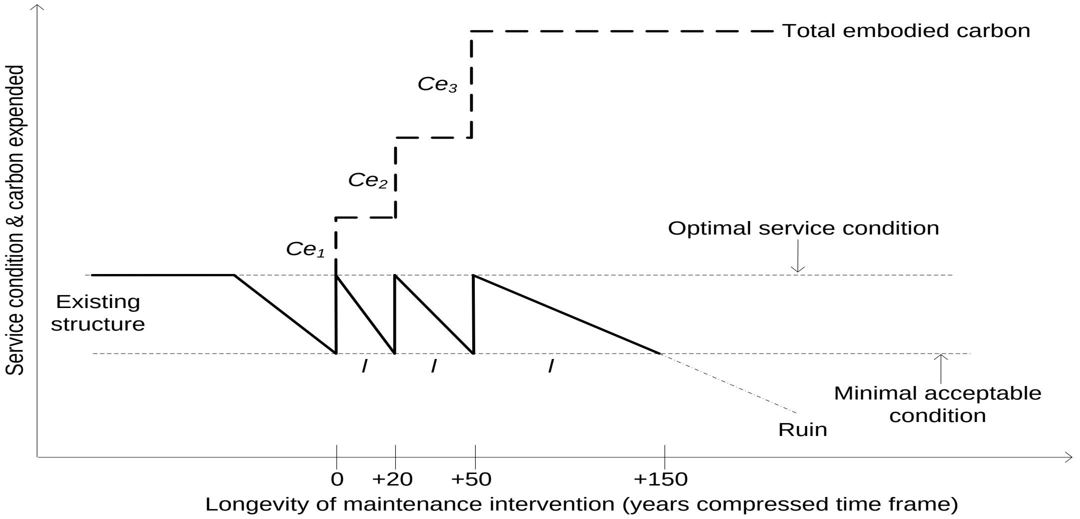


Figure 3.3: Relationship between longevity of repair and embodied carbon expenditure Source: Adopted from Forster, et al., 2011.

An appropriate boundary of LCA and maintenance profile period must be set in order to appreciate fully the Environmental Maintenance Impact (EMI). 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 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 'green' procurement. Our society is increasingly aware of the importance of selection and prioritises low embodied carbon materials. Additionally, as low carbon trading becomes more prevalent, this method of evaluation can be converted into a supplementary financial cost.

This significant concept and methodology can be developed into a new model of 'Green Maintenance'. 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 methods become more accurate, the evaluation of selected stone masonry wall repair techniques efficiency in terms of embodied carbon expenditure will have greater efficacy.

Meanwhile, it is of paramount importance to understand the embodied carbon expenditure associated with maintenance and repair; therefore, a multi-criteria approach is required. Obviously, for the 'Green Maintenance' model to be of rational use, the embodied carbon expenditure of the repairs must be evaluated using comparable, reproducible methods.

With regard to historic masonry buildings, the frequency of their maintenance interventions clearly affects their embodied carbon expenditure. It must be emphasised that the time between interventions is influenced by many variables, such as longevity of repair, resourcing and geographical location, technological development, mode of transportation used, degree of wall exposure, building and wall detailing, quality of initial work and specification.

Figure 3.4 shows how the 'Environmental Maintenance Impact' (EMI) of repair builds up. In the case of historic masonry buildings, this is the cumulative effect of maintenance interventions over the stone masonry walls' life, denoted by n1, n2 and n3. Each intervention (repair) has embodied carbon expenditure (ce) and a longevity of repair (*l*). The total embodied carbon expended by maintenance interventions through repair is illustrated by Equation No. (1).

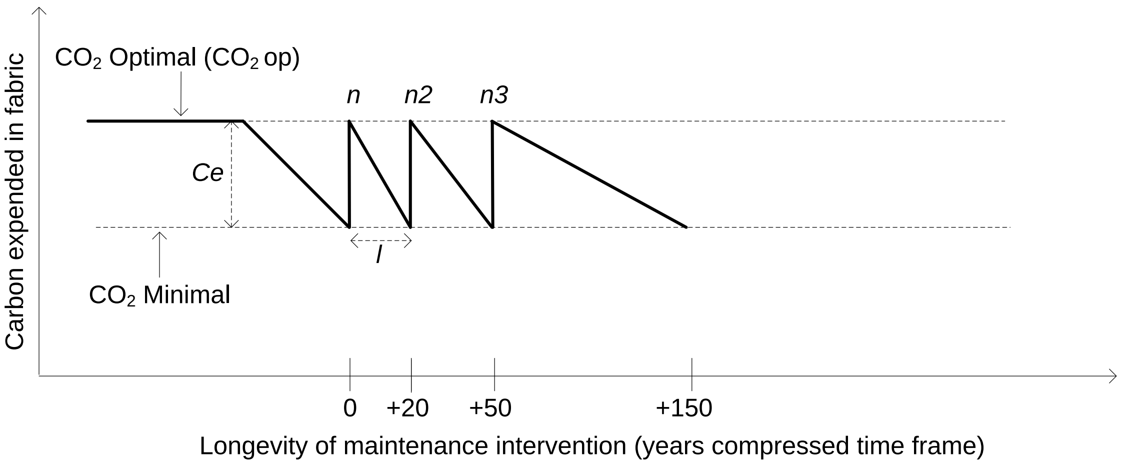


Figure 3.4: Determination of theoretical 'Environmental Maintenance Impact' (EMI) of maintenance interventions

Source: Adopted from Forster, et al., 2011.

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

Equation No. (1)

where;

n = number of interventions

ce_i = embodied carbon expenditure for the ith maintenance intervention [evaluated by within 'cradle-to-site' tools of LCA] [kgCO_2e/kg/m^2]

If we include the initial state of a building in the form of its total embodied carbon (CO_2op), the total carbon after the n^{th} intervention is given by Equation No. (2). The total carbon embodied in building structure is from the 'before use' stage, while the carbon expended in repairs is defined in the 'maintenance, repair and refurbishment' stage.

$$\textit{Total embodied carbon + carbon expended for repair} = \mathrm{CO_2op} + \sum_{i=1}^{n} ce_i$$

Equation No. (2)

Equation No. (2) correlates with the steps associated with the maintenance interventions shown in Figure 3.4. It assumes that all repairs are immediately replaced once their life expectancy (longevity of repair) has been reached. By adding the total embodied carbon expended within the maintenance interventions to the total embodied carbon in the fabric in the initial state of the building, we can determine the total embodied carbon expenditure at any point over the building's life span.

3.2 Testing the 'Green Maintenance' Model

Over time, the rate of natural deterioration in a stone masonry wall's fabric is variable. This varying rate is commonly due to different natural surface dissolution, delaminated surfaces, spalling due to freeze thaw, chemical deterioration, erosion of lime mortar pointing/plaster over time and other such factors. To fix these diverse deterioration processes in stone masonry walls, different repair techniques (either singly or using a combination in different repair scenarios) are needed.

It must be emphasised, however, that certain combinations of stone masonry wall repair are more common than others; for example, pinning and consolidation would be undertaken once, followed later by stone replacement. Practically, it would be highly unusual to pin and consolidate a plastic repair. Using the 'Green Maintenance' model, efficiency of these repair techniques (in terms of embodied carbon expenditure) can be evaluated based on their respective 'Environmental Maintenance Impact' (EMI).

Table 3.1 summarises the EMI, evaluated in terms of embodied carbon expenditure, over the 100-year maintenance profile period for each repair scenario. In each scenario, the EMI is calculated from data relating to the average embodied carbon expended for repair to 1 m^2 area of stone masonry wall within the 'cradle-to-site' boundary of LCA.

Table 3.1 shows that, of the individual interventions, stone replacement has the highest initial embodied carbon expenditure (in every 1 m^2 stone masonry wall repaired or $kgCO_2e/kg/m^2$). However, when this is placed in context of a 100-year maintenance profile period, it has the lowest EMI because of the short life expectancy of the other interventions. In particular, repeated plastic repair turns out to have a nearly a 40% higher EMI over the 100-year period than replacement stone. The results shown in this table indicate that efficiency of these repair techniques (in terms of embodied carbon expenditure) can be evaluated based on their respective 'Environmental Maintenance Impact' (EMI) using the 'Green Maintenance' model.

Table 3.1: Environmental Maintenance Impact (EMI) expended in different repair scenarios undertaken on 1 m^2 of stone masonry wall

		Scenario 1 Stone replacement	**Scenario 2** Pinning and consolidation, then stone replacement	**Scenario 3** Plastic repair	**Scenario 4** Plastic repair, then stone replacement
Stone replacement	$kgCO_2e/m^2$	36.4	36.4	-	36.4
	Number of interventions	1	0.8	-	0.7
Pinning and consolidation	$kgCO_2e/m^2$	-	13.9	-	-
	Number of interventions	-	1	-	-
Plastic repair	$kgCO_2e/m^2$	-	-	15.1	15.1
	Number of interventions	-	-	3.33	1
Total EMI	$kgCO_2e/m^2$	36.4	43.0	50.3	40.6

*Materials data derived from: Crishna et al., 2011; Hammond and Jones, 2008a, 2008b. Transport data derived from DEFRA/DECC, 2009; IFEU, 2008.

Chapter 4: Research Methods

4.1 Introduction

This chapter explains the research methods used for evaluating the efficiency of the stone masonry wall repair techniques of historic masonry buildings based upon how ‘green’ they are in terms of embodied carbon expenditure. The evaluations were made within the ‘cradle-to-site’ of Life Cycle Assessment (LCA) and selected maintenance periods. The previous chapter outlined current literature underpinning the research. Subsequently, relevant organisations responsible for the maintenance of historic masonry buildings in Scotland have also been identified and selected as collaborative partners. Collected data from these collaborative partners was then utilised to test the ‘Green Maintenance’ modelling. Finally, the ‘Green Maintenance’ model was tested using Environmental Maintenance Impact (EMI) for each stone masonry wall repair technique (single or in combination) in different scenarios within selected maintenance profiles. The testing of the research was undertaken by using a comprehensive evaluation of case studies identified from the industrial partners. The epistemological underpinning for this research is grounded in case studies that are typically associated with the use of multiple sources of evidence and a strong context (Knight and Ruddock, 2008). The documentation data provided by the companies was sufficiently complete to enable wide scale, meaningful analysis. This is clearly a pivotal consideration in determining a suitable research method and more specifically a rigorous case study approach. The number of case studies was large and therefore enabled great validity in testing the proposed model (Knight and Ruddock, 2008). Determination of the suitability of the case studies was primarily assessed on the intactness of data relating to the longevity of repairs and measurement of quantities of materials utilised over a minimum 10 year period. The gathering of key variables was essential for research success. The documents evaluated were retrieved from archival records within the three companies and were used to test the hypothesis established and the broader conceptual model (Collins, 2010).

4.2 Collaborative Partners and Efforts

Historic Scotland, National Trust for Scotland (NTS) and The City of Edinburgh Council (CEC) were selected as collaborative partners for this research. The rationale for the selection of these organisations was that they are entrusted with the maintenance of historic masonry buildings with significantly large property portfolios, across different regions of Scotland. These collaborative partners provided access to maintenance records (primary data) for stone masonry wall repairs within the 2001–10 maintenance period. In the early stages of this research, each selected collaborative partners was contacted, with their agreement and consent to collaborate being attained prior to the primary data collection process. Consequently, visits to their offices were also arranged. The visits were essentially to gain a deeper understanding of their maintenance policies and strategies, as well as determining the available stone masonry wall repair data records in their possession. It must be emphasised that comprehensive checks were undertaken on the stone masonry wall repair data supplied by the collaborative partners through a verification process. This included face-to-face interviews, either with relevant individuals or with groups, as well as acquiring an expert's opinions and judgements.

4.3 Case Studies

The selected case studies for this research were historic masonry buildings that were owned and managed by selected collaborative partners. They were 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 selected case studies all had large areas of exposed stone masonry wall elements. In addition, the stone masonry wall elements of each selected case study were different in terms of type of wall construction and stone used. Selected case studies had different localities (different local climate) and dissimilar weathering effects (rate of deterioration) in their stone masonry. 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 focal point of this research centred on how selected stone masonry wall repairs to historic masonry buildings can be achieved from the perspectives of both building conservation (Historic Scotland and National Trust for Scotland) and non-heritage organisations (e.g. Property Conservation, CEC of The City of Edinburgh Council) influenced the embodied carbon expenditure, through the use of Life Cycle Assessment (LCA). LCA evaluation for this research was mainly focused on the embodied carbon (CO_2 emissions) expended for stone masonry wall repair techniques within the 'cradle-to-site' and maintenance of ten years i.e. for the period of 2001–10 for the selected case studies (Table 4.1).

Table 4.1: Selected case studies and profile

	Collaborative Partners/Property	**Address/Location**	**Region**
No. (code)	**Historic Scotland**		
HS1	Doune Castle	Doune Castle, Castle Rd, Doune, Perthshire FK16 6EA, United Kingdom	Central and West
HS2	Melrose Abbey	Melrose Abbey, Abbey Street Melrose TD6 9LG, United Kingdom	Scottish Borders
HS3	Glasgow Cathedral	High Kirk of Glasgow, Cathedral Square, Castle Street, Glasgow G4 0QZ, United Kingdom	Glasgow, Clyde and Ayrshire
HS4	Old Palace/Palace of James V, Stirling Castle	Stirling Castle, Castle Wynd, Stirling FK8 1EJ, United Kingdom	Central and West
HS5	King's Old Building/Douglas Block, Stirling Castle	Stirling Castle, Castle Wynd, Stirling FK8 1EJ, United Kingdom	Central and West
HS6	Great Hall/Old Parliament House, Stirling Castle	Stirling Castle, Castle Wynd, Stirling FK8 1EJ, United Kingdom	Central and West
HS7	Craignethan Castle	Craignethan Castle, Lesmahagow, Lanark ML11 9PL, United Kingdom	Glasgow, Clyde and Ayrshire
HS8	Jedburgh Abbey	Jedburgh Abbey, Abbey Bridge End, Jedburgh, TD8 6JQ, United Kingdom	Scottish Borders
HS9	Linlithgow Palace	Linlithgow Palace, Kirkgate, Linlithgow EH49 7AL, United Kingdom	Edinburgh and The Lothians
	National Trust for Scotland (NTS)		
NTS1	Newhailes Estate, Stable Block	Newhailes, Newhailes Road, Musselburgh, Edinburgh & The Lothians, EH21 6RY, United Kingdom	Edinburgh and The Lothians
NTS2	Newhailes Estate, Mainhouse	Newhailes, Newhailes Road, Musselburgh, Edinburgh & The Lothians, EH21 6RY, United Kingdom	Edinburgh and The Lothians
NTS3	Culross Palace	The Palace/West Green, Dunfermline KY12 8JH, United Kingdom	Fife
NTS4	Falkland Palace	Falkland Palace & Garden, Falkland, Cupar, Fife KY15 7BU, United Kingdom	Fife
NTS5	House of The Binns	House Of The Binns, Linlithgow, Edinburgh & The Lothians EH49 7NA, United Kingdom	Edinburgh and The Lothians
NTS6	Threave House, Threave Estate-Threave Estate, Castle Douglas	Threave House, Threave Estate, Castle Douglas, Dumfries and Galloway DG7 1RX, United Kingdom	Dumfries and Galloway
NTS7	Gate Lodge, Threave Estate, Castle Douglas	Gate Lodge, Threave Estate, Castle Douglas, Dumfries and Galloway DG7 1RX, United Kingdom	Dumfries and Galloway
NTS8	Kilton Mains, Threave Estate, Castle Douglas	Kilton Mains, Threave Estate, Castle Douglas, Dumfries and Galloway DG7 1RX, United Kingdom	Dumfries and Galloway
NTS9	Harmony House/St. Cuthbert House, Melrose	Harmony Garden, St Mary's Road, Melrose, Scottish Borders, TD6 9LJ, United Kingdom	Scottish Borders
NTS10	Hamilton House, East Lothian	Hamilton House, Stanley Rd, Gullane, EH31 2AD, United Kingdom	Edinburgh and The Lothians
	The City of Edinburgh Council (CEC)		
CEC1	15 Hillside Crescent & 30-32 Hillside Street	15 Hillside Crescent, Edinburgh, City of Edinburgh EH7 5EA, United Kingdom	Edinburgh and The Lothians
		30-32 Hillside Street, Edinburgh, City of Edinburgh EH7 5HB, United Kingdom	Edinburgh and The Lothians
CEC2	15, 16, 16A, 17-19 Hillside Crescent	15, 16, 16A, 17-19 Hillside Crescent , Edinburgh, City of Edinburgh EH7 5EA, United Kingdom	Edinburgh and The Lothians
CEC3	21-31 Hillside Street	21-31 Hillside Street, Edinburgh, City of Edinburgh EH7 5HB, United Kingdom	Edinburgh and The Lothians
CEC4	22-30 Shandwick Place, Edinburgh	22-30 Shandwick Place, Edinburgh, City of Edinburgh EH2 4RT, United Kingdom	Edinburgh and The Lothians
CEC5	131-141 Bruntsfield Place, Edinburgh	131-141 Bruntsfield Place, Edinburgh, City of Edinburgh, EH10 4EB, United Kingdom	Edinburgh and The Lothians
CEC6	36-42 Forbes Road, Edinburgh	36-42 Forbes Road, Edinburgh, City of Edinburgh EH10 4ED, United Kingdom	Edinburgh and The Lothians
CEC7	4-11 Elm Row, Edinburgh	4-11 Elm Row, Edinburgh, City of Edinburgh EH7 4AA, United Kingdom	Edinburgh and The Lothians
CEC8	148-164 Bruntsfield Place, Edinburgh	148-164 Bruntsfield Place, Edinburgh, City of Edinburgh EH10 4ER, United Kingdom	Edinburgh and The Lothians
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	20-24A Frederick Street, Edinburgh,City of Edinburgh, EH2 2JR, United Kingdom	Edinburgh and The Lothians
		71-81 Rose Street, Edinburgh, City of Edinburgh EH2 3DT, United Kingdom	Edinburgh and The Lothians
		52 Rose Street Lane, Edinburgh, City of Edinburgh EH2 3DX, United Kingdom	Edinburgh and The Lothians

Source: Author, 2012.

4.4 Research Data

4.4.1 Data Evaluation and Presentation

Data evaluation and presentation for this research was undertaken as based on the following approach:

(a) Determine repair material profile used in stone masonry wall repair of historic masonry buildings and evaluate the influences on embodied carbon expenditure;

(b) Understand efficiency of stone masonry wall repair techniques for historic masonry buildings in terms of embodied carbon expenditure;

(c) Modelling 'Green Maintenance' using generated results of embodied carbon expenditure from repairs to stone masonry walls of historic buildings; and

(d) Test newly developed 'Green Maintenance' model by generation of Environmental Maintenance Impact (EMI) for historic buildings maintenance intervention, focusing on stone masonry wall repair.

4.4.2 Primary Data

Primary data for this research was collected from maintenance interventions for stone masonry wall repairs undertaken by collaborative partners, namely Historic Scotland, National Trust for Scotland (NTS) and The City of Edinburgh Council (CEC) within the 2001–10 maintenance period, in the form of historic records. The resources for this primary data are explained in the following section.

4.4.2.1 Building Maintenance Documents

Relevant maintenance documents, seen in Table 4.2, were used as primary data sources, and were available for determining any stone masonry wall repairs undertaken by collaborative partners.

Table 4.2: Primary data sources and documents availability

Documents (data comprising of stone repair works)	**Historic Scotland**	**National Trust for Scotland**	**The City of Edinburgh Council**
Works planning/programme			
(a) Building Maintenance Programme	✓	✓	✓
(b) Periodic Maintenance	✓ (4, 5 & 10 years plan)	(up to 10 years plan)	(up to 4 years plan)
(c) Yearly Works Planning	✓	✓	✓
(d) Maintenance Audit		✓	
(e) Maintenance Quality Assurance Systems	✓		
(f) Maintenance Standards Specification (including methods statement)	✓		✓
(g) Tender and Contract Documents for Stone Repair Works (including drawing and specification)	*in-house procurement	✓	✓
(h) Repair Design Report	✓	✓	
(i) Conservation Strategy	✓	✓	
(j) Conservation Plan	✓	✓	
Financial & budget planning			
(a) Maintenance Master Resources and Budget Planning	✓	✓	✓
(b) Regional Maintenance Budget Planning	✓	✓	✓
(c) Individual Building Maintenance Budget Planning	✓	✓	✓
(d) Quantity Surveyors Financial Appraisal Report (including repair cost estimates)	✓	✓	✓
(e) Final Account (including summary)	✓	✓	✓
Funding	✓	✓	✓
(a) Maintenance Plan Grants Aid Scheme	✓	✓	✓
(b) Building Repair Grants Aid Scheme	✓	✓	✓
Property database & inspection			
(a) Historical & Background (Property Statement)	✓	✓	
(b) Building Condition Survey Report (including Building Assessment/Appraisal Report)	✓	✓ (building survey)	✓
(c) Quinqennial Survey	✓	✓	
(d) Petrographic and Decay Analysis and Identification of Matching Stone (e.g. by British Geological Survey)	✓	✓	✓
(e) Mortar Analysis Report (e.g. by British Geological Survey and the Scottish Lime Centre Trust)	✓	✓	✓
(f) Engineering Reports (e.g. of Stone Masonry Wall Structure Analysis Report, etc.)	✓	✓	✓
(g) Architects Reports (including materials appraisal and matching reports)	✓	✓	✓
(h) Curators Report	✓	✓	
(i) Statutory Notices for Repairs			✓

Source: Author, 2012.

4.4.2.2 Historic Maintenance Materials Repair Records for Stone Masonry Wall

To suit the purpose of this research, a list of the historic maintenance records (such as in Table 4.2) was drawn up as means of primary data sources, based on the availability and quality criteria of each. Due to the limited number of selected collaborative partners (three organisations), only historic maintenance records of stone masonry wall repairs with similar information and quality were used as primary data sources for this research enabling comparative analysis to be undertaken.

As the evaluation of embodied carbon expenditure stone masonry wall repair of historic masonry buildings was the priority for this research, data collection mainly focused on number of interventions (n), total area repaired (m^2), repair materials used (type, mix proportion, mass, density, volume, procurement, etc.) and longevity of repair for typical mass (kg) of repair material assumptions used in every $1m^2$ of wall repaired).

In this research, repair material profiles used in stone masonry walls of historic masonry buildings have undergone their repairs based on mix/volume/weight/mass. The mass (in kilograms) used for repairing a square metre (m^2) of stone masonry wall (or kilogram per square metre of stone masonry wall repaired) was determined. Historic data and records were collected from maintenance interventions (n) (in this research, the maintenance period of 2001–10) on stone masonry walls of historic masonry buildings samples owned and under the care of selected collaborative partners.

4.4.2.3 Repair Materials Used in Repairing $1m^2$ (Per kg Data) Stone Masonry Wall

In this research, per kg data of repair materials used in repairing $1m^2$ wall were generated from ‘cradle-to-gate’ and ‘gate-to-site’ of LCA. Preparations of per kg of repair materials used were traced back, starting at their extraction, then quarrying and processing (‘cradle-to-gate’), followed by transportation to site (‘gate-to-site’). Within these boundaries, different methods of production, energy feedstocks and modes of transportation for procuring and transporting per kg of these repair materials were also determined where applicable.

4.4.2.4 Interviews

Wherever appropriate, interviews (with the relevant individuals from the aforementioned selected collaborative partners and organisations) have been undertaken as the means of determining and verifying data sources for this research.

4.4.3 Secondary Data

4.4.3.1 Longevity of Repair

The efficiency of each selected stone masonry wall repair technique, in terms of embodied carbon expenditure, was evaluated using data that indicated the longevity of the repair. Commonly, any natural stone replacement could have a life expectancy of one hundred years or more while the life expectancy for re-pointing, pinning and consolidation, and plastic repair with lime mortar, is twenty-five, twenty and thirty years respectively (Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurst and Dimes, 1998; McMillan et al. 1999; Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al. 2003; BCIS, 2006; BRE, 2010).

For the evaluation of the Environmental Maintenance Impact (EMI), 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. 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. 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. In reality, it must be emphasised that natural stone replacement commonly outlived Predicted Life of one hundred years. This is highly influenced by stone profiles as well as longevity of repair of for natural stone.

4.4.3.2 Inventory of Carbon and Energy (ICE)

Industry-generated average figures of embodied carbon coefficient values for stone masonry wall repair materials have been wherever available utilised for this research. These sources are mainly generated and are directly relevant to individual organisations, and companies. These include the carbon trust (e.g. embodied carbon coefficient value of Version 2.0 (2011) the Inventory of Carbon and Energy (ICE) by University of Bath and SISTech (Hammond and Jones, 2011) [Refer to Appendix A]. Embodied carbon coefficient values (kgCO_2e/kg) of respective stone masonry wall repair materials from this inventory were used to calculate embodied carbon expenditure for each selected repair technique within the context of 'cradle-to-gate'.

4.4.3.3 CO_2 Emission Factors

CO_2 emissions factors per kg km (for all HGVs road freight based on UK average, as published by IFEU, Defra/DECC) were applied in this research. The calculation was made to generate CO_2 emissions emitted for stone masonry wall repair materials transportation from their respective resourcing locations to building sites. Where possible, details of the rules and conventions imposed on these industry-generated supplementary data were also adopted in this research.

For this research, the embodied carbon expenditure for transporting repair materials to building site ('gate-to-site) were calculated using the updated 2008 CO_2 emission factors per tonne km (converted to kg km emission in this instance) of all HGVs' road freight (based on average vehicle loads in the UK in 2005) (IFEU, 2008; Defra/DECC, 2009) [Refer to Appendix B].

4.4.3.4 Transportation Data

For this research, embodied carbon expended in the transportation (per kilogram) of stone masonry wall repair materials was considered within the 'gate-to-site' boundary. Expended embodied carbon within this boundary was calculated based on the transportation of 1kg repair materials, mode and kg km emission factors of transport (in this case, all average HGVs in the UK) [Refer to Appendix B], and the shortest and most direct distance travelled for repair material transportation from resourcing location (quarrying or mining) to building site (in km).

For this research, the transportation distance between resourcing location and building site was considered to the nearest kilometre, with the shortest road-driving distance using land transportation (including the Channel Tunnel between Europe and the UK). This information was generated from Google Maps, with the conversion of every mile being approximately 1.609km.

It must be emphasised that the shortest materials transportation road distance was based on the assumption that the materials were transported directly to the site during the repair process. The transportation distance from the secondary resourcing location, such as a warehouse, port, airport or other point of procurement (from supplier or manufacturer), were not considered for the calculation of embodied carbon expenditure (CO_2 emissions within gate to site boundaries) of LCA for this research.

Due to issues of complexity and non-reliability, it must also be stated that further manufacturing activity for mixing of materials, for example in epoxy resin production, was not included for embodied carbon expenditure calculations for this research (for another example see Venkitachalam, 2008: 22, 40 and SISTech, 2010: 14).

4.4.3.5 Previous LCA Data Sources

Secondary data sources for this research were also gathered from previous LCA sources, including direct measurements, industrial reports, laboratory measurements, governmental and institutional documents, trade association reports and databases, national databases (i.e. statistical), economic or environmental inventories, other publically available databases, consultancies (generally commercial), academic journals (see Selmes, 2005: 96 and Menzies et al. 2007: 136 for examples), papers and books, as well as the best engineering judgments, as determined in Chapter 2: Literature Reviews. These data sources were used only where applicable for the research. In addition, whenever the data for embodied carbon coefficient values and CO_2 emissions factors per kg km of other products that constitute the main ingredients for stone masonry wall repair materials could not be derived from industry-generated data, their data was obtained from commercial databases (see Menzies et al. 2007: 136; Guinée, 2002, ix; SISTech, 2010: 6).

Meanwhile, LCA databases for secondary fixing materials, such as stainless dowels and non-ferrous tying wire, were collected from APME (the Association of Plastics Manufacturers), Plastics Europe, IAI (the International Aluminium Institute), the Nickel Institute and the International Iron and Steel Institute respectively (see Guinée, 2002: ix; Selmes, 2005: 97; Menzies et al. 2007: 136).

4.5 'Green Maintenance' Modelling

Data for longevity of repair for each selected stone masonry wall repair technique was vital to ensure accuracy of the 'Green Maintenance' model. In this research, comparisons were made to evaluate embodied carbon expended on repair for stone masonry walls of historic masonry buildings. The efficiency of each selected stone masonry wall repair technique in terms of embodied carbon energy expenditure was set against with their longevity of repair. However, it must emphasised that assumptions were made upon longevity of repair for each stone masonry wall repair technique based upon previous literature (Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurst and Dimes, 1998; McMillan et al. 1999; Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al. 2003; BCIS, 2006; BRE, 2010). Due to this, assumptions about and comparisons of longevity of repair for each selected stone masonry wall repair technique were made either in graphical form or highlighted as and when they occurred.

In the 'Green Maintenance' model, comparison of efficiency between each different repair technique is in terms of embodied carbon expenditure based on its number of intervention (n) and total repaired stone masonry wall (m^2) within selected maintenance periods i.e. 2001–10. Time between maintenance interventions (longevity of repair) is influenced by many variables, however, including material durability, degree of exposure, building detailing, and quality of repair and specification. Additionally, undertaking repairs at frequent intervals increases the risk of mechanical damage to the masonry, such as that 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. Within selected boundary of LCA and maintenance periods, the 'Green Maintenance' model for this research was tested using the Environmental Maintenance Impact (EMI) for single or a combination of repair techniques in different repair scenarios.

4.5.1 LCA for 'Green Maintenance' Model

To achieve consistency for this research, five main criteria of LCA were applied to attain the best values of embodied carbon coefficient and CO_2 emissions factors per kg km for individual materials used in stone masonry wall repairs of historic masonry buildings. The criteria were compliance with approved methodologies/standards, clearly specified system boundaries, justification for origin of data (a stronger preference was given for data from the UK), age of data and means of sources. But it must be emphasised that, although variability in LCA data sources for embodied carbon coefficient used for this research was prevalent, this did not invalidate the research. All previous work of LCA by various researchers and authors (as highlighted in Chapter 2: Literature Reviews) was undertaken within these constraints and problems. Concurrently, as improvements in the input data increased over time, the 'Green Maintenance' model operated in a realistic and accurate manner.

4.5.2 Selected 'Cradle-to-Site' Boundaries

In this research, embodied carbon expenditure for each selected stone masonry repair technique was evaluated within the 'cradle-to-site' boundary of LCA. The 'cradle-to-site' selected comprehensively took into account all stages in the life cycle of materials used for repair to stone masonry walls of historic masonry buildings, starting with quarrying, mining, manufacturing and processing, to eventual transportation to site.

It must be noted that selected boundaries of 'cradle-to-site' for this research were determined using LCA requirements [see ISO 14040 (ISO 2006a: 5)] and ISO 14044 (ISO, 2006b: 8). Additionally, this was in accordance with BRE *Methodology for Environmental Profiles of Construction Materials*, Components and Buildings (see Howard et al., 1999: 6) and was consistent with the Business-to-Business (B2B) approach outlined in PAS 2050 (British Standard Institution, 2008: 12, 16), as well as complying with ISO 14040/44 (see ISO 2006a: 5; 2006b: 8).

4.5.3 Inclusion

Calculations on embodied carbon expenditure stone masonry wall repairs for historic masonry buildings in this research included the relevant data as follows:

(a) All direct embodied carbon use from fuels and electricity at raw material extraction (embodied carbon co-efficient for quarrying, mining, manufacturing and processing); and

(b) Off-site embodied carbon (CO_2 emissions) used related to stone masonry wall repair materials transportation.

Evaluation of embodied carbon for this research included;

(a) 98% of all of materials (by mass such as lime mortar/plaster);

(b) All materials used for stone masonry wall repair repairs with a mass greater than 2%;

(c) Materials that have significant effects on embodied carbon expenditure, either at quarrying and processing (such as stone) or transportation (such as lime).

(d) Materials with a low mass, but contributing to a significant proportion of the embodied carbon expenditure (lime/limestone); and

(e) Materials outputs of brick dust/fire clay/fly ash or crushed limestone. At any stage in this research, however, if the material was assumed to be a waste (for example, certain stone masonry wall repairs by Historic Scotland have re-used waste materials from brick dust and crushed limestone at building site) then the embodied carbon expenditure value was considered as zero. If they were extracted from the same location as the primary materials (such as brick for brick dust/fire clay/fly ash), their embodied carbon expenditure is considered similar to the primary materials.

4.5.4 Exclusion

In line with PAS 2050, some sources of embodied carbon were excluded in LCA for this research, including:

(a) Embodied carbon from direct consumption of fuels for running of facilities (heating, lighting) on site (e.g. site offices, offsite, etc.);

(b) Embodied carbon used to dispose of material waste, including highly toxic and hazardous waste materials;

(c) 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);

(d) Embodied carbon in water (including water purchased from water companies and private suppliers, ground water and recycled water) that has an impracticality issue of usage on site during stone masonry wall repair activities, such as with lime mortar and plaster materials preparation;

(e) Embodied carbon of initial construction; and

(f) Embodied carbon for other stone masonry wall repair techniques due to no replacement to stone masonry wall materials (do nothing, de-scaling) and very complex embodied carbon expenditure (painting) resulting from production of paint; and

(g) Embodied carbon for capital equipment, including frequently ‘consumed’ materials used in stone quarrying and processing (e.g. stone saw blades, sand paper and mould oil).

4.6 Materials Transportation

For the purpose of this research, updated 2008 CO_2 emission factors per tonne km for all HGVs road freight (based on UK average vehicle loads in 2005) (IFEU, 2008; Defra/DECC, 2009) were used to calculate embodied carbon expended in the transportation of stone masonry wall repair materials to building sites. It was assumed that embodied carbon expended within ‘gate-to-site’ is at 132gm CO_2 emission factors per tonne km or 1.32×10^{-4}kgCO_2 per kg km emission. It must be emphasised that embodied carbon expenditure for stone masonry wall repair materials transportation was only included for direct delivery from resourcing location to building site (refer to Appendix B).

The embodied carbon expenditure for transporting materials used for repairing every 1m^2 stone masonry wall to site (for each repair technique) were generated by multiplying the mass (kg) of transported materials (for every 1m^2 wall repaired) with kg km emission factors (kgCO$_2$/kg/m^2) of road freight (in this case average UK HGVs) and distance travelled (km).

The mode of transportation used for stone masonry wall repair materials delivery from their respective resourcing locations to building sites ('gate-to-site') was solely based on one type of mode of transportation, i.e. UK Heavy Goods Vehicles (HGVs). The average gross weight in tonnes of these vehicles (over 35000 kg), their height laden (percentage), size, body type (rigid and articulated), distance travelled (in kilometres), number of deliveries [within the historic masonry buildings maintenance period (repair of stone masonry walls within 2001–10 maintenance periods)], delivery weight (in tonnes) and what is carried on the return journey (on percentage part load) were excluded in this research. An estimate of the tonnage from each delivery (such as delivery from different warehouses where more than one supplier was used) was also omitted from calculation in this research.

4.7 'Green Maintenance' Modelling: Methodological Framework

Process analysis assessment methods of LCA (process analysis (P-LCA) were adopted for the 'Green Maintenance' model in order to evaluate carbon expenditure for stone masonry walls of historic masonry buildings within the 'cradle-to-site' boundary. This research attempts to evaluate how maintenance intervention (n), total wall repaired area (m^2) and longevity of repair influenced embodied carbon expenditure using the 'Green Maintenance' model. The 'Green Maintenance' aim is to evaluate all relevant activities and materials for each selected stone masonry wall repair technique (Figure 4.1).

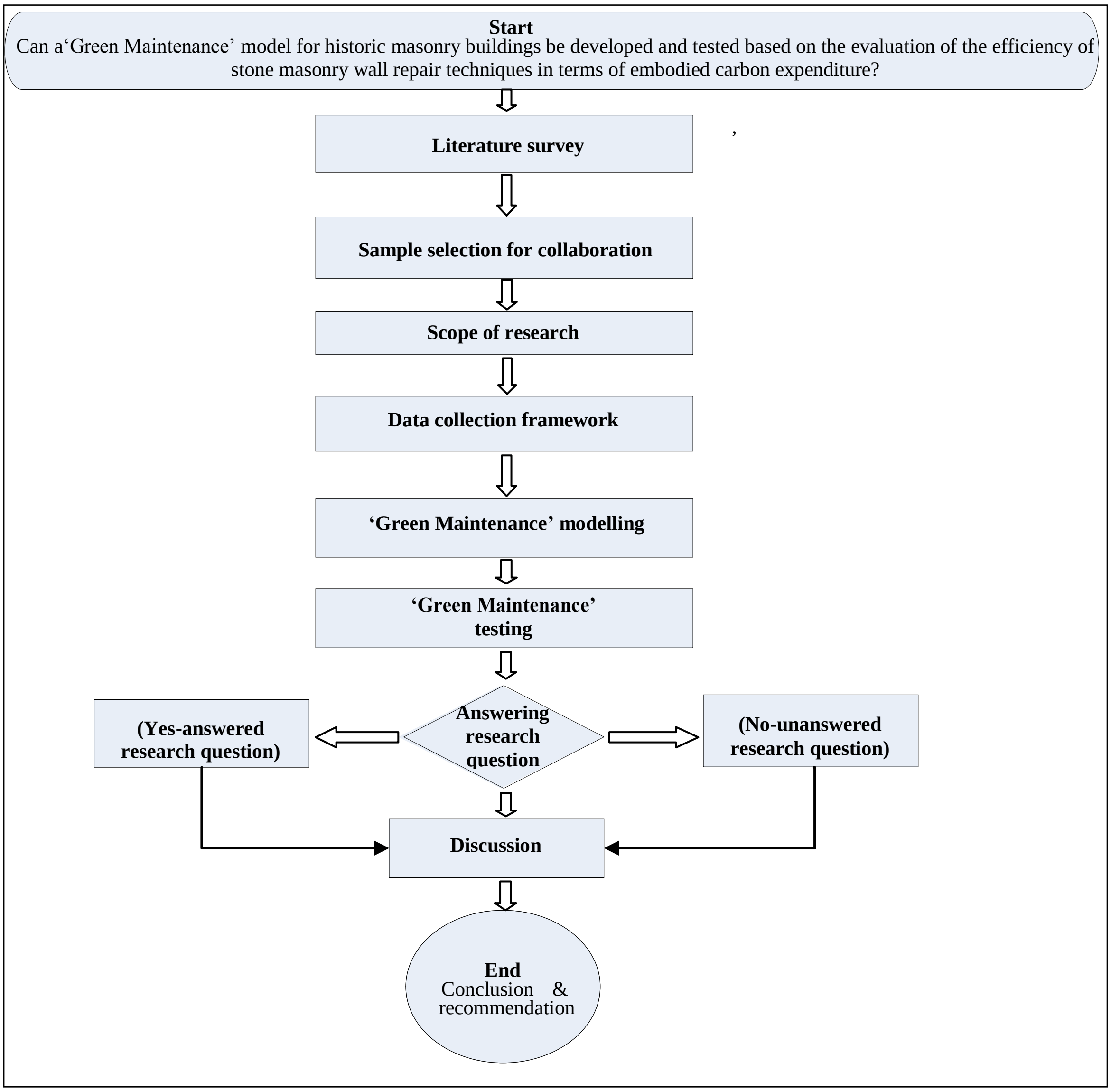


Figure 4.1: 'Green Maintenance' model methodological framework

Source: Author, 2012.

The first step of the 'Green Maintenance' model methodological framework attempted to investigate the stone masonry wall repair association with embodied carbon expenditure. In this first step, the life cycle of stone masonry walls for historic masonry buildings was represented in a repair process map (Figure 4.2). The repair processes of stone masonry walls were illustrated in a flow diagram of their life cycle, starting from their resourcing to eventual repair. Prior to mapping out the process, it must be noted that repair processes of stone masonry walls were verified by selected collaborative partners for this research. Wherever applicable, justifications were clearly stated throughout this research for any selected relevant criteria, assumptions and decisions, and inclusions or exclusions of life cycle stages of stone masonry wall repair materials for embodied carbon expenditure calculations (see Optis and Wild, 2010: 647).

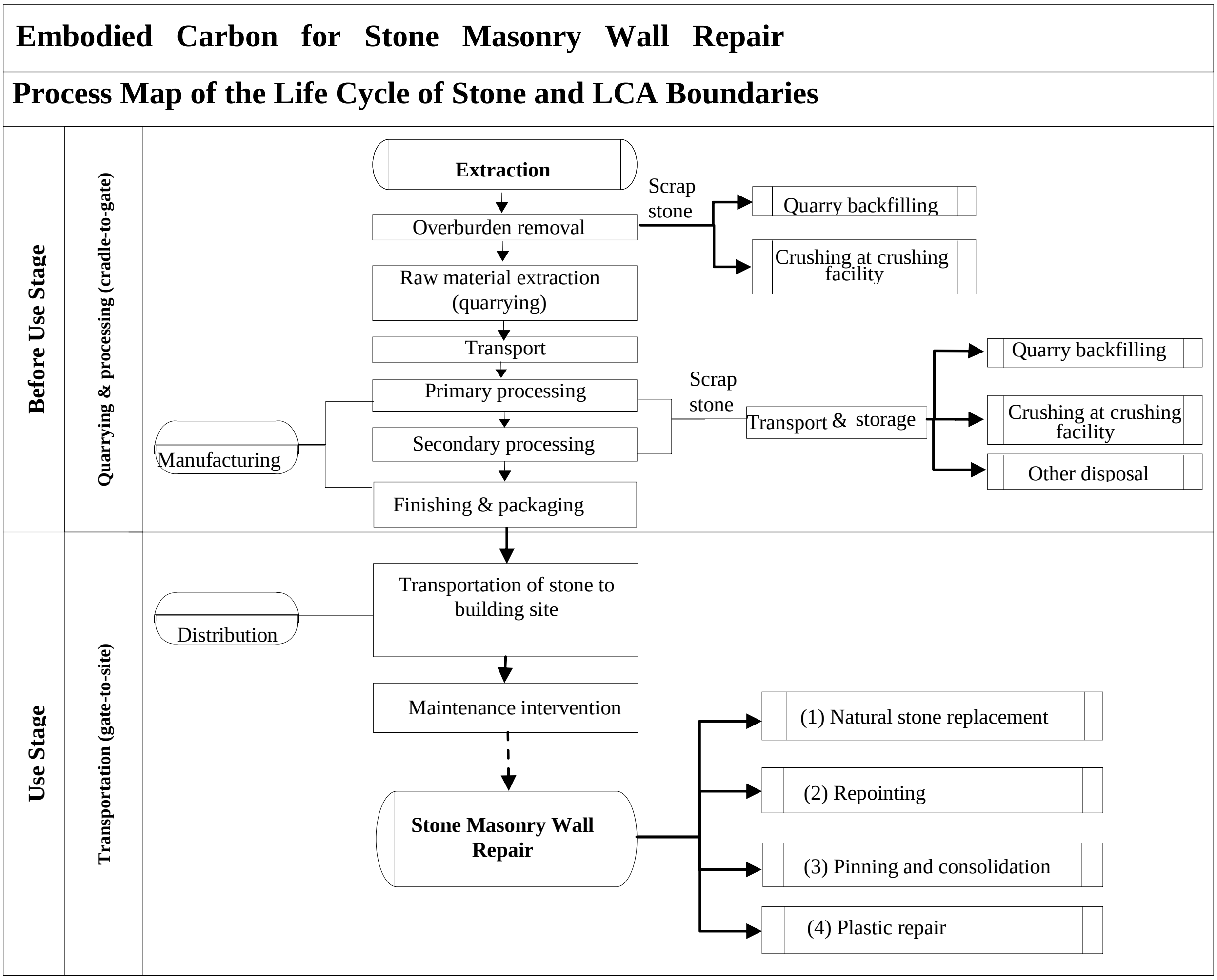


Figure 4.2: Process map of the life cycle of stone for historic buildings

Source: Author, 2012.

Efficiency of each selected stone masonry wall repair technique for this research was evaluated by determining how ‘green’ it was using normalised embodied carbon expenditure (total embodied carbon expenditure divided by total area repaired within selected maintenance periods) [(Total $kgCO_2e/kg$)/(Total m^2)] and Environmental Maintenance Impact (EMI). Different efficiencies of stone masonry wall repair techniques of historic masonry buildings (either single or combination) were tested based on their EMI. This forms the basis for ‘Green Maintenance’ methodological framework.

For this research, the Inventory of Carbon and Energy (ICE) and kg km emission factors ($kgCO_2/kg/m^2$) of road freight (average UK HGVs in this instance) were used to calculate the embodied carbon expenditure for each selected repair technique for stone masonry walls of historic masonry buildings. The rationale of using of ICE for this was that the embodied carbon coefficient data value availability for materials commonly used in the building industry was provided in the inventory. This included those frequently used in stone masonry wall repair. It must be noted that the values of embodied carbon coefficient values of ICE (refer to Appendix A) are evidently not precise when applied to a general category of stone masonry wall repair materials (for example, general cement, lime, sand and brick dust/fire clay/fly ash, etc.). Each of these materials experienced a variation in the embodied carbon coefficient value in their specific type.

4.7.1 Functional Units

Dissimilar functional units can lead to diverse LCA results (see Hischier and Reichart, 2003: 202; Kim and Dale, 2006: 11). The selection of LCA's suitable functional units was therefore of prime importance for this research. Selected functional units represent embodied carbon expenditure for repairing 1m^2 of stone masonry wall of historic masonry building (kgCO$_2$e/kg/m^2). It was defined in kilograms of carbon dioxide emissions, equivalent per kilogram of stone masonry wall repair materials or kgCO$_2$e/kg. The approximate mass (in kg) of stone used in every 1m^2 wall repaired was mainly based on bulk density value (refer to BRE Stone List) (BRE, 2010). Stone mass (kg) functional units were derived from stone dimension (length, height and width) and volume (m^3) for repairing 1m^2 stone masonry wall and were mainly used in the natural stone replacement technique. The mass (kg) of other materials was derived from the proportion mixes (such as lime mortar/grout mix/lime plaster) and usage specifications (secondary fixing materials).

4.7.2 The Selection of the Life Cycle Assessment Boundaries System

The 'cradle-to-site' LCA boundary system was selected for this research as a means for evaluating the embodied carbon expenditure for stone masonry wall repair. The evaluation was made on repair materials, beginning with the quarrying, mining, processing, manufacturing phase ('cradle-to-gate'), and extending to the transportation to building site phase ('gate-to-site'). This boundary was deemed to be consistent with the Business-to-Business (B2B) approach as outlined in PAS 2050.

4.7.3 Functional Units Application

The functional units of $kgCO_2e/kg/m^2$ were defined as embodied carbon expenditure for mass (kg) of CO_2 emission per mass (kg) of materials used over the total wall area repaired (m^2). It must be noted that, as the per kilogram of data of stone masonry repair materials within 'cradle to-site' could arise from different methods, their routes to production, or different energy feedstock, were appropriately taken into account whenever they had been deemed applicable.

4.8 Utilisation of Research Data

The primary data for this research was largely collected from maintenance records i.e. stone masonry wall repairs which had been undertaken by collaborative partners on their historic masonry buildings within a 10 year period from 2001-2010. It must be emphasised that the focus of primary data collection for this research focused on the number of interventions (n) and the total area of wall which had been repaired (m^2) within the selected maintenance period for each selected stone masonry wall repair technique. The quantity of data evaluated and the relative intactness of the data sets relating the maintenance records was achievable due to the range of the industrial partners. The intactness and accuracy of the industrial partners records enabled meaningful research outputs to be fed into the green maintenance model.

In order to determine the data quality for this research, each collaborative partner had specified their source (whether they were official maintenance and repair records or estimations). Wherever possible, relevant data on stone masonry repair materials profiles (e.g. bulk density, proportion mixes, mass (kg), volume and etc.) as well as the quantity, durability and resources were specified accordingly.

It was considered preferable to collect data from building materials, products and components which had been commonly used in the maintenance of UK historic masonry buildings. Industry-generated figures of embodied carbon coefficients for repair materials used in stone masonry walls of historic masonry buildings together with their full details of rules and conventions (either from relevant individual organisations companies or trusts) were also used as sources of research data wherever applicable.

LCA data characteristics for this research were deemed to be dependent upon their availability, quality and reliability. Therefore, supplementary secondary data sources for LCA were mainly gathered from scientific research, academic sources, from industries, the government, trading associations, national databases, economic inventories, relevant publications and professional judgements.

Various forms of LCA inventory data has been used for this work. This has provided a useful comparison tool for the evaluation of embodied carbon expenditure for stone masonry wall repair comprised of either the inclusion or exclusion of the life cycle stages; the unit process; calculation procedure and selection of the boundary system. This has included an explanation based upon the data acquisition method (measurement, calculation and assumptions); verification methods and a number of collection points, periods and representativeness. Additionally, the year of the original measurement, the geographical area, the process technology or technological level for representativeness of used LCA have been specified accordingly whenever they have been deemed applicable. It must be emphasised that relevant considerations and assumptions of LCA's have also been made whenever applicable. Supplementary data for selected boundaries were collected from sources that had been associated with the embodied carbon expenditure from both the international and local context (UK and Scotland). Discussion on the supplemental data adopted for this research will be explained in the following section.

4.8.1 Reliability of Embodied Carbon Inventories as a Reference

To date, it has been found that the applicability of data inventories for stone masonry wall repair materials remain doubtful. In addition, the reliability of these inventories as a means of reference for embodied carbon expenditure which has been expended in historic masonry buildings repair remains unclear. Additionally, discussion among the construction and building conservation organisations regarding the implications of these inventories on stone masonry wall repair remains inconclusive, as it has not been considered as a maintenance decisive factor. Therefore, sufficient consideration has been made on the best way to apply relevant inventories of this kind for this research (e.g. Inventory of Carbon and Energy (ICE) was used a means of reference.)

4.8.2 Varying Value of the Embodied Carbon Coefficient

This research have shown there to be a 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 for their quarrying or mining, manufacturing and processing. It must be emphasised that, these differences are very much related to their respective regional usage. Commonly, the greater the embodied carbon coefficients value of materials used in repair, the greater the embodied carbon expenditure (within 'cradle-to-gate'). The use of the Inventory of Carbon and Energy (ICE) as a means of reference for this research was made with sufficient consideration to its applicability and reliability.

4.8.3 Stone Masonry Wall Details Influences

The research showed that different construction types of stone masonry walls influence the quantity of materials used in their repair. Therefore it could be concluded that the greater the quantity of materials that were used, the greater the embodied carbon that was expended for repair.

Additionally, stone masonry wall exposure also influences the total embodied expenditure for stone masonry wall repair. An exposed stone masonry wall will face direct exposure to weathering effects on a constant basis and such weathering effects can cause continuous deterioration of stone masonry wall elements. The wall deterioration rate is very much dependent on its exposure. In general, the faster the deterioration rate the greater the amount of repair that has to be undertaken. Thus in terms of embodied carbon expenditure, the greater the amount of repair that is undertaken on deteriorated stone the more embodied carbon that will be expended.

The research also showed that stone masonry walls with thicker or deeper pointing joints pointing would require more lime mortar materials as opposed to thinner or shallow pointing. Thus the greater the thickness of the joints pointing; the more lime mortar materials (in mass kg) that would be needed for repair (such as in the repointing technique). In addition the greater the weight (kg) of lime mortar materials that has been used for the repointing of loose wall joints, the greater the amount of embodied carbon that would be expended.

In addition, the thicker the joint size of the stone masonry wall, the larger the surface area that would be exposed to weathering agents. This causes the deterioration of the joints pointing at a faster rate which results in an increasing amount of repointing which needs to be undertaken. Therefore, as a consequence of this, a greater amount of embodied carbon is expended within the selected maintenance period. In general, the embodied carbon which is expended on repair is also significantly influenced by their repair material profiles.

4.8.4 Repair Materials Profile Influences

Previous LCA works have shown that there are various ecotoxicology, indicators and weighing systems in the environmental profile of building materials (for example by the Building Research Establishment (BRE), Construction Industry Research and the Information Association, UK (CIRIA). With regards to buildings of particular architectural merit or historic interest such as historic masonry buildings, there has been no consensus of opinion on the appropriate benchmark of material environmental profiles, particularly for their stone masonry wall repair materials. Additionally, there has been no consensus of opinion amongst previous researchers with regards to the selection of "best values" for carbon embodiment of repair materials for these buildings.

In terms of the use of low carbon materials (the low embodied carbon coefficient value), the selection process of stone masonry wall repair materials including cement, lime, sand, brick dust/fire clay/fly ash, aggregates, crushed limestone/limestone gravel and secondary fixing materials (stainless steel dowels/rod, nylon rod, lime grout mix, epoxy resin and non-ferrous tying wire) needs to be evaluated with regards to their porosity, hygroscopic nature and flexibility.

In terms of the Environmental Maintenance Impact (EMI) and embodied carbon expenditure, these materials also need to be scrutinised with regards to minimal embodied carbon expenditure in terms of quarrying/mining, processing and manufacturing as well as the least amount of CO_2 emissions for materials transportation (preference on locally sourced materials as opposed to imported materials).

The research showed that varying strengths of stone could influence the different rates of deterioration of the stone masonry wall or their life expectancy. Thus, more durable stones would contribute to slower rates of deterioration when compared to less durable stones. This characteristic can influence the quantity of the stone (particularly for natural stone replacement techniques).

In this technique the varying value of the bulk density of stone can also influence the volume (m^3) of stone that is needed for replacement. Different bulk density also contributes towards a different mass (in kg) of stone. The greater the mass (kg) of stone that is required for repair, the greater the amount of embodied carbon that is expended for repair.

The mass (kg) and proportion mixes of other repair materials used across stone masonry wall repair techniques also influences the embodied carbon expenditure to a considerable extent.

4.8.5 Mass and Mixes of Materials Influences

The approximate mass (kg) of repair materials across stone masonry wall repair techniques is very much influenced by the proportion and mixes used in the lime mortar, lime grout mix, lime plaster and secondary fixing materials.

In the case of secondary fixing materials, their mass is associated with these types of repair techniques: usage of dowels for the indenting of stone in natural stone replacement, pinning and consolidation and multi-layer plastic repair.

However it must be emphasised that the number and mass (kg) of dowels which is used is dependent upon the number of drilled holes and the total area of the delaminated wall surface (in pinning and consolidation).

The different mass (kg) of materials which is used influences the varying embodied carbon expenditure for each stone masonry wall repair technique. Within the ‘cradle-to-gate’ boundary, the total embodied carbon which is expended on every material for each repair technique results in multiplication of their mass (kg) with their respective embodied carbon coefficient value. Normally, the greater the mass (kg) of these materials the higher their expended carbon value for repair within this boundary.

The transportation of stone (with a different mass in kg) contributes towards the embodied carbon expenditure (CO_2 emissions) within the ‘gate-to-site’ boundary. It must be noted that every mode which is used is associated with carbon emissions factors.

The research also showed that the greater the mass (kg) of stones that were required to be transported to the building site, the greater the amount of kg km emissions that were required. Meanwhile, a comparison of different characteristics of materials provided an insight for the best materials in repair in terms of their environmental impact (such as lime against cement materials).

4.8.6 Mathematical Framework

This research adopted a mathematical framework to quantify the embodied energy 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.

Primarily, the calculation procedure for this research focuses on the embodied carbon expended in stone masonry wall repairs of historic masonry buildings, particularly during the maintenance phase.

Recurring embodied carbon expended for repairing stone masonry walls was calculated within ‘cradle-to-gate’ (for quarrying, mining, manufacturing and processing) and ‘gate-to-site’ (transportation to site). While considerations regarding longevity of repair for each stone masonry wall repair technique (determining total number of maintenance interventions (n) and total area of wall repaired (m^2)) during historic buildings maintenance phases across the 2001–10 maintenance periods were undertaken, the efficiency of each repair technique in terms of embodied carbon expenditure ($kgCO_2e/kg/m^2$) was also compared by Environmental Maintenance Impact (EMI).

4.9 Calculations Procedures for 'Green Maintenance' Model

Calculations procedures for this research attempted to evaluate the embodied carbon association with maintenance interventions, i.e. stone masonry wall repair. The calculation was adopted for all the organisations (collaborative partners) in the study and creating consistency.

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.

In this research, the calculations were based on the embodied carbon expenditure to repair $1m^2$ wall for each stone masonry wall repair technique ($kgCO_2e/kg$), within the 'cradle-to-site' of LCA on a yearly basis, for the period of 2001–10. The embodied carbon expenditure expended for each stone masonry wall repair technique was then calculated by multiplying the total area of wall repaired (m^2) by the generated functional units (embodied carbon expended for repairing $1m^2$ stone masonry wall, i.e. $kgCO_2e/kg/m^2$). The overall total embodied carbon expenditure for each selected sample of historic masonry buildings within selected maintenance periods were calculated based on the total combination of embodied carbon expended for stone masonry wall repair. The 'Green Maintenance' 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. The test was formed by evaluating the influences of longevity of repair within selected maintenance profiles.

4.9.1 Cumulative Embodied Carbon Expenditure

The cumulative embodied carbon expenditure in this research was generated by multiplying the total repaired stone masonry wall area (m^2) by the embodied carbon expenditure for repairing $1m^2$ wall for each repair technique within a selected maintenance period. This also derived a value for the annual embodied carbon expended in stone masonry wall repair without ascertaining the life expectancy (longevity of repair). 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_i = embodied carbon expenditure for the ith maintenance intervention [evaluated by within 'cradle-to-site' of LCA] [$kgCO_2e/kg/m^2$]

Additionally, the efficiency of one individual stone masonry wall repair technique in terms of embodied carbon expenditure (CO_2 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. Based on this function, the efficiency of single or combination of stone masonry wall repair techniques in different repair scenarios could be compared based on their Environmental Maintenance Impact (EMI).

Emphasis must be placed on the calculation procedures for this research, which should be able to draw rational comparisons between individual and multiple cumulative maintenance interventions. Formulaic expressions, as 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 noted 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_2 emissions per mass kg of every transported repair material due to varying transportation distances. Additionally, the differences in CO_2 emissions in materials transportation was also dependant on the mode/vehicle of transport used.

In this research, 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_2 emissions for imported repair materials (such as lime) was due to the long distance between the resourcing location and building site.

Theoretically, organisation 'A' could repair a 1m^2 area of deteriorated stone masonry wall structure of a historic masonry building using different types of repair techniques. An evaluation of the embodied carbon expenditure could then be calculated for each of these repairs techniques within the selected boundary of LCA.

Through the formulaic expression in Equation No. (2), the embodied carbon expenditure was evaluated in the form of kgCO_2e/kg. This was completed by summing the embodied carbon expended in quarrying and processing ('cradle-to-gate') and CO_2 emitted in transporting repair materials to building sites ('gate-to-site') for all undertaken maintenance interventions within selected maintenance periods. Note that the calculation based on Equation No. (2) does not include major refurbishment building.

$$\textit{Total embodied carbon + carbon expended for repair} = CO_2op + \sum_{i=1}^{n} ce_i$$

Equation No. (2)

where;

CO_2op = embodied carbon expended for building operation

n = number of interventions

ce_i = embodied carbon expenditure for the ith maintenance intervention within 'cradle-to-site' [kgCO_2e/kg/m^2]

For the purpose of this research, however, only the total embodied carbon expenditure for the repair of deteriorated stone masonry during the maintenance phase (within the 2001–10 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 in this research.

4.9.2 Total Approximate of Embodied Carbon Expenditure for Repairing 1 m^2 Stone Masonry Wall (kgCO$_2$e/kg/m^2) Within 'Cradle-to-Gate'

The total approximate embodied carbon (kgCO$_2$e/kg) of mass (kg) of repair materials expended in repairing every 1m^2 area of stone masonry wall for each selected technique within 'cradle-to-gate' could be calculated using Equation No. (3):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (per\ m2\ stone\ masonry\ wall\ repaired)$$

$$\sum_{i=1}^{n} ECEcradle-to-gate\ (m2)_{i=} m_1 * ecc_1 + m_2 * ecc_2 \cdots m_n * ecc_n$$

Equation No. (3)

where;

m_n = mass (kg) of materials used in every 1m^2 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 1m^2 stone masonry wall repaired within 'cradle-to-gate'

4.9.3 Total Approximate of Embodied Carbon Expenditure for Transporting Repair Materials Used in Repairing 1m^2 Stone Masonry Wall Within 'Gate-to-Site'

The total approximate embodied carbon (kgCO$_2$e/kg) for transportation of mass (kg) repair materials used in repairing every 1m^2 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):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (per\ m2\ stone\ masonry\ wall\ repaired)$$

$$\sum_{i=1}^{n} ECEgate-to-site\ (m2)_i = m_1 * ef_1 * km_1 + m_2 * ef_2 * km_2 \cdots m_n * ef_n * km_n$$

Equation No. (4)

where;

m_n= mass (kg) of materials used in every 1m^2 stone masonry wall repaired transported from resourcing location to building site

ef_n = emission factors per kg km 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 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)

4.9.4 *Embodied Carbon Per m^2 Wall Repaired ('Cradle-to-Gate')*

The total approximate embodied carbon (kgCO_2e/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):

$$\begin{gathered}Embodied\ Carbon\ Per\ m2\ (for\ every\ m2\ stone\ masonry\ wall\ repaired)\\ \sum_{i=1}^{n} ECEcradle-to-gate_i = {m^2}_1 * ECEcradle-to-gate\ (m2)_1 + {m^2}_2\\ * ECEcradle-to-gate\ (m2)_2 \ldots {m^2}_n * ECEcradle-to-gate\ (m2)_n\end{gathered}$$

Equation No. (5)

where;

m^2_n = area (m^2) of stone masonry wall repaired using relevant repair techniques

ECEcradle-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.

4.9.5 *Embodied Carbon Per m^2 Wall Repaired ('Gate-to-Site')*

Total approximate embodied carbon (kgCO_2e/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):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (for\ every\ stone\ masonry\ wall\ area\ repaired)$$

$$\sum_{i=1}^{n} ECEgate-to-site_i\ = m^2{}_1 * ECEgate-to-site\ (m2)_1 + m^2{}_2 * ECEgate-to-site\ (m2)_2 + \cdots m^2{}_n * ECEgate-to-site\ (m2)_n$$

Equation No. (6)

where;

$m^2{}_n$ = area (m^2) of stone masonry wall repaired using relevant repair technique

ECEgate-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)]

4.9.6 Total Embodied Carbon Per m^2 (‘Cradle-to-Site’)

The total approximate embodied carbon ($kgCO_2e/kg$) 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):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (for\ total\ area\ of\ stone\ masonry\ wall\ repaired)$$

$$\sum_{i=1}^{n} ECEcradle-to-site_i = m^2{}_1 * ECEcradle-to-site\ (m2)_1 + m^2{}_2 * ECEcradle-to-site\ (m2)_2 + \cdots m^2{}_n * ECEcradle-to-site\ (m2)_n$$

Equation No. (7)

where;

$m^2{}_n$ = area (m^2) of stone masonry wall repaired using relevant repair technique

ECEcradle-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)]

4.9.7 Functional Units of Embodied Carbon Per m^2 (kgCO$_2$e/kg/m^2)

The total embodied carbon per m^2 (kgCO$_2$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):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (per\ 1\ m2\ stone\ masonry\ wall\ repaired)$$

$$= \sum ECEcradle-to-site\ (m2)_{n=} ECEcradle-to-gate\ (m2)_n + ECEgate-to-site\ (m2)_n$$

Equation No. (8)

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 [generated from Equation No.(5)]

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 [generated from and Equation No. (6)]

4.9.8 Total Embodied Carbon Expenditure for Stone Masonry Wall Repair Within ('Cradle-to-Gate')

The total embodied carbon ($kgCO_2e/kg$) 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):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (for\ total\ area\ of\ stone\ masonry\ wall\ repaired)$$

$$\sum_{ti=1}^{n} ECEcradle - to - gate_{ti} = m^2{}_{t1} * ECEcradle - to - gate\ (m2)\ _{t1} + m^2{}_{t2} * ECEcradle - to - gate\ (m2)\ _{t2} + \cdots m^2{}_{tn} * ECEcradle - to - gate\ (m2)_{tn}$$

Equation No. (9)

where;

$m^2{}_{tn}$ = area (m^2) of stone masonry wall repaired using relevant repair technique (*tn*)
ECEcradle-to-site $(m^2)_{tn}$ = 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)]

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

The total embodied carbon ($kgCO_2e/kg$) 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):

$$\text{Total approximate of embodied carbon expenditure (for total area of stone masonry wall repaired)}$$

$$\sum_{ti=1}^{n} ECEgate-to-site_{ti} = m^{2}{}_{t1} * ECEgate-to-site\ (m2)\ _{t1} + m^{2}{}_{t2} * ECEgate-to-site\ (m2)\ _{t2} + \cdots m^{2}{}_{tn} * ECEgate-to-site\ (m2)_{tn}$$

Equation No. (10)

where;

$m^2{}_{tn}$ = area (m^2) of stone masonry wall repaired using relevant repair technique (*tn*)

$ECEgate\text{-}to\text{-}site\ (m^2)_{tn}$ = 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)]

4.9.10 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):

$$\text{Overall total of embodied carbon expenditure}$$

$$\sum_{ti=1}^{n} ECEcradle-to-site_{ti} = [ECEcradle-to-gate\ _{t1} + ECEgate-to-site\ _{t1}] + [ECEcradle-to-gate\ _{t2} + ECEgate-to-site\ _{t2}] \ldots [ECEcradle-to-site\ _{tn} + ECEgate-to-site\ tn]$$

Equation No. (11)

where;

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

$ECEcradle\text{-}to\text{-}gate_{tn}$ = 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)]

$ECEgate\text{-}to\text{-}site_{tn}$ = 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)]

4.9.11 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):

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

Equation No. (12)

where:

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

$ECEcradle\text{-}to\text{-}site_{tn}$ = 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)]

As previously mentioned, the majority of the data for this research was collected from collaborative partners. The calculation procedures represent the evaluation of the Environmental Maintenance Impact (EMI) of the materials used in repairing stone masonry walls of historic masonry buildings (see Environmental Maintenance Impact (EMI) in Harris, 1999: 752). Using the generated EMI for each single repair or combination of stone masonry wall techniques in different repair scenarios was sufficiently rigorous to enable the testing of the ‘Green Maintenance’ model.

4.10 Testing the ‘Green Maintenance’ Model

Testing the ‘Green Maintenance’ model was undertaken by comparing the embodied carbon expended with either a single or combination of stone masonry wall repair techniques in different repair scenarios, based on their Environmental Maintenance Impact (EMI) within selected maintenance profiles (in this research, over a hundred years).

Four repair scenarios were compared based on their Environmental Maintenance Impact (EMI), including natural stone replacement, pinning and consolidation followed by replacement, repeated plastic repair and single plastic repair followed by stone replacement. Details of different repair scenarios compared are explained as follows:

4.10.1 Scenario 1: Replacement

Natural stone replacement was assumed to require the cutting back or indenting of approximately 100mm (0.1m) or 0.10m^3 of volume (1m x 1m x 0.1m = 0.10m^3) of the defective material in natural stone. This 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 research, 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).

4.10.2 Scenario 2: Repeated Repointing

Repeated repointing is common in repairing loose, open, soft, crumbling or washed out bedding and jointing mortar in stone masonry walls. For this repair scenario, lime-based mortar was encouraged as it lets the wall breathe. 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). 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). Repeated repointing intervention is commonly reapplied every twenty-five years (five times of intervention in a hundred selected specified periods).

4.10.3 Scenario 3: Pinning and Consolidation, Followed by Stone Replacement

In general, pinning and consolidation 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 research, 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). 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. The replacement stone will last beyond the hundred years and so only 0.8 of its EMI was attributed to the study period.

4.10.4 Scenario 4: Repeated Plastic Repair

Under the repeated plastic 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. 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. Meanwhile, a minimum depth of 40mm were 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. Commonly, the intervention was reapplied every thirty years (3.33 times in the hundred-year study period).

4.10.5 Scenario 5: Single Plastic Repair Followed by Stone Replacement

In contrast to scenario four, if deterioration had occurred to the substrate forming the base of the plastic repair, it is necessary to cut back the natural stone further. This prevented repeated plastic repairs due to the build up of excessive thickness. In this scenario, the plastic repair and the decayed natural stone is assumed to be removed after thirty years and new stone built in to a depth of 100mm. As with scenario three, the replacement stone will last beyond the hundred-year study period. Therefore, only 0.7 of its EMI was attributed to the study period.

An estimated longevity of repair for stone masonry wall repairs techniques was based on life expectancy data. Within selected maintenance profiles of one hundred years, the number of maintenance interventions (n) will be a function of life expectancy of each selected repair technique (see BGS, 2008) and the EMI is diagrammatically represented in Figure 4.3.

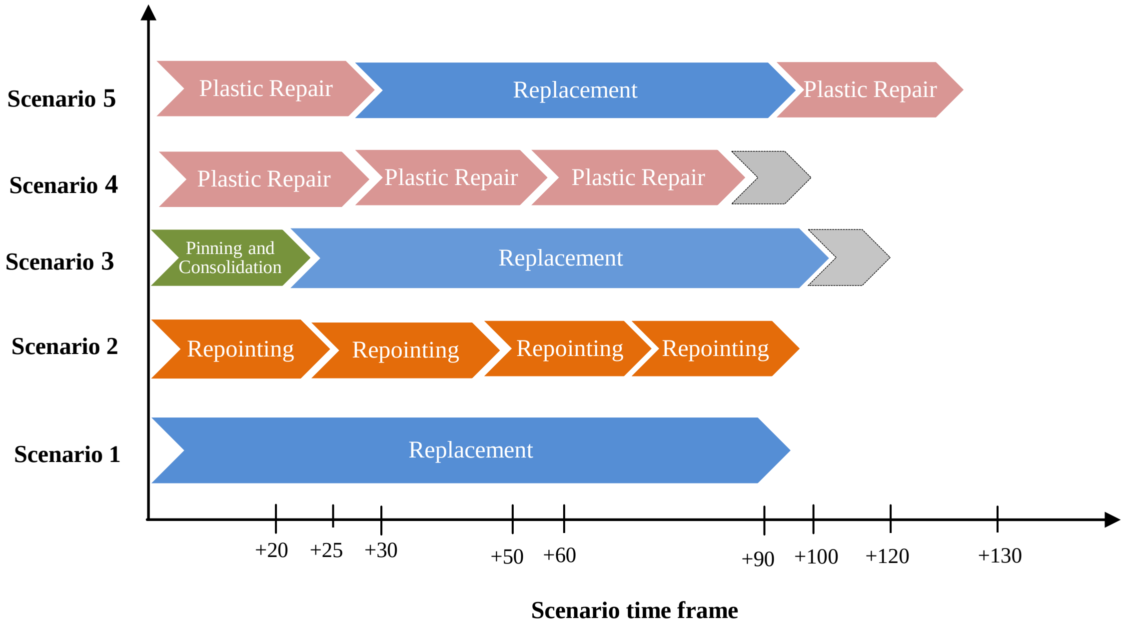


Figure 4.3**:** Repair scenarios

Source: Adopted from Forster, et al. 2011.

Within the hundred-year period, the total embodied carbon expenditure for either single or a combination of repair techniques in different repair scenarios or Environmental Maintenance Impact (EMI) in the stone masonry wall structure 'cradle-to-site' could be expressed as Equation No. (13):

$$\begin{aligned} &Total\ \ of\ environmental\ maintenance\ impact\ (EMI)\ (100\ years) \\ &\qquad = \sum_{ti=1}^{n} EMIcradle-to-site_{tn}\ \ = EMIcradle-to-site_{\ t1} \\ &\qquad + \ EMIcradle-to-site_{\ t2} \ldots EMIcradle-to-site_{\ tn} \end{aligned}$$

Equation No. (13)

where;

$_{tn}$ = either single or a combination of repair techniques in different repair scenarios or techniques (t_n) for one hundred years of maintenance profile periods

$EMIcradle\text{-}to\text{-}site_{tn}$ = total embodied carbon expenditure for quarrying/mining, processing and manufacturing and transporting of repair materials used in repairing stone masonry walls of historic masonry, using either single or a combination of repair techniques in different repair scenarios within one hundred years of maintenance profile periods within the 'cradle-to-site' boundary [generated from Equation No. (12)]

It must be emphasised that certain combinations of stone masonry wall repair are more common than others, 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.

4.11 Overall Total of Normalised Embodied Carbon Expenditure [(Total kgCO$_2$e/kg/)/(Total m^2) for the 2001–10 Maintenance Periods Within '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 1m^2 stone masonry walls for each selected technique within 'cradle-to-site' and selected maintenance periods could be calculated using Equation No. (14):

$$Overall\ Total\ Normalised\ embodied\ carbon\ expenditure\ (for\ 1\ m^2\ stone\ masonry\ wall\ repaired)$$

$$= \sum ECEcradle-to-site_{m^2} = ECEcradle-to-gate_{\ m^2} + ECEgate-to-site_{\ m^2}$$

Equation No. (14)

where;

ECEcradle-to-site$_{m}{}^{2}$ = embodied carbon expenditure value for quarrying/mining, processing and manufacturing and transporting repair materials used in repairing 1m^2 stone masonry walls using selected repair techniques for the 2001–10 maintenance periods within the ‘cradle-to-site’ boundary [generated from Equation No. (7)]

4.12 Summary

It can be summarised that the efficiency of each stone masonry wall repair technique for historic masonry buildings can be evaluated in terms of embodied carbon expenditure. Based on the number of interventions (n), total wall repaired (m^2), evaluation of the embodied carbon expenditure for stone masonry walls of historic masonry buildings for the ‘cradle-to-site’ and selected maintenance period can be evaluated based on the ‘Green Maintenance’ model. This can be evaluated using the embodied carbon coefficient value and kg km emission factors for quarrying, mining, manufacturing, processing and transportation respectively. This model can be tested within selected boundaries and maintenance periods by comparing the embodied carbon expended by either a single or combination of stone masonry wall repair techniques in different repair scenarios, based on their Environmental Maintenance Impact (EMI).

Chapter 5: Data Analysis - Results

5.1 Introduction

This chapter analyses the results of embodied carbon expenditure for stone masonry wall repairs within ‘cradle-to-site’ Life Cycle Assessment during selected maintenance periods. Test results on the applicability of the ‘Green Maintenance’ model are also generated, based on the use of ‘green’ selected stone masonry wall repair techniques for historic masonry wall buildings using Environmental Maintenance Impact (EMI).

5.2 Stone Masonry Wall Details

Table 5.1 shows the stone masonry wall details for selected sample properties. It was found that details vary in terms of construction type, exposure, type of stone used and the pointing thickness of joints depending on both function and appearance. Dissimilar construction types of wall contribute to the different use of repair materials of different profiles. Additionally, the use of materials of different profiles for stone masonry wall construction result in varying embodied carbon expenditure for repair. This is due to differences in their embodied carbon coefficient and the kg/km emissions factor value expended for quarrying, mining, processing and manufacturing and transportation to the site.

Exposed wall (external wall) is commonly highly affected by weathering effects and generally has a faster degradation rate. It must be noted that the faster the rate of degradation, the greater the amount of maintenance intervention needed. As the amount of maintenance intervention increases, more embodied carbon is expended on repair.

Meanwhile, the quantity of lime mortar materials used in wall pointing is very much dependent on the thickness of joints. In general, the deeper and thicker the pointing joints, the greater the amount of lime mortar materials that will be used in stone masonry wall repointing. Subsequently, the greater quantity of materials used (in this case mass kg of lime mortar, grout mix and lime plaster materials), the greater the amount of embodied carbon expended for repair.

Table 5.1: Stone masonry wall details

		Masonry wall details (existing)			
	Collaborative partners/property	**Construction (type of wall) (Glasgow West Conservation Trust, 1999; http://www.lime-mortars.co.uk/calculators/mortar)**	**Exposure* (external wall)**	**Type of stone (BRE Stone List, 2010)**	**Joints pointing (thickness in mm)**
No. (code)	**Historic Scotland**				
HS1	Doune Castle	Rubble wall with standard block stone	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (Historic Scotland, 2006)
HS2	Melrose Abbey	Rubble wall with standard block stone	Exposed	Red Copp-Crag Sandstone	5-10 mm (Historic Scotland, 2005)
HS3	Glasgow Cathedral	Rubble wall with standard block stone	Exposed	Dunhouse Buff	5-10 mm (Historic Scotland, 2005)
HS4	Old Palace/Palace of James V, Stirling Castle	Mix of ashlar and rubble wall with standard block stone	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (Historic Scotland, 2005)
HS5	King's Old Building/Douglas Block, Stirling Castle	Mix of ashlar and rubble wall with standard block stone	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (Historic Scotland, 2007)
HS6	Great Hall/Old Parliament House, Stirling Castle	Mix of ashlar and rubble wall with standard block stone	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (Historic Scotland, 2006)
HS7	Craignethan Castle	Rubble wall with standard block stone	Exposed	Clashach Sandstone	5-10 mm (Historic Scotland, 2005)
HS8	Jedburgh Abbey	Rubble wall with standard block stone	Exposed	Caithness Flagstone	5-10 mm (Historic Scotland, 2006)
HS9	Linlithgow Palace	Rubble wall with standard block stone	Exposed	Caithness Flagstone	5-10 mm (Historic Scotland, 2007)
	National Trust for Scotland (NTS)				
NTS1	Newhailes Estate, Stable Block	Rubble wall with ashlar dressing using standard block stone in 300 -600 mm course	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (NTS, 2009)
NTS2	Newhailes Estate, Mainhouse	Ashlar wall using standard block stone in 300 mm height course	Exposed	Red Copp-Crag Sandstone	3-12 mm (NTS, 2005)
NTS3	Culross Palace	Ashlar wall using standard block stone in 300 mm height course	Exposed	Dunhouse Buff	5-10 mm (NTS, 2004)
NTS4	Falkland Palace	Ashlar wall using standard block stone in 300-600 mm height course	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (NTS, 2004)
NTS5	House of The Binns	Ashlar wall using standard block stone in 300-600 mm height course	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (NTS, 2003)
NTS6	Threave House, Threave Estate-Threave Estate, Castle Douglas	Ashlar wall using standard block stone in 300 mm height course	Exposed	Dunhouse Sandstone (Catcastle Grey)	5-10 mm (NTS, 2003)
NTS7	Gate Lodge, Threave Estate, Castle Douglas	Ashlar wall using standard block stone in 300 mm height course	Exposed	Clashach Sandstone	5-10 mm (NTS, 2002)
NTS8	Kilton Mains, Threave Estate, Castle Douglas	Ashlar wall using standard block stone in 300 mm height course	Exposed	Caithness Flagstone	5-10 mm (NTS, 2004)
NTS9	Harmony House/St. Cuthbert House, Melrose	Ashlar wall using standard block stone in 300 mm height course	Exposed	Caithness Flagstone	3-12 mm (NTS, 2004)
NTS10	Hamilton House, East Lothian	Ashlar wall using standard block stone in 300-600 mm height course	Exposed	Stainton Sandstone	5-10 mm (NTS, 2004)
	The City of Edinburgh Council (CEC)				
CEC1	15 Hillside Crescent & 30-32 Hillside Street, Edinburgh	Ashlar wall using standard block stone in 300 mm height course	Exposed	Doddington Sandstone	3-12 mm (CEC, 2008)
CEC2	15, 16, 16A, 17-19 Hillside Crescent , Edinburgh	Ashlar wall using standard block stone in 300 mm height course	Exposed	Doddington Sandstone	3-12 mm (CEC, 2008)
CEC3	21-31 Hillside Street, Edinburgh	Ashlar wall using standard block stone in 300 mm height course	Exposed	Doddington Sandstone	3-12 mm (CEC, 2009)
CEC4	22-30 Shandwick Place, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	Dunhouse Sandstone (Buff-Pale)	3-12 mm (CEC, 2008)
CEC5	131-141 Bruntsfield Place, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	(Type A) Stainton Sandstone	3-12 mm (CEC, 2007)
		Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	(Type B) Dunhouse Sandstone (Buff-Pale)	3-12 mm (CEC, 2007)
CEC6	36-42 Forbes Road, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	Stainton Sandstone	3-12 mm (CEC, 2007)
CEC7	4-11 Elm Row, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300 mm height course	Exposed	Peakmoor Sandstone	3-12 mm (CEC, 2009)
CEC8	148-164 Bruntsfield Place, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	Stainton Sandstone	3-12 mm (CEC, 2003)
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	Mix of ashlar and rubble wall using standard block stone in 300-600 mm height course	Exposed	Stanton Moor Sandstone	3-12 mm (CEC, 2003)
Notes:	*External wall				

Source: Author, 2012.

5.3 Profile of Stone Masonry Wall Repair Materials

Table 5.2: Profile of **s**tones (for the natural stone replacement technique)

		Natural stone used for replacement		**Resourcing details**	
	Collaborative partners/property	**Type of Stone (BRE Stone List, 2010)**	**Bulk density (kg/m^3) (BRE Stone List, 2010)**	**Resourcing location**	**Distance to building site (nearest km) ≈ 1 mile = 1.609 km (Google Map, 2011)**
No. (code)	**Historic Scotland**				
HS1	Doune Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	Cleatleam, Darlington, Co. Durham, England	233.31
HS2	Melrose Abbey	Red Copp-Crag Sandstone	2186.00	Staindrop, Darlington, Co. Durham England	152.37
HS3	Glasgow Cathedral	Dunhouse Buff	2202.00	Darlington, Co. Durham, England	210.78
HS4	Old Palace/Palace of James V, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	Cleatleam, Darlington, Co. Durham, England	233.31
HS5	King's Old Building/Douglas Block, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	Cleatleam, Darlington, Co. Durham, England	233.31
HS6	Great Hall/Old Parliament House, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	Cleatleam, Darlington, Co. Durham, England	233.31
HS7	Craignethan Castle	Clashach Sandstone	2084.00	Birnie, Elgin, Moray, Scotland	296.06
HS8	Jedburgh Abbey	Caithness Flagstone	2684.00	Spittal Quarry, Caithness, Scotland	485.92
HS9	Linlithgow Palace	Caithness Flagstone	2684.00	Spittal Quarry, Caithness, Scotland	405.47
	National Trust for Scotland (NTS)				
NTS1	Newhailes Estate, Stable Block	Dunhouse Sandstone (Catcastle Grey)	2220.00	Barnard Castle, Co. Durham, England	199.52
NTS2	Newhailes Estate, Mainhouse	Red Copp-Crag Sandstone	2220.00	Barnard Castle, Co. Durham, England	199.52
NTS3	Culross Palace	Dunhouse Buff	2220.00	Barnard Castle, Co. Durham, England	278.36
NTS4	Falkland Palace	Dunhouse Sandstone (Catcastle Grey)	2220.00	Barnard Castle, Co. Durham, England	273.53
NTS5	House of The Binns	Dunhouse Sandstone (Catcastle Grey)	2220.00	Barnard Castle, Co. Durham, England	275.14
NTS6	Threave House, Threave Estate-Threave Estate, Castle Douglas	Dunhouse Sandstone (Catcastle Grey)	2220.00	Barnard Castle, Co. Durham, England	181.82
NTS7	Gate Lodge, Threave Estate, Castle Douglas	Clashach Sandstone	2220.00	Barnard Castle, Co. Durham, England	181.82
NTS8	Kilton Mains, Threave Estate, Castle Douglas	Caithness Flagstone	2220.00	Barnard Castle, Co. Durham, England	181.82
NTS9	Harmony House/St. Cuthbert House, Melrose	Caithness Flagstone	2220.00	Barnard Castle, Co. Durham, England	155.91
NTS10	Hamilton House, East Lothian	Stainton Sandstone	2220.00	Barnard Castle, Co. Durham, England	214.00
	The City of Edinburgh Council (CEC)				
CEC1	15 Hillside Crescent & 30-32 Hillside Street	Doddington Sandstone	2135.00	Doddington Quarry (near Wooler), Northumberland, Barnard Castle, Durham England	209.17
CEC2	15, 16, 16A, 17-19 Hillside Crescent	Doddington Sandstone	2135.00	Doddington Quarry (near Wooler), Northumberland, Barnard Castle, Durham England	209.17
CEC3	21-31 Hillside Street	Doddington Sandstone	2135.00	Doddington Quarry (near Wooler), Northumberland, Barnard Castle, Durham England	209.17
CEC4	22-30 Shandwick Place, Edinburgh	Dunhouse Sandstone (Buff-Pale)	2202.00	Dunhouse Quarry Works, Staindrop Darlington, Co. Durham, England.	209.17
CEC5	131-141 Bruntsfield Place, Edinburgh	(Type A) Stainton Sandstone	2220.00	Stainton Quarry, Barnard Castle, Durham, England	214.00
		(Type B) Dunhouse Sandstone (Buff-Pale)	2202.00	Dunhouse Quarry Works, Staindrop Darlington, Co. Durham, England.	212.39
CEC6	36-42 Forbes Road, Edinburgh	Stainton Sandstone	2220.00	Stainton Quarry, Barnard Castle, Durham, England	214.00
CEC7	4-11 Elm Row, Edinburgh	Peakmoor Sandstone	2210.00	Bolehill Quarry, Wingerworth, (near Matlock), Derbeyshire, England	424.78
CEC8	148-164 Bruntsfield Place, Edinburgh	Stainton Sandstone	2220.00	Stainton Quarry, Barnard Castle, Durham, England	214.00
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	Stanton Moor Sandstone	2259.00	Dale View/Palmer's Quarry, Grangemill, Matlock, Derbyshire, England	416.73

Source: Author, 2012.

Table 5.2 shows that the type of stone used for the repair of stone masonry walls in the selected case studies (particularly for natural stone replacement) are mainly sandstone: Dunhouse (Catcastle Grey, Buff and Buff Pale); Red Copp-Crag; Clashach; Caithness Flagstone; Stainton; Doddington; Peakmoor and Stanton Moor.

It was found that the stones used to replace deteriorated stone in stone masonry walls in the selected case studies were mainly quarried in England (nearly 90%), compared to 10% in Scotland. The lack of stone quarries in Scotland is mainly due to their closure (see Appendix A). As most stone is quarried in England, the distance travelled from the stone resourcing location to the building site is much greater. This study found that the average distance over which stone was transported to the building site from quarries of both England and Scotland ranged from 150 to 500km.

5.3.1 Lime Mortar Materials Mixes

It was found that the proportion of mixes for lime mortar materials (including lime grout mix and lime plaster) are generally in accordance with conservation guidelines set by collaborative partners (see Appendix C). Additionally, their volumes are normally based on the statement of methods in tender documents as well as on the general rule of thumb for stone masonry wall repair (Table 5.3). This research found that both Historic Scotland and the National Trust for Scotland have consistently adopted recommended proportion mixes or volumes of lime materials according to tender documents. This is in accordance with the requirements of conservation approaches imposed on their properties (fully protected and mostly under the listed building category). In comparison, the City of Edinburgh council adopted proportion mixes of lime materials according to both references. This research also found that the adoption of different lime mortar mixes across collaborative partners is applied to different stone masonry wall repair techniques. The proportion and volume of binder materials are mainly formed using lime materials as opposed to general cement.

Table 5.3: Typical lime mortar, lime grout mix and lime plaster mix used for stone laying in natural stone replacement in (volume/weight) for 1m^2 stone masonry wall

	Lime Mortar, Lime Grout Mix and Lime Plaster (volume/mass (kg))				
	Cement	Lime Putty	NHL 3.5	Sand	Brick dust
Historic Scotland [1] (Doune Castle) (Historic Scotland, 2006)	1/16 or 0.560 kg	1 or 8.970 kg		3 or 26.910 kg	1/16 or 0.560 kg
National Trust for Scotland (NTS) [1] (Newhailes Estate, Stable Block) (NTS, 2009)		0.75 or 7.400 kg	1 or 9.867 kg	2 or 19.734 kg	
The City of Edinburgh Council (CEC)[2] (15 Hillside Crescent & 30-32 Hillside Street) (CEC, 2008)		1 or 8.800 kg	1 or 8.800 kg	3 or 26.400 kg	

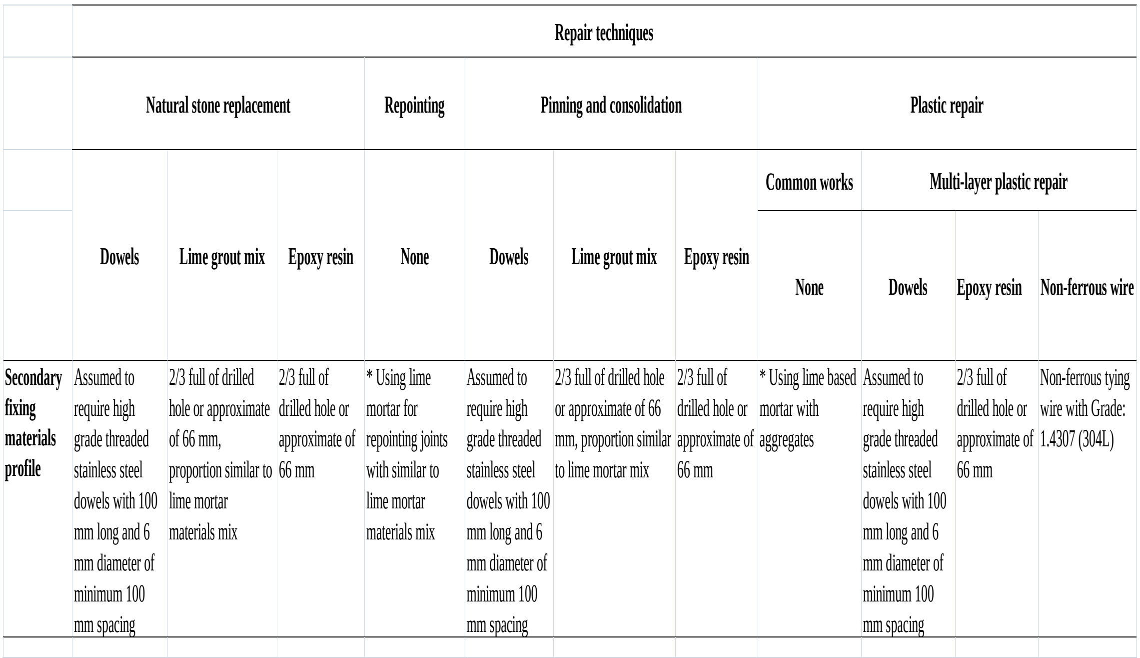
Source: Historic Scotland, 2006; CEC, 2008; NTS, 2008.

Note: [1] Approximate mass in kilograms of lime mortar materials in 1 m^2 masonry stone laying for natural stone replacement with 10mm joint thickness is 37kg (http://www.lime-mortars.co.uk/calculators/ mortar)

[2] Approximate mass in kilogram of lime mortar materials in 1m^2 masonry stone laying for natural stone replacement with 12mm joint thickness is 44kg (http://www.lime-mortars.co.uk/calculators/ mortar

5.3.2 *Secondary Fixing Materials*

Table 5.4: Secondary fixing materials for stone masonry wall repair



	Repair techniques										
	Natural stone replacement			Repointing	Pinning and consolidation			Plastic repair			
								Common works	Multi-layer plastic repair		
	Dowels	Lime grout mix	Epoxy resin	None	Dowels	Lime grout mix	Epoxy resin	None	Dowels	Epoxy resin	Non-ferrous wire
Secondary fixing materials profile	Assumed to require high grade threaded stainless steel dowels with 100 mm long and 6 mm diameter of minimum 100 mm spacing	2/3 full of drilled hole or approximate of 66 mm, proportion similar to lime mortar materials mix	2/3 full of drilled hole or approximate of 66 mm	* Using lime mortar for repointing joints with similar to lime mortar materials mix	Assumed to require high grade threaded stainless steel dowels with 100 mm long and 6 mm diameter of minimum 100 mm spacing	2/3 full of drilled hole or approximate of 66 mm, proportion similar to lime mortar mix	2/3 full of drilled hole or approximate of 66 mm	* Using lime based mortar with aggregates	Assumed to require high grade threaded stainless steel dowels with 100 mm long and 6 mm diameter of minimum 100 mm spacing	2/3 full of drilled hole or approximate of 66 mm	Non-ferrous tying wire with Grade: 1.4307 (304L)

Source: Author, 2012.

Table 5.4 shows that stainless dowels are mainly used in natural stone replacement (stone indenting), pinning and consolidation (mainly used to repair delaminated wall) and multi-layer plastic repair using non-ferrous tying wire (for tying up dowels). The quantity of materials (length, diameter and spacing in millimetres for dowels, length for non-ferrous tying wire) used in stone masonry wall repair is highly dependent on the area of both deteriorated stone and delaminated surface of the wall. It was also found that both materials are commonly procured at a similar location (produced and manufactured at the same plant). This contributes to a similar travelled distance for transporting both materials from their resourcing location to the building site.

Comparatively, lime grout mix is mainly used in stone indenting (natural replacement technique) and pinning and consolidation techniques. In comparison, it was found that epoxy resin was mainly used in indenting stone (natural stone replacement) for repairing delaminated stone by setting stainless steel dowels in drilled holes. The quantity of both materials is influenced by the volume of indented stone and the total delaminated surface area of wall.

5.4 Functional Units for Stone Masonry Wall Repair Life Cycle Assessment (LCA)

5.4.1 Embodied Carbon Coefficient of Repair Materials

Table 5.5 shows the embodied carbon coefficient (kgCO_2e/kg) value of materials commonly used in stone masonry wall repair. These values were used to calculate the embodied carbon expenditure for each selected stone masonry wall repair technique using relevant materials within the ‘cradle-to-gate’ boundary. It must be emphasised that the embodied carbon coefficient value of the repair materials used is highly influenced by the embodied carbon and energy expended for the quarrying, mining, processing and manufacturing processes.

Table 5.5: Embodied carbon coefficient of materials commonly used for stone masonry wall repair

Repair Materials	**Embodied Carbon Coefficient (kgCO$_2$e/kg) Value**
1. Stone* **	0.064*
2. Lime mortar materials	
Cement	0.74**
Lime Putty	0.78**
Natural Hydraulic Lime (NHL 3.5)	0.78**
Natural Hydraulic Lime (NHL 5)	0.78**
Jurra Kalk	0.78**
Sand	0.0051**
Brick Dust/Fire Clay/Fly Ash (Approx.)	0.24**
Crushed limestone/gravel/chippings (aggregates)	0.09**
3. Secondary fixing materials	
Stainless steel dowels	6.15**
Epoxy resin	5.70**
Non-ferrous tying wire	3.02**

Source: Author, 2012.

Notes:

* Crishna et al., 2011

**Inventory of Carbon & Energy (ICE), Version 2.0, 2011 (Hammond and Jones, 2011).

*** 1.0 m x 1.0 m x 0.1 m (cutback indenting) *bulk density (BRE Stone List, 2010) (BRE, 2010)

5.4.2 Approximate Stone Mass (kg)

Table 5.6 shows the range of mass (kg) of stones for every 1m^2 area of wall repaired in selected case studies. Historic Scotland and the National Trust for Scotland use Dunhouse (Catcastle Grey, Buff and Buff-Pale) (220-236 kg/m^2); Red Copp-Crag Sandstone (218-222 kg/m^2); Clashach Sandstone (208-222 kg/m^2) and Caithness Flagstone (222-268 kg/m^2). Additionally, the latter have also used Stainton Sandstone (222 kg/m^2). In comparison, the City of Edinburgh Council has used Doddington Sandstone (222 kg/m^2); Peakmoor Sandstone (221 kg/m^2) and Stanton Moor Sandstone (226 kg/m^2). It was found that the mass (kg) of stone used to repair 1m^2 of stone masonry wall varied between the collaborative partners. This is mainly determined by the different types of stone masonry wall, stones used and the quarry location.

Table 5.6: Approximate mass of stones (kg) used in stone masonry wall repair

		Stone Used for Replacement		**Functional Unit of Stone Per 1 M^2 Masonry Wall Replacement**		
	Collaborative Partners/Property	**Type of Stone (BRE Stone List, 2010)**	**Bulk Density (kg/m^3) (BRE Stone List, 2010)**	**Dimension (L) x (H) X (W) (meter) (Standard Stone Block)**	**Volume (m^3)**	**Mass (kg)= volume * bulk density**
No. (code)	**Historic Scotland**					
HS1	Doune Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	1m x 1m x 0.1m	0.10	**235.70**
HS2	Melrose Abbey	Red Copp-Crag Sandstone	2186.00	1m x 1m x 0.1m	0.10	**218.60**
HS3	Glasgow Cathedral	Dunhouse Buff	2202.00	1m x 1m x 0.1m	0.10	**220.20**
HS4	Old Palace/Palace of James V, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	1m x 1m x 0.1m	0.10	**235.70**
HS5	King's Old Building/Douglas Block, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	1m x 1m x 0.1m	0.10	**235.70**
HS6	Great Hall/Old Parliament House, Stirling Castle	Dunhouse Sandstone (Catcastle Grey)	2357.00	1m x 1m x 0.1m	0.10	**235.70**
HS7	Craignethan Castle	Clashach Sandstone	2084.00	1m x 1m x 0.1m	0.10	**208.40**
HS8	Jedburgh Abbey	Caithness Flagstone	2684.00	1m x 1m x 0.1m	0.10	**268.40**
HS9	Linlithgow Palace	Caithness Flagstone	2684.00	1m x 1m x 0.1m	0.10	**268.40**
	National Trust for Scotland (NTS)					
NTS1	Newhailes Estate, Stable Block	Dunhouse Sandstone (Catcastle Grey)	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS2	Newhailes Estate, Mainhouse	Red Copp-Crag Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS3	Culross Palace	Dunhouse Buff	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS4	Falkland Palace	Dunhouse Sandstone (Catcastle Grey)	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS5	House of The Binns	Dunhouse Sandstone (Catcastle Grey)	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS6	Threave House, Threave Estate- Threave Estate, Castle Douglas	Dunhouse Sandstone (Catcastle Grey)	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	Clashach Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	Caithness Flagstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS9	Harmony House/St. Cuthbert House, Melrose	Caithness Flagstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
NTS10	Hamilton House, East Lothian	Stainton Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
	The City of Edinburgh Council (CEC)					
CEC1	15 Hillside Crescent & 30-32 Hillside Street	Doddington Sandstone	2135.00	1m x 1m x 0.1m	0.10	**213.50**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	Doddington Sandstone	2135.00	1m x 1m x 0.1m	0.10	**213.50**
CEC3	21-31 Hillside Street	Doddington Sandstone	2135.00	1m x 1m x 0.1m	0.10	**213.50**
CEC4	22-30 Shandwick Place, Edinburgh	Dunhouse Sandstone (Buff-Pale)	2202.00	1m x 1m x 0.1m	0.10	**220.20**
CEC5	131-141 Bruntsfield Place, Edinburgh	(Type A) Stainton Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
		(Type B) Dunhouse Sandstone (Buff-Pale)	2202.00	1m x 1m x 0.1m	0.10	**220.20**
CEC6	36-42 Forbes Road, Edinburgh	Stainton Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
CEC7	4-11 Elm Row, Edinburgh	Peakmoor Sandstone	2210.00	1m x 1m x 0.1m	0.10	**221.00**
CEC8	148-164 Bruntsfield Place, Edinburgh	Stainton Sandstone	2220.00	1m x 1m x 0.1m	0.10	**222.00**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	Stanton Moor Sandstone	2259.00	1m x 1m x 0.1m	0.10	**225.90**

Source: Author, 2012.

5.4.3 Approximate of Mass (kg) of Lime Binders and Secondary Fixing Materials

Research results shows that the approximate mass (kg) of materials used in stone masonry wall repair varies (see Appendix D). The mass (kg) across all binder materials (lime mortar, grout mix, plaster) as well as secondary fixing materials varies due to their dissimilar proportions and the mixes adopted for stone masonry wall repair. Research results also show that the mass (kg) of epoxy resin used is determined by the total area of delaminated wall surface. The larger the delaminated wall surface area to be repaired, the more epoxy resin (volume) needed. Meanwhile, the mass (kg) of non-ferrous tying wires is determined by the number of dowels that need to be tied in multi-layer plastic repair. It was found that the greater the number of stainless steel dowels inserted in the drilled holes, the more wires that need to be used to tie them up.

Additionally, it was found that the mass (kg) of lime mortar used in the joint repointing of stone masonry walls was mainly determined by the thickness of the joints (in millimetres). In general, the greater the thickness (mm), the greater the mass (kg) of lime mortar used in repairing deteriorated and loose joints. On the other hand, the mass (kg) of lime plaster (lime-based mortar) used in plastic repair is mainly determined by the proportions used in the mixes.

5.4.4 Value for CO_2 Emission Factors

For the purpose of this research, the CO_2 emission factor for the transportation of stone masonry wall repair materials (‘gate-to-site’) was 132gm of CO_2 per tonne km (1.32×10^{-4} kgCO_2 per kg km). It must be noted that this value was derived 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). In order to generate comparable embodied carbon expenditure within the ‘gate-to-site’ boundary, one mode of transportation, namely HGV road freight, was assumed to be used for all transportation of stone masonry wall materials from their respective resourcing locations directly to the building site. It must be emphasised that transportation from secondary resourcing locations such as warehouses and supplying and manufacturing factories was not considered in the calculation. The embodied carbon expenditure expended on the delivery of stone masonry wall repair materials to the building site was calculated by multiplying the mass (kg) of materials with CO_2 emission factors and their transportation distance (km) [Mass (kg) x CO_2 emission factors per kg km x transportation distance (km)].

5.5 Resourcing Location and Transportation Distance for Repair Materials

The materials used in the stone masonry wall repair of selected historic masonry buildings for this research were procured from both locally sourced and imported materials (see Appendix E). It was found that most of the stones used are mainly procured from England. This is a better alternative of resourcing stone for the selected case studies as the number of quarries in Scotland has declined and those that remain had minimal operations at the time of the research (see Appendix A). It was also found that other stone masonry wall repair materials are locally sourced, including cement (all from Dunbar, Scotland), sand (all from Scotland), brick dust, fire clay and fly ash (all from Bathgate, Scotland), aggregates (all from Shap, Cumbria, England), stainless steel dowels, epoxy resin (from Cowie, Stirling, Scotland) and non-ferrous tying wire (all from North Lincolnshire and Yorkshire, England). In comparison, all types of lime materials used are mainly imported from St Astier in southwest France and the Canton of Jura in northwest Switzerland (Jura Kalk). The resourcing location influences the embodied carbon emissions (CO_2 emissions) from transportation to the building site. The greater the distance between the material resourcing location and the building site (the transportation distance in miles or km), the higher embodied carbon expended for material delivery.

Table 5.7 shows that the transportation distance for materials used in stone masonry wall repair varies and is mainly determined by their respective resourcing location. The transportation distance for imported materials (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). It was found that the transportation distance for the former was approximately 1400-2000km as it was mostly transported from St Astier in southwest France and the Canton of Jura in northwest Switzerland. This is up to 140 to 200 times further than the latter, particularly considering the transportation distance of locally sourced sand between 9.81 km (HS1-Doune Castle) and 231.70 km (NTS6-Threave House). It must be emphasised that the stainless dowels and non-ferrous tying wire used in stone masonry wall repair in this research were transported over similar distances as they are commonly produced at the same processing plant. In order to minimise the transportation distance between the building site and resourcing location, the use of locally sourced materials is highly encouraged. The shorter the transportation distance to the building site for locally sourced materials, the lower the embodied carbon expended on material delivery. Appendix F and Appendix G provide more detailed information on the total and minimum, maximum and average of transportation distance (km) needed for material delivery to the building site for each of the sample properties.

Table 5.7: Resourcing location and transportation distance for the delivery of stone masonry wall repair materials

Materials	Procurement Methods		Transportation Distance (km)		Distance Travelled/No. of Properties Using Materials			Cumulative Distance Travelled (km)	Total Number of Properties Using Materials	Average (km) [cumulative distance travelled/total no.of properties using materials]
	Locally Sourced	Imported	Nearest (km)/Sample Properties	Furthest (km)/Sample Properties	HS	NTS	CEC			
Stone	*		152.367/HS2	485.92/HS8	2483.84/9	2141.14/10	2536.58/10	7161.56	29	246.95
Lime Mortar/Grout Mix/Plaster Materials										
Cement (General)	*		34.75/NTS10	188.25/NTS8	685.92/7	594.68/4	0.00/0	1280.60	11	116.42
Lime Putty		*	1467.41 /HS3	1758.64/NTS4	9095.68/6	10131.88/6	16804.41/10	36031.97	22	1637.82
Natural Hydraulic Lime (NHL 3.5)		*			3359.60/2	15026.45/9	6728.83/4	25114.88	15	1674.33
Natural Hydraulic Lime (NHL 5)		*			4584.05/3	1568.78/1	10075.58/6	16228.41	10	1622.84
Jurra Kalk		*	1412.70/HS2		1412.70/1	0.00/0	0.00/0	1412.70	1	1412.70
Sand	*		9.81/HS1	231.70/NTS6	507.14/9	1274.83/10	817.03/10	2599.00	29	89.62
Brick Dust/Fire Clay/Fly Ash	*		37.97/HS4, HS5 & HS6	48.50/HS1	162.41/4	0.00/0	0.00/0	162.41	4	40.60
Crushed limestone/gravel/chippings (aggregates)	*		64.68/CEC9	265.49/NTS4	1803.57/9	1910.25/10	1263.40/10	4977.22	29	171.63
Secondary Fixing Materials										
Stainless steel dowels	*		311.00/HS8	462.00/NTS4	3666.00/9	3864.00/10	3985.00/10	11515.00	29	397.07
Epoxy resin	*		9.60/HS4 & HS6	177.00/NTS6,NTS7 & NTS8	437.30/9	975.10/10	581.20/10	1993.60	29	68.74
Non-ferrous tying wire	*		311.00/HS8	462.00/NTS4	3666.00/9	3864.00/10	3985.00/10	11515.00	29	397.07

Source: Author, 2012.

Note:

HS1-Doune Castle, HS2-Melrose Abbey, HS3-Glasgow Cathedral, HS4-Old Palace/Palace of James V, Stirling Castle, HS5-King's Old Building/Douglas Block, Stirling Castle, HS6-Great Hall/Old Parliament House, HS8-Jedburgh Abbey, NTS4-Falkland Palace, NTS6-Threave House, Threave Estate, Castle Douglas, NTS7-Gate Lodge, Threave Estate, Castle Douglas, NTS8-Kilton Mains, Threave Estate, Castle Douglas, NTS10-Hamilton House, East Lothian and CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh

5.6 'Green Maintenance' Modelling

5.6.1 'Green Maintenance' Modelling for Historic Masonry Buildings

The research results reveal that the efficiency of embodied carbon expenditure for different selected stone masonry wall repair techniques can be evaluated. This method relies on the use of 'cradle-to-site' boundary components of the life cycle assessment (LCA) over the lifetime of historic masonry buildings, and focuses specifically during the use stage (maintenance phase). In the maintenance of these buildings, it was found that the 'Green Maintenance' model is able to determine how 'green' selected repair techniques for stone masonry walls are in terms of embodied carbon expenditure.

It can be concluded that there are differences in embodied carbon expenditures when different techniques are undertaken to repair the stone masonry walls of historic masonry buildings. Using the 'Green Maintenance' model, the efficiency of stone masonry wall repair techniques in terms of embodied carbon expenditure was determined. This evaluation was based on maintenance interventions and enable comparisons to be achieved for the appropriate selection of repair types. For this work the efficiency of a single or multiple stone masonry wall repair techniques were evaluate over a 100 year specified maintenance period. This evaluation enables the determination of the relative environmental maintenance impact (EMI) of the repair to be achieved. Therefore, the 'Green Maintenance' model could act as a tool for decision making process, particularly for practitioners repairing buildings. This model shows that, the attitude of both decision makers and practitioners towards repair may change. To achieved sustainability, selection criteria for repair is not only based on cost, philosophical framework, but also on how 'green' repair techniques are.

5.6.2 The Influences of the Number of Maintenance Intervention (n) and Total Area of Repaired Wall (m^2) on Embodied Carbon Expenditure

The research results show that the number of interventions (n) and the total area of the repaired wall (m^2) are the main factors that contribute to the total embodied carbon expenditure value. It can be concluded that the greater the value of these factors, the greater the total embodied carbon expenditure ($kgCO_2e/kg$) for stone masonry wall repairs. Theoretically, natural stone replacements contribute the highest value of embodied carbon expenditure for every 1 m^2 of wall repaired (this technique has the highest functional units of $kgCO_2e/kg/m^2$ value). However, within the same boundary of the LCA and the selected maintenance period (2001-2010 for this research), the overall total embodied carbon expended on this repair technique is normally lower than repointing, pinning and consolidation and plastic repair techniques. It can be concluded that replacing natural stone in historic masonry buildings consumes less carbon than the other three selected stone masonry wall repair techniques and therefore the 'greenest' in terms of embodied carbon expenditure. It must be emphasised that this result is only valid when applied within the context of long term maintenance profile.

Despite similar numbers of interventions (n) for repointing, pinning and consolidation and plastic repairs they do not perform favourably in terms of carbon when compared to natural stone replacement. It is evident that the former interventions are the main contributors to the total embodied carbon expenditure within the selected maintenance period (10 years), as opposed to the latter. This is due to the higher longevity of the natural stone repair compared to the relatively less durable alternatives. In order to reduce embodied carbon expenditure for the repair, this research shows that both decision makers and practitioners need to consider repairs with a low number of maintenance interventions (i.e. more durable), but also exhibit a preference towards repairs with minimal total wall area requirement within longer maintenance profile (higher longevity of repair). This approach could be seen as favoring a minimal intervention philosophical approach.

5.6.3 Longevity of Repairs Impact

The 'Green Maintenance' model has demonstrated that the different life expectancy or longevity of repair materials contribute to the diverse embodied carbon expenditures. It was found that the higher the longevity of the repairs, the lower the embodied carbon expended for stone masonry wall repairs was noted. This is due to the fact that fewer interventions (n) needed to be undertaken within the same period using this technique. Due to the fact that it has the longest longevity of repairs, natural stone replacement necessitates the fewest interventions (n) undertaken within a 100-year period (only once every 100 years) (see Table 5.8). The results show that natural stone has the lowest embodied carbon expenditure within selected maintenance profiles, as it has the highest longevity of repairs compared to the other repair techniques.

Table 5.8: Longevity of repair for stone masonry wall repair techniques

Repair Techniques	**Longevity of repair***	**No. of repairs(n)/ 100 years**
Replacement		
(a) Indenting + lime grout mix	100 years	1
(b) Indenting + dowels + lime grout mix	100 years	1
(c) Dowels + epoxy resin	100 years	1
Repointing		
(a) Lime mortar repointing	25 years	4
Pinning & consolidation		
(a) Dowels + lime grout mix	20 years	5
(b) Dowels + epoxy resin	20 years	5
Plastic repair		
(a) Lime base mortar + aggregates	30 years	3.33
(b) Lime base mortar (multi-layer plastic repair)	30 years	3.33

Source: Author, 2012.

*Ashurst and Ashurst, 1988; Ashurst, 1994a and 1994b; Ashurst and Dimes, 1998; McMillan et al. (1999); Historic Scotland 2003b, 2007b, 2007c and 2007d; Young et al., 2003; BCIS, 2006; BRE, 2010).

The environmental maintenance impact (EMI) of 'Green Maintenance' model testing results shows that repeated single natural stone replacement resulted in the lowest embodied carbon expenditure within the selected 'cradle-to-site' boundary and maintenance period (100 years).

5.6.4 The Impact of Selected Materials

It was found that embodied carbon expenditure varies despite similar repair techniques being applied to the same stone masonry wall area (1 m^2) by collaborative partners. The varying values of embodied carbon expenditure are very much influenced by the diverse characteristics of the repair materials used for the stone masonry wall repairs. This includes differences in their sourcing process and transportation, as well as variances in material profiles.

‘Green Maintenance’ test results also show that the profiles (weight/volume/mass/density and so on) of stone masonry wall repair materials are also influencing factors for embodied carbon expenditure. Within the ‘cradle-to-gate’ boundary of the LCA, it was found that the higher the embodied carbon coefficient value (kgCO_2/kg) and mass (kg) of the repaired materials used in stone masonry wall repairs, the greater the embodied carbon expenditure on repairs.

It was found that different lime mortar mixes used for repairs on the same building elements (in this case a stone masonry wall) contribute to diverse kgCO_2e/kg sequestration capabilities. It was also found that secondary fixing materials used in stone masonry wall repairs, such as stainless steel dowels, epoxy resin, non-ferrous tying wire etc, also have a significant impact on the embodied carbon expenditure.

With regards to natural stone replacement, differences in embodied carbon expenditure are mainly due to the varying distance of the quarry and the bulk density (kg/m^3) of the stone used. The research results also show that the greater the bulk density (kg/m^3) of the stone used in natural stone replacement for stone masonry walls, the greater the embodied carbon expended on repairs.

Meanwhile, the results from this research suggest that the mass (kg) of lime grout and lime-based mortar materials used in stone masonry wall repairs are very much dependent upon their mix proportion. Generally, the higher the mass of these materials, the more embodied carbon expended for repairs. It was also found that, within the ‘gate-to-site’ boundary of the LCA, the higher the mass of the stone masonry repair materials (heavier), the more embodied carbon is expended to transport them to the building site (in this research, there were more CO_2 emissions per kg km for heavy goods vehicles (HGVs) used for transportation). This trend occurred across all types of the repair materials used. The research results suggest that both decision makers and practitioners need to make preference towards repair materials with low embodied carbon coefficient in repair works. Locally sourced materials need to be gain a higher preference set against imported materials, as this will reduce the embodied carbon expenditure for materials transportation.

5.6.5 The Influences of Deterioration Rates

The rate of the degradation processes on building elements (in this case a stone masonry wall) is very much dependent on the local climate surrounding them. In addition, the building and the stone masonry wall orientation (exposure to weather) is also an influencing factor that is very much associated with the rate of degradation. In general, the faster the rate of degradation of a stone masonry wall, the larger the area of the wall surface (m^2) that deteriorates and more maintenance intervention (n) (i.e. more stone masonry wall repairs) will need to be undertaken. This will contribute to a higher embodied carbon expenditure, as more frequent repairs are needed.

Meanwhile, the EMI of the 'Green Maintenance' test results shows that the longevity of the repairs are very much influenced by the degradation process of stone masonry walls. Therefore, it could summed up that natural stone replacement is the most efficient repair technique in terms of embodied carbon expenditure, and should be highly encouraged over the other repair techniques to reduce rate of degradation process of stone masonry wall.

5.6.6 The Impact of Sourcing Materials and Transportation

The research results reveal that the efficacy of repairs to the stone masonry walls of historic masonry buildings is very much influenced by the geographical location of the materials' source. It can be concluded that the greater the transportation distance between resourcing location and building site, the greater the CO_2 emitted for materials delivery. In the case of plastic repair techniques, the research results show that the total approximate embodied carbon expenditure is significantly influenced by the source location of the imported lime-based mortar materials. From this research, it is found that locally sourced stone has contributed to less embodied carbon expenditure compared to imported materials. For multi-layer plastic repair technique, the research results show that the total approximate embodied carbon expenditure is significantly influenced by the source location of its secondary fixing materials.

Commonly, shorter distances are needed to transport locally sourced materials to the building site, as opposed to imported materials. Within the 'gate-to-site' boundary of the LCA, transportation of the former contributes much less to the embodied carbon expenditure than the latter.

In the case of natural stone replacement techniques, the higher the value of mass (kg) of the stone (heavier), the more embodied carbon is expended to transport the stone to the building site (in this research there are more CO_2 emissions per kg km for HGVs used for transportation). This also applies to other repair materials used for stone masonry wall repairs.

It can also be suggested that locally sourced materials used for stone masonry wall repairs of historic masonry buildings contribute much less in terms of embodied carbon expenditure than imported materials, largely due to having to transport them over less distance.

5.6.7 The Impact of Functional Units

In this research, the embodied carbon expenditure for the repair of every 1 m^2 (functional units of $kgCO_2e/kg/m^2$) of wall for each selected repair technique is one of the prime factors influencing the overall total embodied carbon expenditure; i.e. it is likely that the higher the average value of functional units for repair techniques, the higher the total embodied carbon expenditure on their application (see Table 5.9).

5.6.8 Approximate Embodied Carbon Expenditure for Repairing 1m^2 Stone Masonry Wall ($kgCO_2e/kg/m^2$)

Based on Equation No. (3) (shown in Chapter 4), the total approximate embodied carbon ($kgCO_2e/kg$) of mass (kg) of repair materials used in repairing every 1m^2 area of stone masonry wall for each selected 'cradle-to-gate' technique was generated as shown in Table 5.9.

Equation No. (4) (as shown in Chapter 4) was used to calculate the total approximate embodied carbon ($kgCO_2e/kg$) for transporting a mass (kg) of repair materials used in repairing every $1m^2$ area of stone masonry wall from the resourcing location to building site for each selected technique within ‘gate-to-site’.

Table 5.9: Embodied carbon expenditure per 1m^2 stone masonry wall repaired

Repair Techniques	Within 'cradle-to-gate'								Within 'gate-to-site'							
	Minimum (kgCO$_2$e/kg/m^2) /Sample Properties	Maximum (kgCO$_2$e/kg/m^2)/ Sample Properties	Total/No. Of Sample Properties			Cumulative	Total Number of Properties Using Repair Techniques	Average (kgCO$_2$e/kg/m^2)	Minimum (kgCO$_2$e/kg/m^2) /Sample Properties	Maximum (kgCO$_2$e/kg/m^2)/ Sample Properties	Total/No. Of Sample Properties			Cumulative	Total Number of Properties Using Repair Techniques	Average (kgCO$_2$e /kg/m^2)
			HS	NTS	CEC						HS	NTS	CEC			
1. Natural stone replacement																
a. Indenting + lime mortar grout mix	16.589/NTS9	27.777/NTS1, NTS3, NTS4 & NTS5	210.116/9	245.867/10	182.629/10	638.612	29	22.021	5.339/NTS9	18.397/HS8	96.678/9	91.238/10	86.285/10	274.201	29	9.456
b. Indenting + dowels + lime grout mix	45.543 /NTS9	57.192/NTS1, NTS3, NTS4 & NTS5	470.860/9	539.120/10	475.030/10	1485.010	29	51.207	5.757/NTS9	18.683/HS8	100.350/9	96.459/10	91.608/10	288.417	29	9.945
c. Dowels + epoxy resin	62.361/NTS9	73.549/NTS1, NTS3, NTS4 & NTS 5	621.064/9	703.587/10	640.259/10	1964.910	29	67.756	5.588/NTS9	18.640/HS8	99.083/9	93.980/10	88.943/10	282.006	29	9.724
2. Repointing																
Lime mortar repointing	0.867/NTS9	4.036/NTS1, NTS2, NTS3, NTS4 & NTS5	22.003/9	31.407/10	14.093/10	67.503	29	2.328	0.280/NTS9	1.260/CEC2	5.175/9	8.631/10	5.285/10	19.091	29	0.658
3. Pinning and consolidation																
a.Dowels + lime grout mix	28.809/HS1, HS4,HS5 & HS6	29.237/NTS1, NTS2, NTS3, NTS4 & NTS5	259.706/9	291.047/10	289.674/10	840.427	29	28.980	0.259/CEC7 & CEC9	0.573/NTS4	3.487/9	4.619/10	4.467/10	12.573	29	0.434
b. Dowels + epoxy resin	45.772/all properties*		411.948/9	457.720/10	457.720/10	1327.388	29	45.772	0.243/HS8	0.305/NTS4	2.405/9	2.742/10	2.658/10	7.805	29	0.269
4. Plastic repair																
a. Lime based mortar with aggregates	3.595/NTS5	7.491/HS2	49.236/9	54.336/10	53.063/10	5.401	29	5.401	0.903/HS8	1.974/NTS9	11.876/9	15.246/10	16.328/10	43.45	29	1.498
b. Lime based mortar (multi-layer plastic repair)	108.309/NTS5	114.429/HS2	1001.284/9	1111.967/10	1109.971/10	3223.222	29	111.146	2.055/HS8	3.760/NTS9	25.251/9	31.318/10	32.913/10	89.482	29	3.086

Source: Author, 2012.

Note:

HS1-Doune Castle, HS2-Melrose Abbey, HS4-Old Palace/Palace of James V, Stirling Castle, HS5-King's Old Building/Douglas Block, Stirling Castle, HS6-Great Hall/Old Parliament House, Stirling Castle, HS8-Jedburgh Abbey, NTS1-Newhailes Estate, Stable Block, NTS2-Newhailes Estate, Mainhouse, NTS3-Culross Palace, NTS4-Falkland Palace, NTS5-House of the Binns, NTS9-Harmony House/St. Cuthbert House, Melrose, CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh, CEC7-4-11 Elm Row, Edinburgh and CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh.

*****All 29 sample properties expended the same kgCO$_2$e/kg/m^2 using stainless dowels and epoxy resin of pinning and consolidation techniques.

Table 5.9 shows the embodied carbon expenditure per 1m^2 stone masonry wall repaired (kgCO$_2$e/kg/m^2) within the 'cradle-to-gate' and 'gate-to-site' boundaries. Research results show that the minimum, maximum and average kgCO$_2$e/kg/m^2 values were highly influenced by the embodied carbon coefficient value of repair materials and their profiles (bulk density for stone and mass in kilogrammes used) within the former boundary. In comparison, for the latter boundary, kg/km emissions factors (mode of transport and in this case the mass in kg of materials transported, resourcing location and transportation distance) also had an effect. The higher the embodied carbon coefficient value and mass (kg) of materials used for repair, the greater the value of (kgCO_2e/kg/m^2) expended within 'cradle-to-gate' boundaries. Meanwhile, the greater the value of the mass (kg) of materials transported and the transportation distance needed for their delivery to the building site, the higher kgCO_2e/kg/m^2) expended within 'gate-to-site' boundaries. This trend applies across sample properties.

Within 'cradle-to-gate', it was found that the highest average value of 111.146 kg CO_2e/kg/m^2 was expended on multi-layer plastic repair techniques. This is up to approximately 50 times greater than lime mortar repointing (particularly considering the lowest average of 2.328 kg CO_2e/kg/m^2). Table 5.9 represents average differences of kgCO_2e/kg/m^2 of different stone masonry wall repair techniques in relative order of magnitude. It must be emphasised that the high embodied carbon coefficient value for the secondary fixing materials, namely stainless dowels, epoxy resin and non-ferrous tying wire, used in multi-layer plastic repair is the main factor behind the highest values for the minimum, maximum and average kgCO_2e/kg/m^2 expended.

Meanwhile, it was found that an average of 9.456 to 9.724 kgCO_2e/kg/m^2 within 'gate-to-site' was expended in natural stone replacement. This is relatively high compared to other repair techniques across all the selected sample properties. This is up to approximately 35 to 36 times greater than the use of stainless dowels and epoxy resin in pinning and consolidation, particularly considering the lowest average of 0.269 kgCO_2e/kg/m^2. Within the same boundary, the use of stone led to more carbon being emitted during transportation, as stones generally have a high bulk density (kg/m^3) and mass (kg) and are transported longer distances to the building site. It must be emphasised that the lowest kgCO_2e/kg/m^2 was expended when locally sourced stainless dowels and epoxy resin were used for pinning and consolidation within the same boundary, mainly due to the lower carbon emissions during the shorter transportation distance to the building site).

Appendix H and Appendix I provide detailed information on the total, minimum, maximum and average of kgCO_2e/kg/m^2 expended on each sample property within 'cradle-to-gate' and 'gate-to-site' boundaries respectively.

5.6.9 Typical Evaluation of Embodied Carbon Expenditure

Research results show that comparisons may be made between the embodied carbon expenditure for every $1m^2$ of wall repaired within both the ‘cradle-to-gate’ and ‘gate-to-site’ LCA boundaries for different selected stone masonry wall repair techniques (see the example in Table 5.10).

Table 5.10: Different stone masonry wall repair techniques and embodied carbon expenditure of $1m^2$ wall

	Embodied Carbon ($kgCO_2e/kg/m^2$)		
Repair Techniques	**Quarrying and processing (cradle-to-gate)**	**Transportation (gate-to-site)**	**Total approximate (cradle-to-site)**
(1) Replacement			
(a) Indenting + lime mortar grout mix	22.767	9.086	**31.853**
(b) Indenting + dowels + lime grout mix	51.694	9.513	**61.207**
(c) Dowels + epoxy resin	68.539	9.370	**77.909**
(2) Repointing using lime mortar	2.285	0.543	**2.828**
(3) Pinning and Consolidation			
(a) Dowels + Lime Grout	28.809	0.417	**29.226**
(b) Dowels + Epoxy Resin	45.772	0.284	**46.056**
(4) Plastic repair			
(a) Lime-based mortar + aggregates	4.744	1.306	**6.050**
(b) Lime-based mortar (multi-layer plastic repair)	110.112	2.840	**112.952**

Source: Author, 2012.

Note: Typical samples of stone masonry wall repair techniques undertaken at HS1-Doune Castle by Historic Scotland.

Table 5.10 shows that each of the repair techniques undertaken by the collaborative partners to repair the stone masonry walls of their historic masonry buildings differ in terms of the sequestered value of embodied carbon expenditure. From the typical result in Table 5.10, it was found that a high total value of approximately 61.207 $kgCO_2e/kg/m^2$ was expended on natural stone replacement techniques. This value was highly influenced by the use of high embodied carbon coefficient materials (as stainless steel dowels) within ‘cradle-to-site’ component of the calculation. Within the same boundary, the use of high embodied carbon materials (stainless steel dowels and non-ferrous tying wire) contributed to the highest total approximate 112.952 kgCO_2e/kg/m^2 expended on profiled plastic repair (multi-layer plastic repair). Although similar repair techniques applied to the same total area (1 m^2) of stone masonry wall, results show that the embodied carbon expenditure varied due to the different usage of repair materials. This variation occurred across selected sample properties in this research.

5.6.10 Typical Intervention (n) and Total Wall Area Repaired (m^2)

Table 5.11: Typical number of interventions (n) and total area repaired (m^2)-
Doune Castle

		Repair Techniques/Total Maintenance Intervention (n) and Wall Repaired Area (m^2) for HS1-Doune Castle							
		(1) Natural Stone Replacement			**(2) Repointing**	**(3) Pinning and consolidation**		**(4) Plastic repair**	
Year	**Intervention (n)**	(a) Indenting using lime grout mix	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin	*Using lime mortar	(a) Using stainless steel dowels and lime grout mix	(b) Using stainless steel dowels and epoxy resin	(a) Using lime based mortar and aggregates	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair
2001	1				20.00				
	2							48.00	
	3				26.00				
	4								17.00
	5					36.00			
2002	6	1.00							
	7							18.00	
	8				18.00				
2003	9					27.00			
2004	10		2.50						
	11				20.00				
2005	12					45.00			
	13				60.00				
2006	14							20.00	
	15				42.00				
2007	16					45.00			
	17			1.50					
2008	18						10.00		
2009	19				49.00				
2010	20				25.00				
Total Wall Repaired Area (m^2)		**1.00**	**2.50**	**1.50**	**260.00**	**153.00**	**10.00**	**86.00**	**17.00**
Total Maintenance Intervention (n)		1	1	1	8	4	1	3	1

Source: Author, 2012.

The results in Table 5.11 show that lime mortar repointing techniques contributed to the highest number of interventions (eight out of 20 or 40% of total interventions) for Doune Castle within the 2001 to 2010 maintenance periods. Within the same periods, 260.00m^2 (49% or nearly half of total area of 531.00 m^2) of stone masonry wall was repaired using this technique compared to the lowest intervention (5% each of the total intervention) for each technique of natural stone replacement, pinning and consolidation (using stainless steel dowels and epoxy resin) and multi-layer plastic repair. It was also found that the higher the number of maintenance interventions (n) undertaken within the selected maintenance periods, the larger the area of stone masonry wall (m^2) repaired.

5.6.11 Typical Total Approximate Embodied Carbon Per m^2 Wall Repaired Within 'Cradle-to-Gate'

The typical total approximate embodied carbon (kgCO$_2$e/kg) expended in quarrying, mining, processing and manufacturing the repair materials used in repairing stone masonry wall for each of the selected 'cradle-to-gate' techniques was calculated using Equation No. (5) (as shown in Chapter 4).

Table 5.12: Typical embodied carbon expenditure for repair within ‘cradle-to-gate’-Doune Castle

		Repair Techniques/Embodied Carbon Expenditure ($kgCO_2e/kg$) Within 'Cradle-to-Gate' for HS1-Doune Castle							
		(1) Natural Stone Replacement			(2) Repointing	(3) Pinning and consolidation		(4) Plastic repair	
Year	**Intervention (n)**	(a) Indenting using lime grout mix **@ 22.767 $kgCO_2e/kg$**	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix **@ 51.694 $kgCO_2e/kg$**	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin **@ 68.539 $kgCO_2e/kg$**	*Using lime mortar **@ 2.285 $kgCO_2e/kg$**	(a) Using stainless steel dowels and lime grout mix **@ 28.809 $kgCO_2e/kg$**	(b) Using stainless steel dowels and epoxy resin **@ 45.772 $kgCO_2e/kg$**	(a) Using lime based mortar and aggregates **@ 4.744 $kgCO_2e/kg$**	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair **@ 110.112 $kgCO_2e/kg$**
2001	1				45.700				
	2							227.712	
	3				59.410				
	4								1871.904
	5					1037.124			
2002	6	22.767							
	7							85.392	
	8				41.130				
2003	9					777.843			
2004	10		129.235						
	11				45.700				
2005	12					1296.405			
	13				137.100				
2006	14							94.880	
	15				95.970				
2007	16					1296.405			
	17			102.809					
2008	18						457.720		
2009	19				111.965				
2010	20				57.125				
Total ($kgCO_2e/kg$)		**22.767**	**129.235**	**102.809**	**594.100**	**4407.777**	**457.720**	**407.984**	**1871.904**

Source: Author, 2012.

In the example of Doune Castle (Table 5.12), the highest value of embodied carbon expended within ‘cradle-to-gate’ was associated with the plastic repair technique used in multi-layer substrate build up. This expended 110.112 $kgCO_2e/kg/m^2$ for every $1m^2$ of wall repaired, compared to the lowest figure of 2.285 $kgCO_2e/kg$ using the lime mortar repointing technique. Despite resulting in the fifth highest figure of 28.809 $kgCO_2e/kg/m^2$, the pinning and consolidation technique (using stainless steel dowels and lime grout mix) contributed to the highest total of typical embodied carbon expenditure of 4407.777 $kgCO_2e/kg$ out of total 7944.296 $kgCO_2e/kg$, or a contribution of 55.5%.

This research shows that the largest area of stone masonry wall was repaired using lime mortar repointing (260.00 m^2 out of 531 m^2 or 49.0 % of total wall repaired area). However, within the same boundary and maintenance period, this technique contributed to a total of only 594.10 $kgCO_2e/kg$ (a contribution of only 7.5%). It must be noted that this value is highly subjected to commonly large area of delaminated stone masonry wall surface.

In comparison, the natural stone replacement technique accounted for the lowest total area of stone masonry wall repaired (5.00 m^2 out of 531.00 m^2 or 0.9%) with 254.811 $kgCO_2e/kg$ out of 7944.296 $kgCO_2e/kg$ (3.2%). Research results show that the higher the value of embodied carbon per m^2 wall repaired within 'cradle-to-gate' and the total area repaired (m^2), the greater the embodied carbon expenditure.

5.6.12 Typical Embodied Carbon Per m^2 Wall Repaired Within 'Gate-to-Site'

The typical total approximate embodied carbon ($kgCO_2e/kg$) expended in transporting the repair materials used in every repaired area stone masonry wall for each selected technique within 'gate-to-site' was calculated using Equation No. (6), as shown in Chapter 4.

Table 5.13: Typical embodied carbon expenditure for repair within ‘gate-to-site’-Doune Castle

		Repair Techniques/Embodied Carbon Expenditure (kgCO$_2$e/kg) Within' Gate-to-Site' for HS1-Doune Castle							
		(1) Natural Stone Replacement			**(2) Repointing**	**(3) Pinning and consolidation**		**(4) Plastic repair**	
Year	**Intervention (n)**	(a) Indenting using lime grout mix **@ 9.086 kgCO$_2$e/kg**	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix **@ 9.513 kgCO$_2$e/kg**	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin **@ 9.370 kgCO$_2$e/kg**	*Using lime mortar **@ 0.543 kgCO$_2$e/kg**	(a) Using stainless steel dowels and lime grout mix **@ 0.417 kgCO$_2$e/kg**	(b) Using stainless steel dowels and epoxy resin **@ 0.284 kgCO$_2$e/kg**	(a) Using lime based mortar and aggregates **@ 1.306 kgCO$_2$e/kg**	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair **@ 2.840 kgCO$_2$e/kg**
2001	1				10.860				
	2							62.688	
	3				14.118				
	4								48.280
	5					15.102			
2002	6	9.086							
	7							23.508	
	8				9.774				
2003	9					11.259			
2004	10		23.783						
	11				10.860				
2005	12					18.765			
	13				32.580				
2006	14							26.120	
	15				22.806				
2007	16					18.765			
	17			14.055					
2008	18						2.840		
2009	19				26.607				
2010	20				13.575				
Total (kgCO$_2$e/kg)		**9.086**	**23.783**	**14.055**	**141.180**	**63.891**	**2.840**	**112.316**	**48.280**

Source: Author, 2012.

In the example of Doune Castle (Table 5.13), the highest value of embodied carbon (within ‘gate-to-site’) was expended for stone indenting using lime grout mix and the secondary fixing of stainless steel dowels in natural stone replacement techniques with 9.513 kgCO$_2$e/kg/m^2 expenditure per m^2 wall repaired, compared to the lowest figure of 0.284 kgCO$_2$e/kg/m^2 for pinning and consolidation using stainless steel dowels and the epoxy resin technique. Despite having the sixth highest figure of 0.543 kgCO$_2$e/kg/m^2, lime mortar repointing contributed to the highest total of 141.180 kgCO$_2$e/kg out of a total of 415.341 kgCO$_2$e/kg, or 34%. This is due to this technique being used to repair the largest area of stone masonry wall (260.00 m^2 out of 531.00 m^2, or 49%) within the same boundary and maintenance periods. Plastic repair using lime-based mortar and aggregates accounted for the second highest total embodied carbon expenditure, with a total of 112.316 kgCO$_2$e/kg or 27%, which represented the fifth highest value per m^2 of 1.306 kgCO$_2$e/kg/m^2. In comparison, the use of stainless steel dowels and epoxy resin in the pinning and consolidation techniques had the lowest total embodied carbon expenditure of only 2.840 kgCO$_2$e/kg, despite accounting for the fifth-largest area of stone masonry wall area repaired (10.00 m^2 out of total 531.00 m^2 or 0.9%). The lowest figure of 0.284 $kgCO_2e/kg/m^2$ was expended using this technique within the same boundary and maintenance periods.

Results from Doune Castle show that the larger the area of stone masonry wall repaired (m^2) and the greater the value of embodied carbon expenditure in every m^2 wall repaired ($kgCO_2e/kg/m^2$), the higher the total and percentage of contribution of embodied carbon expenditure ($kgCO_2e/kg$) within the same ‘gate-to-site’ boundary during the selected maintenance periods. This result also shows that the total embodied carbon expenditures within this boundary are highly dependent on kg/km emission factors for the delivery of repair materials from the resourcing location to the building site. The greater the transportation distance needed in the delivery of repair materials, the higher the $kgCO_2e/kg/m^2$ and the total embodied carbon expenditure.

5.6.13 Typical Total Embodied Carbon Per m^2 Within ‘Cradle-to-Site’

The typical total approximate embodied carbon ($kgCO_2e/kg$) expended during processing, manufacturing and the transportation of repair materials to historic masonry building sites for the repair of stone masonry walls within ‘cradle-to-site’ was calculated for each selected technique using Equation No. (7) as described in Chapter 4.

Table 5.14: Typical embodied carbon expenditure for repair within ‘cradle-to-site’- Doune Castle

		Repair Techniques/Embodied Carbon Expenditure ($kgCO_2e/kg$) Within' Cradle-to-Site' for HS1-Doune Castle							
		(1) Natural Stone Replacement			**(2) Repointing**	**(3) Pinning and consolidation**		**(4) Plastic repair**	
Year	**Intervention (n)**	(a) Indenting using lime grout mix **@ 31.853 $kgCO_2e/kg$**	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix **@ 61.207 $kgCO_2e/kg$**	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin **@ 77.909 $kgCO_2e/kg$**	*Using lime mortar **@ 2.828 $kgCO_2e/kg$**	(a) Using stainless steel dowels and lime grout mix **@ 29.226 $kgCO_2e/kg$**	(b) Using stainless steel dowels and epoxy resin **@ 46.056 $kgCO_2e/kg$**	(a) Using lime based mortar and aggregates **@ 6.050 $kgCO_2e/kg$**	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair **@ 112.952 $kgCO_2e/kg$**
2001	1				56.560				
	2							290.400	
	3				73.528				
	4								1920.184
	5					1052.136			
2002	6	31.853							
	7							108.900	
	8				50.904				
2003	9					789.102			
2004	10		153.018						
	11				56.560				
2005	12					1315.170			
	13				169.680				
2006	14							121.000	
	15				118.776				
2007	16					1315.170			
	17			116.864					
2008	18						460.560		
2009	19				138.572				
2010	20				70.700				
Total ($kgCO_2e/kg$)		**31.853**	**153.018**	**116.864**	**735.280**	**4471.578**	**460.560**	**520.300**	**1920.184**

Source: Author, 2012.

In the example of Doune Castle (Table 5.14), multi-layer plastic repair techniques accounted for the highest total value of embodied carbon per m^2 wall repaired within ‘cradle-to-site’ and during the 2001 to 2010 maintenance period (112.952 $kgCO_2e/kg/m^2$). Repointing with lime mortars accounted for the lowest figure (2.828 $kgCO_2e/kg$). Despite having the sixth highest figure of 29.226 $kgCO_2e/kg/m^2$ for the pinning and consolidation technique using stainless steel dowels and lime grout mix, this technique accounted for the highest total (4471.578 $kgCO_2e/kg$; 53.17%) out of a total figure of 8409.637 $kgCO_2e/kg$. This technique was also adopted to repair the second-largest area of stone masonry wall (153.00 m^2 out of 531.00 m^2, or 28.88%). In comparison, multi-layer plastic repair accounted for the second highest total of 1920.184 $kgCO_2e/kg$, or 22.83%, within the same boundary and maintenance periods, despite it having the highest figure of 112.952 $kgCO_2e/kg/m^2$. In contrast, indenting using lime grout mix in natural stone replacement techniques accounted for the lowest total of 31.853 $kgCO_2e/kg$, with the smallest area of stone masonry wall area repaired ($1m^2$ out of a total $531m^2$, or 0.19%). Despite accounting for the fifth-highest value of embodied carbon expenditure in every m^2 of stone masonry wall repair, expenditure using this technique was only 31.853 $kgCO_2e/kg$ out of an overall total of 8409.637 $kgCO_2e/kg$, or 0.40%, within the same boundary and maintenance periods.

The results from Doune Castle show that the larger the area of stone masonry wall repaired (m^2) and the higher the value of embodied carbon expenditure in every m^2 of wall repaired ($kgCO_2e/kg$ /m^2), the higher the total and percentage embodied carbon expenditure ($kgCO_2e/kg$) within the 'cradle-to-site' boundary and selected maintenance periods. It was found that total embodied carbon expenditure for each stone masonry wall repair technique was highly dependent on both the embodied coefficient value of materials within 'cradle-to-gate' (expended in mining, quarrying, processing and manufacturing) as well as the kg/km emissions factors emitted within 'gate-to-site' (CO_2 emissions for the transportation of materials from the resourcing location to building site (expended in materials transportation). Research results showed that the higher the value of the embodied carbon coefficient of materials used and the greater the transportation distance needed for the delivery of materials, the higher the value of $kgCO_2e/kg$ /m^2. The $kgCO_2e/kg/m^2$ value resulted in a greater total embodied carbon expenditure expended for repair to stone masonry walls within the 'cradle-to-site' boundary and selected maintenance periods.

5.7 Efficacy of Stone Masonry Wall Repairs to Historic Masonry Buildings in Terms of Embodied Carbon Expenditure

5.7.1 Total Number of Maintenance Intervention (n)

The total number of interventions (n) undertaken within the 2001 to 2010 maintenance period for stone masonry wall repair using selected techniques was generated in Table 5.15.

Table 5.15: Total number of maintenance interventions (n)

		Repair Techniques/Total Number of Intervention (n) Within 2001-2010 Maintenance Periods								
		(1) Natural Stone Replacement			(2) Repointing	(3) Pinning and consolidation		(4) Plastic repair		
No. (code)	**Property**	(a) Indenting using lime grout mix	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin	*Using lime mortar	(a) Using stainless steel dowels and lime grout mix	(b) Using stainless steel dowels and epoxy resin	(a) Using lime based mortar and aggregates	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair	**Total (n)**
	Historic Scotland									
HS1	Doune Castle	1	1	1	8	4	1	3	1	**20**
HS2	Melrose Abbey	1	1	1	2	3	3	1	1	**13**
HS3	Glasgow Cathedral	5	1	1	1	3	3	1	1	**16**
HS4	Old Palace/Palace of James V, Stirling Castle	1	1	1	2	1	1	2	1	**10**
HS5	King's Old Building/Douglas Block, Stirling Castle	1	1	1	1	1	1	2	1	**9**
HS6	Great Hall/Old Parliament House, Stirling Castle	1	1	1	2	1	1	1	2	**10**
HS7	Craignethan Castle	1	1	1	4	3	1	3	1	**15**
HS8	Jedburgh Abbey	1	1	1	5	5	6	5	4	**28**
HS9	Linlithgow Palace	1	1	1	9	1	1	1	1	**16**
	National Trust for Scotland (NTS)									
NTS1	Newhailes Estate, Stable Block	1	1	1	2	1	1	2	1	**10**
NTS2	Newhailes Estate, Mainhouse	1	1	1	2	1	1	1	1	**9**
NTS3	Culross Palace	1	1	1	3	1	1	1	1	**10**
NTS4	Falkland Palace	1	1	1	4	2	2	1	1	**13**
NTS5	House of The Binns	1	1	1	2	1	1	1	1	**9**
NTS6	Threave House,Threave Estate, Castle Douglas	1	1	1	1	1	1	1	1	**8**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	1	1	1	1	1	1	1	1	**8**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	1	1	1	1	1	1	1	1	**8**
NTS9	Harmony House/St. Cuthbert House, Melrose	1	1	1	1	1	1	1	1	**8**
NTS10	Hamilton House, East Lothian	1	1	1	1	1	1	1	1	**8**
	The City of Edinburgh Council (CEC)									
CEC1	15 Hillside Crescent & 30-32 Hillside Street	1	1	1	1	1	1	1	1	**8**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	1	1	1	1	2	1	1	1	**9**
CEC3	21-31 Hillside Street	1	1	1	2	1	1	1	1	**9**
CEC4	22-30 Shandwick Place, Edinburgh	6	1	4	2	6	10	1	1	**31**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	4	2	2	1	4	4	0	1	**18**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	1	0	0	3	1	1	1	0	**7**
CEC6	36-42 Forbes Road, Edinburgh	1	1	1	1	1	1	1	1	**8**
CEC7	4-11 Elm Row, Edinburgh	3	1	1	1	4	3	1	1	**15**
CEC8	148-164 Bruntsfield Place, Edinburgh	3	2	1	4	1	1	2	5	**19**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	2	1	1	5	1	2	1	1	**14**

Source: Author, 2012.

Table 5.15 shows that the highest total number of interventions (n) within the 2001 to 2010 maintenance period used the pinning and consolidation technique, which accounted for 40 interventions out of a total of 137 (29.20%) across all of Historic

Scotland's sample properties. A total of 16.06% or 22 interventions involved the use of stainless dowels and lime grout mix compared to 13.14% (18) that used stainless dowels with epoxy resin. The lime mortar technique accounted for the second lowest number of interventions (24.82% or 34 interventions out of 137). Conversely, the lowest total number of interventions (n) within the same period (22.63%) involved the natural stone replacement technique. Both indenting using lime grout mix with stainless steel dowels and stainless dowels with epoxy resin contributed to 6.57% (nine interventions each) compared to 9.49% (13 interventions) indenting using lime grout mix.

In the case of the National Trust for Scotland's sample properties, the highest total number of interventions (n) over the same period involved the replacement of natural stone, which accounted for a total of 32.97% or 30 interventions out of 91 overall. Proportionally, 10.99% or 10 interventions involved indenting using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin. Meanwhile, the lime mortar or repointing technique accounted for the lowest total number of interventions (n) within a similar maintenance period (19.78%; 18 interventions out of a total of 91).

In comparison, the highest total number of interventions (n) within similar periods for the City of Edinburgh Council's sample properties involved natural stone replacement and pinning and consolidation, which accounted for a total of 34.06% or 47 interventions out of 138 overall. In the case of natural stone replacement, 16.67% or a total of 23 interventions involved indenting using lime grout mix, 7.97% or 11 interventions involved the use of lime grout mix with stainless steel dowels and 9.42% or 13 interventions involved the use of lime grout mix with stainless steel dowels and epoxy resin. For pinning and consolidation, 15.94% or a total of 22 interventions involved the use of stainless steel dowels and lime grout mix and 18.12% or 25 interventions involved the use of stainless steel dowels and epoxy resin. On the other hand, the lowest total number of interventions (n) within the same period (15.22%; 21 out of 138) occurred during the use of the repointing technique to repair stone masonry walls using lime mortar.

The research results potentially highlight that there are differences in the organisations philosophical attitude towards repair, with some having a greater propensity for an interventionist approach as opposed to a minimal intervention strategy. This is illustrated by the number of interventions (n) undertaken by respective organisation relative to each other.

5.7.2 Total Repaired Wall Area (m^2)

The total area of stone masonry wall (m^2) repaired from 2001 to 2010 using selected techniques was generated in Table 5.16.

Table 5.16 shows that the area (m^2) of stone masonry wall repaired from 2001 to 2010 by each collaborative partner ranged between 50.00m^2 (CEC 2-15,16, 16A, 17-19 Hillside Crescent) to 765.07 m^2 (CEC5-131-141 Bruntsfield Place, Edinburgh: Stone Type B). It was also found that 127.11 m^2 and 5117.50 m^2 of wall area was repaired at HS5-King's Old Building/Douglas Block at Stirling Castle and HS9-Linlithgow Palace in Historic Scotland's sample properties respectively. In comparison, between 61.52 m^2 (NTS9-Harmony House/St. Cuthbert House, Melrose) and 1706.16 m^2 (NTS5-House of the Binns) of stone masonry wall repair was undertaken within the same period across National Trust for Scotland properties. In the case of Historic Scotland's sample properties (such as HS5-King's Old Building/Douglas Block of Stirling Castle), the smallest total area of 3.11 m^2 was repaired using the natural stone replacement technique. Proportionately, out of a total of 127.11 m^2, 2.00 m^2 (1.57%), 1.00 m^2 (0.79%) and 0.11 m^2 (0.09%) of stone masonry wall area was indented using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin respectively. On the other hand, the largest area (51.00 m^2) of stone masonry wall at this property was repaired using pinning and consolidation, which comprised 40.00 m^2 (31.47%) of stainless steel dowels and lime grout mix and 11.00 m^2 (8.65%) of stainless dowels and epoxy resin. In the case of HS9-Linlithgow Palace, out of a total of 5117.50 m^2 of stone masonry wall repaired, at least 17.50 m^2 (0.35%) was repaired using natural stone replacement. In detail, this consisted of 9.00 m^2 (0.18%), 6.00 m^2 (0.12%) and 2.50 m^2 (0.05%) using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin respectively. In comparison, the largest area (4970.00 m^2 out of a total of 5117.50 m^2 or 97.12%) of stone masonry wall at this property was repaired using the lime mortar repointing technique.

Conversely, the National Trust for Scotland's properties, such as NTS9-20-24A Frederick Street, 71-81 Rose Street and 52 Rose Street Lane, Edinburgh, had the smallest total area of wall repaired (5.60m^2) using the natural stone replacement technique. Proportionately, the total area of 61.52m^2 total wall repaired consisted of 3m^2 (4.88%), 2m^2 (3.25%) and 0.6m^2 (0.98%) repaired by indenting using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin respectively. In comparison, the largest area (30m^2) of stone masonry wall at this property was repaired using the lime mortar repointing technique, which accounted for 48.76%. In the case of NTS5-House of the Binns, out of a total of 1706.16 m^2 total stone masonry wall repaired, 89.57 m^2 (5.24%) was repaired using natural stone replacement. In detail, this consisted of 40m^2 (2.34%) for both indenting using lime grout mix and lime grout mix with stainless steel dowels and 9.57m^2 (0.56%) using lime grout mix with stainless steel dowels and epoxy resin. It was also found that out of a total of 1706.16 m^2 or 73.14%, the largest area of 1247.87m^2 of stone masonry wall of NTS5 was repaired using the lime mortar repointing technique.

In comparison, CEC2-15,16, 17-19 Hillside Street, one of the City Edinburgh Council properties, had the smallest total area of wall repaired (11.40 m^2) using the natural stone replacement technique. Out of a total area of 50m^2 repaired stone masonry wall at CEC2, indenting using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin accounted for 6m^2 (12%), 3.2m^2 (6.4%) and 2.20m^2 (4.4%) respectively. In contrast, the largest area (15.30 m^2) of stone masonry wall at CEC2 was repaired using the lime mortar repointing technique, which accounted for nearly one-third of the total percentage (30.6%). Out of a total of 765.07m^2 total stone masonry repaired at CEC5-131-141 Bruntsfield Place, natural stone replacement using Stone Type B accounted for the lowest figure of 2.67m^2 (0.35%). Proportionately, this consisted of 2.67m^2 (2.34%) of stone masonry wall repaired using indenting using lime grout mix. In contrast, no (0m^2 or 0%) area of stone masonry wall was indented within the selected 2001 to 2010 maintenance period using lime grout mix with stainless steel dowels and lime grout mix, stainless steel dowels and epoxy resin. In comparison, the largest areas of 532m^2 out of a total of 765.07 m^2 or (69.54%) of stone masonry wall at CEC5 (Stone Type B) was repaired solely using lime-based mortar and aggregates of plastic repair. Out of this figure, none of the stone masonry wall of CEC5 (Stone Type B) was repaired using the multi-layer plastic repair of the similar plastic repair technique within the same period.

Table 5.16**:** Total stone masonry wall repaired (m^2)

		Repair Techniques/Total Wall Area Repaired (m^2) Within 2001-2010 Maintenance Periods								
		(1) Natural Stone Replacement			**(2) Repointing**	**(3) Pinning and consolidation**		**(4) Plastic repair**		
No. (code)	**Property**	(a) Indenting using lime grout mix	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin	*Using lime mortar	(a) Using stainless steel dowels and lime grout mix	(b) Using stainless steel dowels and epoxy resin	(a) Using lime based mortar and aggregates	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair	**Overall total wall repaired (m^2)**
	Historic Scotland									
HS1	Doune Castle	1.00	2.50	1.50	260.00	153.00	10.00	86.00	17.00	**531.00**
HS2	Melrose Abbey	5.00	1.00	2.00	2160.00	520.00	111.80	300.00	60.00	**3159.80**
HS3	Glasgow Cathedral	20.00	4.00	4.00	48.00	378.00	70.00	15.00	6.00	**545.00**
HS4	Old Palace/Palace of James V, Stirling Castle	21.00	6.00	0.62	453.00	90.00	8.00	36.00	27.00	**641.62**
HS5	King's Old Building/Douglas Block, Stirling Castle	2.00	1.00	0.11	43.00	40.00	11.00	26.00	4.00	**127.11**
HS6	Great Hall/Old Parliament House, Stirling Castle	16.00	8.00	0.77	616.00	60.00	11.00	155.00	59.00	**925.77**
HS7	Craignethan Castle	20.00	6.00	3.75	751.70	175.00	7.50	158.00	3.00	**1124.95**
HS8	Jedburgh Abbey	5.50	1.20	0.72	172.40	54.30	11.25	82.50	19.00	**346.87**
HS9	Linlithgow Palace	9.00	6.00	2.50	4970.00	20.00	20.00	60.00	30.00	**5117.50**
	National Trust for Scotland (NTS)									
NTS1	Newhailes Estate, Stable Block	5.00	3.00	2.00	511.80	100.00	20.70	121.50	5.25	**769.25**
NTS2	Newhailes Estate, Mainhouse	5.00	2.00	0.80	405.00	60.00	37.00	67.60	44.00	**621.40**
NTS3	Culross Palace	15.00	5.00	4.01	831.25	40.00	8.02	48.02	24.01	**975.31**
NTS4	Falkland Palace	50.00	30.00	7.64	1173.36	210.00	102.81	100.00	32.05	**1705.86**
NTS5	House of The Binns	40.00	40.00	9.57	1247.87	100.00	100.00	100.00	68.72	**1706.16**
NTS6	Threave House,Threave Estate, Castle Douglas	50.00	30.00	2.83	576.23	50.00	39.57	60.00	40.00	**848.63**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	4.00	3.00	2.14	40.00	15.00	5.91	20.00	3.56	**93.61**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	20.00	15.00	2.52	200.00	40.00	21.03	70.00	15.88	**384.43**
NTS9	Harmony House/St. Cuthbert House, Melrose	3.00	2.00	0.60	30.00	7.00	0.92	12.00	6.00	**61.52**
NTS10	Hamilton House, East Lothian	10.00	4.00	2.53	44.57	10.00	6.53	40.00	4.57	**122.20**
	The City of Edinburgh Council (CEC)									
CEC1	15 Hillside Crescent & 30-32 Hillside Street	13.60	4.80	1.80	27.50	10.00	4.25	4.70	2.10	**68.75**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	6.00	3.20	2.20	15.30	16.00	2.00	5.00	0.30	**50.00**
CEC3	21-31 Hillside Street	7.00	7.00	0.80	112.90	10.00	7.00	20.00	3.00	**167.70**
CEC4	22-30 Shandwick Place, Edinburgh	107.55	8.53	18.40	407.33	161.97	7.16	17.00	15.00	**742.94**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	11.28	3.63	2.06	135.00	80.00	43.00	0.00	1.44	**276.41**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	2.67	0.00	0.00	212.34	11.06	7.00	532.00	0.00	**765.07**
CEC6	36-42 Forbes Road, Edinburgh	17.00	11.00	2.59	50.00	5.00	2.00	10.00	5.00	**102.59**
CEC7	4-11 Elm Row, Edinburgh	44.69	10.78	2.70	60.32	90.37	12.62	10.00	0.18	**231.66**
CEC8	148-164 Bruntsfield Place, Edinburgh	35.50	7.30	0.07	214.86	0.34	0.14	21.30	6.25	**285.76**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	17.19	2.15	1.67	591.00	40.59	2.62	17.00	16.00	**688.22**

Source: Author, 2012.

Table 5.16 shows the highest total area (m^2) of stone masonry wall repaired during the 2001 to 2010 maintenance period. Across Historic Scotland's properties, two-thirds of the overall total wall repaired (75.67 %; 9474.10 m^2) was done using the lime mortar repointing repair technique. The replace natural stone technique accounted for the smallest total area of stone masonry wall repaired (1.21% or 151.17 m^2). In more detail, indenting using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin respectively accounted for 0.79 % (99.50 m^2), 0.29% (35.70 m^2) and 0.13% (15.97 m^2) of repairs. In comparison, results show that repointing was used for the largest total area of wall repaired across National Trust for Scotland's sample properties (69.43%: 5060.08 m^2 out of an overall total area of 7288.37 m^2) within the same period. Natural stone replacement accounted for the smallest area of stone masonry wall repair (5.09%; 370.64 m^2). In proportion, 2.77% (202m^2), 1.84% (134m^2) and 0.48% (34.64 m^2) of indenting was performed using lime grout mix, lime grout mix with stainless steel dowels and lime grout mix with stainless steel dowels and epoxy resin respectively. Within the same maintenance period, the largest total area of wall repaired across the City of Edinburgh Council's sample properties was performed using the lime mortar repointing technique. This repair technique accounted for more than half of the overall total area of stone masonry wall repaired (1826.55 m^2 or 54.05% out of the overall total of 3379.10 m^2). The natural stone replacement technique accounted for the smallest area (10.64%) of stone masonry wall repaired (353.16 m^2 out of an overall total of 3379.10 m^2). In terms of the proportions comprising the natural stone replacement, 7.77 % or 262.48 m^2 of stone masonry wall was indented using lime grout mix, 1.73 % or 58.39 m^2 using lime grout mix with stainless steel dowels and 0.96% or 32.29 m^2 using lime grout mix with stainless steel dowels and epoxy resin.

Based on aforementioned result, it can be concluded that lime mortar repointing is commonly contributed to the largest stone masonry wall area repaired (both in total m^2 and percentage) compared to other repair techniques. This result pattern is similar across all three organisations and indicates that repointing technique is highly influenced by commonly large area of delaminated wall surface – which mean it will normally contribute to the higher embodied carbon expenditure in longer maintenance time frame.

5.7.3 Total Embodied Carbon Per m^2 Wall Repaired ($kgCO_2e/kg/m^2$)

The total embodied carbon per m^2 repaired wall ($kgCO_2e/kg/m^2$) for each selected techniques within 'cradle-to-site' was calculated using Equation No. (8) as shown in Chapter 4.

Table 5.17 shows the total embodied carbon expenditure per $1m^2$ of stone masonry wall repaired ($kgCO_2e/kg/m^2$) within 'cradle-to-site' boundaries across selected sample properties. Research results show that the minimum, maximum and average $kgCO_2e/kg/m^2$ values within 'cradle-to-gate' were highly influenced by the embodied carbon coefficient value of repair materials and their profiles (bulk density, namely for stone and mass in kilogrammes used).

In comparison, kg/km emission factors (the mode of transport and in this case the mass in kilogrammes of materials transported, the resourcing location and transportation distance) are the main factors influencing the $kgCO_2e/kg/m^2$ expended within ‘gate-to-site’.

In general, the higher the embodied carbon coefficient value and mass (kg) of materials used for repair, the greater the value of ($kgCO_2e/kg/m^2$) expended within ‘cradle-to-gate’ boundaries. Meanwhile, the greater the value of mass (kg) of transported materials and the transportation distance for their delivery to the building site, the higher $kgCO_2e/kg/m^2$) expended within ‘gate-to-site’ boundaries. This trend applies across the sample properties.

Within ‘cradle-to-site’, it was found that the highest total average of 114.230 $kgCO_2e/kg/m^2$ was expended on multi-layer plastic repair techniques. This is up to approximately 38 times greater than for lime mortar repointing, particularly considering the lowest average figure of 2.988 $kgCO_2e/kg/m^2$. It must be emphasised that the high embodied carbon coefficient value for the secondary fixing materials, namely stainless dowels, epoxy resin and non-ferrous tying wire, used in multi-layer patch is the main factor behind their usage accounting for the highest expenditure.

Meanwhile, it was found that an average of between 110.967 $kgCO_2e/kg/m^2$ (NTS5-House of the Binns) and 117.460 $kgCO_2e/kg/m^2$ (HS2-Melrose Abbey) within ‘cradle-to-site’ was expended in multi-layer plastic repair a technique, which is higher than for other repair techniques. This is up to approximately 22 to 97 times than the application of lime mortar repointing, particularly considering the lowest average figures of 1.147 $kgCO_2e/kg/m^2$ (NTS9-Harmony House/St. Cuthbert House, Melrose) and 5.257 $kgCO_2e/kg/m^2$ (NTS5-House of the Binns)].

It was found that the use of secondary fixing materials with a high embodied carbon coefficient value, such as stainless dowels, epoxy resin and non-ferrous tying wire, in multi-layer plastic repair caused a high $kgCO_2e/kg/m^2$ figure. In contrast, the lower figure for $kgCO_2e/kg/m^2$ was mainly accounted for by the use of low carbon materials, such as in lime mortar repointing.

Table 5.17: Total embodied carbon per 1m^2 of stone masonry wall repaired (kgCO$_2$e/kg/m^2) within ‘cradle-to-site’.

Repair Techniques	**Within 'cradle-to-site'**		
	Minimum (kgCO$_2$e/kg/m^2)/Sample Properties	**Maximum (kgCO$_2$e/kg/m^2)/Sample Properties**	**Average (kgCO$_2$e/kg/m^2)**
1. Natural stone replacement			
a. Indenting + lime mortar grout mix	21.928/NTS9	43.745/HS8	31.561
b. Indenting + dowels + lime grout mix	51.300/NTS9	72.998/HS8	61.217
c. Dowels + epoxy resin	67.949/NTS9	89.760/HS8	77.601
2. Repointing			
Lime mortar repointing	1.147/NTS9	5.257/NTS5	2.988
3. Pinning and consolidation			
a. Dowels + lime grout mix	29.121/HS8	29.810/NTS4	29.417
b. Dowels + epoxy resin	46.015/HS8	46.077/NTS4	46.041
4. Plastic repair			
a. Lime based mortar with aggregates	4.815/NTS5	8.994/HS2	6.900
b. Lime based mortar (multi-layer plastic repair)	110.967/NTS5	117.460/HS2	114.230

Source: Author, 2012.

Note:

HS2-Melrose Abbey, HS8-Jedburgh Abbey, NTS4-Falkland Palace, NTS5-House of the Binns and NTS9-Harmony House/St. Cuthbert House, Melrose

Appendix J provides more detailed information on the total, minimum, maximum and average $kgCO_2e/kg/m^2$ expenditure value for each sample property within ‘cradle-to-site’.

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

The total embodied carbon ($kgCO_2e/kg$) expended during the processing and manufacturing of repair materials used in repairing stone masonry walls for each selected technique within ‘cradle-to-gate’ was calculated using Equation No. (9), as shown in Chapter 4.

Table 5.18: Total embodied carbon expenditure for stone masonry wall repair within ‘cradle-to-gate’

Repair Techniques	**Total (kgCO2e/kg) Within 'cradle-to-gate'**		
	Minimum ($kgCO_2e/kg$)/Sample Properties	**Maximum ($kgCO_2e/kg$)/Sample Properties**	**Average ($kgCO_2e/kg$)**
1. Natural stone replacement			
a. Indenting + lime mortar grout mix	22.767/HS1	1888.471/CEC4	453.549
b. Indenting + dowels + lime grout mix	0.000/CEC5-Stone Type B	2287.680/NTS5	459.949
c. Dowels + epoxy resin	0.000/CEC5-Stone Type B	1165.291/CEC4	220.203
Total	46.883/CEC5-Stone Type B	4102.624/NTS5	1094.517
2. Repointing			
Lime mortar repointing	19.278/CEC2	10601.010/HS9	1779.266
Total	19.278/CEC2	10601.010/HS9	1779.266
3. Pinning and consolidation			
a. Dowels + lime grout mix	9.843/CEC8	15068.560/HS2	2867.943
b. Dowels + epoxy resin	6.408/CEC8	5117.309/HS2	1185.303
Total	16.251/CEC8	20185.869/HS2	4053.246
4. Plastic repair			
a. Lime based mortar with aggregates	0.000/CEC5-Stone Type A	2633.932/CEC5-Stone Type B	470.820
b. Lime based mortar (multi-layer plastic repair)	0.000/CEC5-Stone Type B	7442.994/NTS5	2098.617
Total	57.887/CEC2	9113.040/HS2	2540.211
Cumulative expenditure across all techniques and sample properties	**1021.505/CEC2**	**36527.450/HS2**	**9254.534**

Source: Author, 2012.

Notes:

HS1-Doune Castle, HS2-Melrose Abbey, HS9-Linlithgow Palace, NTS5-House of the Binns, CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh, CEC4-22-30 Shandwick Place, Edinburgh, CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A), CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and CEC8-148-164 Bruntsfield Place, Edinburgh

Table 5.18 shows the total embodied carbon expenditure ($kgCO_2e/kg$) for each selected stone masonry wall repair technique across all sample properties within ‘cradle-to-gate’ and the 2001 to 2010 maintenance period. Results show that the minimum, maximum and average $kgCO_2e/kg$ values were highly influenced by the total number of maintenance interventions (n) and total area of wall repaired (m^2). The more frequent the maintenance interventions undertaken and the larger the area of wall repaired, the greater the total $kgCO_2e/kg$ expended within the same boundary and maintenance periods. Meanwhile, the greater the total $kgCO_2e/kg$ expended on selected repair techniques, the higher the cumulative $kgCO_2e/kg$ expenditure. This trend applies across all the selected repair techniques for stone masonry wall repair at all the sample properties.

Within this boundary of LCA, it was found that the highest average value (2867.943 $kgCO_2e/kg$) resulted from the usage of stainless dowels and lime grout mix for pinning and consolidation techniques. This is up to 13 times greater than natural stone replacement techniques, particularly considering the lowest average value is 220.203 $kgCO_2e/kg$. It must be noted that the higher number of maintenance interventions (n) undertaken (lower longevity of repair) contributed to the high $kgCO_2e/kg$ value. In addition, the larger the area of wall repaired (m^2) for the former is the main reason for it accounting for the highest average $kgCO_2e/kg$ expenditure. In comparison, research results show that natural stone replacement is not only more efficient in terms of embodied carbon expenditure compared to pinning and consolidation techniques, but significantly more durable. This illustrates the relative efficiency of natural stone replacement in terms of CO_2.

The research results suggest that greater adoption of natural stone replacement as oppose to other repair techniques are beneficial and are an effective mechanism to reduce embodied carbon expenditure. In addition, the use of alternative materials for dowels that have a lower embodied carbon coefficient, such as nylon rods (generally plastic dowels have an embodied carbon coefficient of 3.31 $kgCO_2e/kg$) should be encouraged as opposed to using stainless dowels (6.15 $kgCO_2e/kg$) (Hammond and Jones 2011). Alternatively, obviating the use of stainless dowels for stone anchorage can be achieved by altering the repair approach adopted such as building a stone into a wall to greater depth (for natural stone replacement). In situations where doweling is unavoidable, such as pinning and consolidation of face bedded stone it is clearly beneficial to use nylon dowels.

For multi layer plastic repairs that require anchorage for wire frameworks it would be prudent to obviate the use of stainless dowels and non-ferrous tying wire and use ceramic T solutions that should have significantly lower embodied carbon (embodied carbon of 0.70 $kgCO_2e/kg$ (Hammond and Jones 2011). This would obviously reduce the embodied carbon expenditure for this type of stone masonry wall repair and make them relatively more favourable.

It was also found that the highest total (4053.246 $kgCO_2e/kg$) was expended on the pinning and consolidation technique. This is up to four times greater than for natural stone replacement, particularly considering the lowest average figure of 1094.517

$kgCO_2e/kg$. This is due to the lower longevity of repair for the former. The lower the longevity of the repair, the more frequent number of maintenance interventions (n). Consequently, the more frequently that repairs need to be undertaken, the larger the area of wall repaired. This will contribute to the higher total embodied carbon expenditure within the same boundary and maintenance periods.

Within the same boundary and maintenance periods, it was also found that the maximum cumulative figure of 36527.45 $kgCO_2e/kg$ was expended for HS2-Melrose Abbey, compared to the lowest cumulative figure of 1021.505 $kgCO_2e/kg$ for CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh. Comparatively, cumulative embodied carbon expenditure for the former was up to 36 times greater than for the latter. It was found that the lower the longevity of the repair, the higher number of maintenance interventions (n) undertaken and the larger area of wall area (m^2) repaired in the former case contributed to the higher total embodied carbon expenditure. More detailed information on the total embodied carbon expenditure ($kgCO_2e/kg$) across all stone masonry wall repair techniques and selected sample properties within 'cradle-to-gate' and the 2001 to 2010 period are shown in Appendix K.

5.7.5 Total Embodied Carbon Expenditure for Stone Masonry Wall Repair Within 'Gate-to-Site'

The total embodied carbon ($kgCO_2e/kg$) expended in the transportation of repair materials used in the repair of stone masonry walls of historic masonry buildings to site within 'gate-to-site' was calculated using Equation No. (10) as shown in Chapter 4.

Table 5.19: Total embodied carbon expenditure for stone masonry wall repair (‘gate-to-site’)

Repair Techniques	**Total (kgCO$_2$e/kg) Within 'gate-to-site'**		
	Minimum (kgCO$_2$e/kg)/Sample Properties	**Maximum (kgCO$_2$e/kg)/Sample Properties**	**Average (kgCO$_2$e/kg)**
1. Natural stone replacement			
a. Indenting + lime mortar grout mix	9.086/HS1	766.186/CEC4	197.407
b. Indenting + dowels + lime grout mix	0.000/CEC5-Stone Type B	510.440/NTS5	92.346
c. Dowels + epoxy resin	0.000/CEC5-Stone Type B	136.141/CEC4	30.791
Total	19.283/CEC5-Stone Type B	1116.163/NTS5	311.305
2. Repointing			
Lime mortar repointing	5.845/CEC2	1973.090/HS9	425.209
Total	5.845/CEC2	1973.090/HS9	425.209
3. Pinning and consolidation			
a. Dowels + lime grout mix	0.148/CEC8	182.520/HS2	40.982
b. Dowels + epoxy resin	0.036/CEC8	31.357/NTS4	7.098
Total	0.184/CEC8	210.917/HS2	47.985
4. Plastic repair			
a. Lime based mortar with aggregates	0.000/CEC5-Stone Type A	818.216/CEC5-Stone Type B	129.950
b. Lime based mortar (multi-layer plastic repair)	0.000/CEC5-Stone Type B	883.427/NTS1	106.529
Total	4.501CEC5-Stone Type A	1090.220/NTS1	216.901
Cumulative expenditure across all techniques and sample properties	**88.939/NTS9**	**2962.677/NTS4**	**940.908**

Source: Author, 2012.

Notes:

HS1-Doune Castle, HS2-Melrose Abbey, HS9-Linlithgow Palace, NTS1-Newhailes Estate, Stable Block, NTS4-Falkland Palace, NTS5-House of the Binns, NTS9-Harmony House/St. Cuthbert House, Melrose, CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh, CEC4-22-30 Shandwick Place, Edinburgh, CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A), CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and CEC8-148-164 Bruntsfield Place, Edinburgh

Table 5.19 shows the total embodied carbon expenditure ($kgCO_2e/kg$) for each selected stone masonry wall repair technique undertaken across all sample properties within ‘gate-to-site’ and the 2001 to 2010 maintenance period. Within the same boundary and maintenance periods, $kgCO_2e/kg$ values were highly influenced by the total number of maintenance interventions (n) and the total area (m^2) of wall repaired. The more frequent the maintenance interventions undertaken and the larger the area of wall repaired, the greater the total CO_2 emissions emitted during the transportation of materials within the ‘gate-to-site’ boundary. Meanwhile, the greater the total $kgCO_2e/kg$ expended during selected repair techniques, the higher the cumulative $kgCO_2e/kg$. This trend applies across all the selected repair techniques for stone masonry wall repair and all sample properties.

Within this boundary, research results show that lime mortar repointing accounted for the highest average figure of 425.209 kgCO_2e/kg. This is up to 60 times greater than the corresponding figure for the use of stainless dowels and epoxy resin during pinning and consolidation, particularly considering the lowest average figure of 7.098 kgCO_2e/kg. This was due to the higher the number of maintenance interventions (n) undertaken (lower longevity of repair), the higher value of kgCO_2e/kg and the larger the area of wall repaired (m^2). Meanwhile, it was found that lime mortar repointing had the highest total (425.209 kgCO_2e/kg) within the same boundary compared to other repair techniques. This is up to approximately nine times greater than the corresponding figure for pinning and consolidation, particularly considering the lowest average of 47.985 kgCO_2e/kg. This is due to lower longevity of repair for the former. The lower the longevity of the repair, the more frequent number of maintenance interventions (n) that need to be undertaken. This will subsequently result in a larger area of wall being repaired, thus contributing to the higher total embodied carbon expenditure within the same boundary and maintenance periods.

Meanwhile, it was found that the transport of repair materials for lime mortar repointing accounted for the highest figures of 5.845 kgCO_2e/kg (CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh) and 1973.090 kgCO_2e/kg (HS9-Linlithgow Palace). This is approximately 63 to 162 times greater than the embodied carbon expended for stainless dowels and epoxy resin delivery to building sites in the pinning and consolidation techniques, particularly considering the lowest range of 0.036 kgCO_2e/kg-31.357 kgCO_2e/kg]. It must be noted that the use of imported lime mortar material led to high carbon emissions during transportation due to the greater distance needed for delivery to the building site.

In comparison, the kgCO_2e/kg/m^2 expended for the transportation of stainless dowels and epoxy resin used for pinning and consolidation within the same boundary was relatively low, mainly due to lower carbon emissions during delivery as a result of the shorter transportation distance needed for locally sourced stainless dowels and epoxy resin. More detailed information on the total embodied carbon expenditure (kgCO_2e/kg) across all stone masonry wall repair techniques and selected sample properties within ‘gate-to-site’ and the 2001 to 2010 maintenance period is shown in Appendix L.

5.8 Cumulative Embodied Carbon Expenditure for Stone Masonry Wall Repair Within ‘Cradle-to-Site’ and 2001 to 2010 Maintenance Period

The overall total embodied carbon expenditure of the number of interventions (n) and area of stone masonry wall repaired within the 2001 to 2010 maintenance period and ‘cradle-to-site’ was calculated using Equation No. (11) as shown in Chapter 4.

Table 5.20: Cumulative embodied carbon expenditure within 'cradle-to-site' and 2001 to 2010 maintenance period

Repair Techniques	Cumulative ($kgCO_2e/kg$) Within 'cradle-to-site' (for 2001-2010 maintenance periods)		
	Minimum ($kgCO_2e/kg$)/Sample Properties	Maximum ($kgCO_2e/kg$)/Sample Properties	Average ($kgCO_2e/kg$)
1. Natural stone replacement			
a. Indenting + lime mortar grout mix	31.853/HS1	2654.657/CEC4	650.956
b. Indenting + dowels + lime grout mix	0.000/CEC5-Stone Type B	2798.120/NTS5	552.295
c. Dowels + epoxy resin	0.000/CEC5-Stone Type B	1301.432/CEC4	250.994
2. Repointing			
Lime mortar repointing	25.123/CEC2	12574.100/HS9	2204.475
3. Pinning and consolidation			
a. Dowels + lime grout mix	9.991/CEC8	15251.080/HS2	2908.925
b. Dowels + epoxy resin	6.444/CEC8	5145.706/NTS4	1192.305
4. Plastic repair			
a. Lime based mortar with aggregates	0.000/CEC5-Stone Type A	3452.148/CEC5-Stone Type B	600.770
b. Lime based mortar (multi-layer plastic repair)	0.000/CEC5-Stone Type B	7625.652/NTS5	2182.540
Cumulative expenditure across all techniques and sample properties	**1125.340/CEC2**	**38892.117/HS2**	**10192.975**

Source: Author, 2012.

Notes:

HS1-Doune Castle, HS2-Melrose Abbey, HS9-Linlithgow Palace, NTS5-House of the Binns, CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh, CEC4-22-30 Shandwick Place, Edinburgh, CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A), CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and CEC8-148-164 Bruntsfield Place, Edinburgh

Table 5.20 shows the cumulative embodied carbon expenditure ($kgCO_2e/kg$) for each selected stone masonry wall repair technique across all sample properties within 'cradle-to-site' and the 2001 to 2010 maintenance periods. Within the same boundary and maintenance periods, $kgCO_2e/kg$ values were highly influenced by the total number of maintenance interventions (n) and the total area of wall repaired (m^2). The more frequent the maintenance interventions undertaken and the larger the area of wall repaired, the greater the total CO_2 emissions during the transportation of materials within the 'gate-to-site' boundary. Meanwhile, the greater the total $kgCO_2e/kg$ expended during selected repair techniques, the higher the cumulative $kgCO_2e/kg$. This trend applies across all selected repair techniques and sample properties.

Within the same boundary, research results show that the highest cumulative average of 2908.925 $kgCO_2e/kg$ was expended during the pinning and consolidation technique using stainless dowels and lime grout mix. This is approximately 12 times higher than the corresponding figure for the use of stainless dowels and epoxy resin in natural stone replacement, particularly considering the lowest cumulative average 250.994 kgCO$_2$e/kg. The higher number of maintenance interventions (n) undertaken (lower longevity of repair), high value of kgCO$_2$e/kg and larger area of wall repaired (m^2) are the main factors behind this technique accounting for the highest average kgCO$_2$e/kg expenditure.

Meanwhile, it was found that the cumulative embodied carbon expended within the same boundary and periods ranged from a minimum of 9.991 kgCO$_2$e/kg (CEC8-148-164 Bruntsfield Place, Edinburgh) to a maximum of 15251.080 kgCO$_2$e/kg (HS2-Linlithgow Palace). It was found that the pinning and consolidation techniques accounted for the highest cumulative kgCO$_2$e/kg expended. This is approximately 12 times greater than the embodied carbon expenditure arising from the use of stainless dowels and epoxy resin of natural stone replacement technique (considering the highest range of 1301.432 kgCO$_2$e/kg).

It was also found that the use of materials with a high embodied carbon coefficient value, namely stainless dowels, and the high carbon emissions due to the greatest transportation distance led the use of lime mortar materials during pinning and consolidation techniques to have the highest range of cumulative embodied carbon expenditure. In comparison, stainless dowels and epoxy resin used in natural stone replacement within the same boundary and maintenance periods had the lowest range of cumulative embodied carbon expenditure, mainly due to the higher longevity of repair (lower number of maintenance interventions) (n), the smaller area (m^2)] of stone masonry wall repaired (m^2) and the shorter transportation distance to the building site, as stainless dowels and epoxy resin are mainly locally sourced. There is no cumulative embodied carbon expended for CEC5-131-141 Bruntsfield Place, Edinburgh (both Stone Type A and Type B). This is due to no intervention being undertaken using relevant repair techniques within the selected maintenance periods.

Research results show that the lowest cumulative embodied carbon expenditure across Historic Scotland's sample properties for all types of repair techniques within 'cradle-to-site' and the 2001 to 2010 maintenance periods occurred at HS5-King's Old Building/Douglas Block, Stirling Castle (2543.531 kgCO$_2$e/kg) compared to the highest figure at HS2-Melrose Abbey (38892.117 kgCO$_2$e/kg) (further details are shown in

Appendix M). Across Historic Scotland's sample properties, the cumulative average of 13645.984 $kgCO_2e/kg$ was expended within the same boundary and maintenance periods. Comparatively, the values were 1304.143 $kgCO_2e/kg$ for NTS9-Harmony House/St. Cuthbert House, Melrose and 27467.891 $kgCO_2e/kg$ for NTS5-House of The Binns with a cumulative average of 10958.383 $kgCO_2e/kg$ across the National Trust for Scotland's sample properties. Meanwhile, the values were 1125.340 $kgCO_2e/kg$ for CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh and 11995.615 $kgCO_2e/kg$ for CEC4-22-30 Shandwick Place, Edinburgh, with a cumulative average of 4356.709 $kgCO_2e/kg$ expended across the City of Edinburgh Council's sample properties.

An overall comparison of the research results shows that the lowest cumulative embodied carbon expenditure within 'cradle-to-site' and the selected maintenance periods from 2001 to 2010 occurred at CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh (1125.340 $kgCO_2e/kg$), compared to the highest figure at HS2-Melrose Abbey (38892.117 $kgCO_2e/kg$) across Historic Scotland sample properties (further details are shown in Appendix M). Within the same boundary and maintenance periods, the cumulative $kgCO_2e/kg$ values across National Trust for Scotland's sample properties were 1304.143 $kgCO_2e/kg$ for NTS9-Harmony House, Melrose and 27467.891 $kgCO_2e/kg$ for NTS5-House of The Binns. In comparison, the values were 1125.340 $kgCO_2e/kg$ for CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh and 11995.615 $kgCO_2e/kg$ for CEC4-22-30 Shandwick Place, Edinburgh across the City of Edinburgh Council's sample properties.

Appendix M shows the overall cumulative embodied carbon expenditure ($kgCO_2e/kg$) for selected stone masonry wall repair techniques within 'cradle-to-site' and the 2001 to 2010 maintenance periods across all selected sample properties.

5.9 Normalised Embodied Carbon Expenditure: Total Embodied Carbon Expenditure Per Total Area Repaired

Table 5.21: Normalised embodied carbon expenditure within ‘cradle-to-site’

Repair Techniques	Normalised Embodied Carbon Expenditure [Total $kgCO_2e/kg$]/[Total m^2] Within 'cradle-to-site' (for 2001-2010 maintenance periods)		
	Minimum [Total $kgCO_2e/kg$]/[Total m^2]/Sample Properties	Maximum [Total $kgCO_2e/kg$]/[Total m^2]/Sample Properties	Average [Total $kgCO_2e/kg$]/[Total m^2]
1. Natural stone replacement			
a. Indenting + lime mortar grout mix	21.928/NTS9	43.745/HS8	31.563
b. Indenting + dowels + lime grout mix	0.000/CEC5-Stone Type B	72.998/HS8	56.342
c. Dowels + epoxy resin	0.000/CEC5-Stone Type B	89.760/HS8	73.125
2. Repointing			
Lime mortar repointing	1.147/NTS9	5.257/NTS5	2.985
3. Pinning and consolidation			
a. Dowels + lime grout mix	29.121/HS8	29.810/NTS4	29.417
b. Dowels + epoxy resin	46.015/HS8	46.223	46.052
4. Plastic repair			
a. Lime based mortar with aggregates	0.000/CEC5-Stone Type A	8.994/HS2	6.538
b. Lime based mortar (multi-layer plastic repair)	0.000/CEC5-Stone Type B	279.682/NTS2	117.539

Source: Author, 2012.

Notes:

HS2-Melrose Abbey, HS8-Jedburgh Abbey, NTS1-Newhailes Estate, Stable Block, NTS4-Falkland Palace, NTS5-House of the Binns, NTS9-Harmony House/St. Cuthbert House, Melrose, CEC1-15 Hillside Crescent & 30-32 Hillside Street, Edinburgh, CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A) and CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B)

Table 5.21 shows the normalised embodied carbon expenditure [(Total of $kgCO_2e/kg$)/(Total m^2)] per total area (m^2) wall repaired for each selected stone masonry wall repair technique across all sample properties within ‘cradle-to-site’ and the 2001 to 2010 maintenance periods. Within the same boundary and maintenance periods, normalised embodied carbon expenditure values are generally influenced by cumulative expenditure and total area of wall repaired (m^2).

Within the same boundary and maintenance periods, research results show that the highest average figure of normalised embodied carbon (117.539 $kgCO_2e/kg/m^2$) was expended on multi-layer plaster repair in which the pinning and consolidation technique was used. This is up to approximately 39 times greater than the corresponding figure for lime mortar repointing, particularly considering the lowest normalised average of 2.985 $kgCO_2e/kg/m^2$. The use of secondary fixing materials (with a high embodied coefficient) for the former technique contributed to the higher average normalised embodied carbon expenditure ($kgCO_2e/kg/m^2$) compared to the latter. Despite the latter accounting for the lowest $kgCO_2e/kg/m^2$ figure, it must be noted that the total embodied carbon expenditure is relatively dependent on the commonly larger area of wall with loose and deteriorated pointing.

Meanwhile, it was found that the highest normalised embodied carbon range, from a minimum of $0kgCO_2e/kg/m^2$ (CEC5-131-141 Bruntsfield Place, Edinburgh, Stone Type B) to a maximum of 279.682 $kgCO_2e/kg/m^2$ (NTS1-Newhailes Estate, Stable Block) occurred during multi-layer plaster repair technique. This is up to approximately 53 times greater than the normalised embodied carbon expenditure expended on the lime mortar repointing technique, considering the lowest range of 1.147 $kgCO_2e/kg/m^2$ (NTS9-Harmony House/St. Cuthbert House, Melrose) to 5.257 $kgCO_2e/kg/m^2$ (NTS5-House of the Binns)]. It was also found that the use of materials with a high embodied carbon coefficient value, namely secondary fixing materials and the transportation of imported materials, such as lime mortar, caused the highest range of normalised embodied carbon expenditure. It must also be emphasised that the lower range of normalised embodied carbon expenditure in the latter technique is mainly due to the usage less quantity (mass of kg of lime mortar) Research results show that the minimum figure of $0kgCO_2e/kg$ for CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A and Type B respectively) was due to no intervention being undertaken using relevant techniques within the selected maintenance periods.

In comparison, research results (refer to Appendix M) show that across Historic Scotland's sample properties, HS1-Doune Castle had the lowest average normalised embodied carbon expenditure within the same boundary and maintenance periods (48.386 $kgCO_2e/kg/m^2$) compared to the highest figure of 52.196 $kgCO_2e/kg/m^2$ at HS8-Jedburgh Abbey. Within the same boundary and maintenance periods, the values were 46.266 $kgCO_2e/kg/m^2$ (NTS9-NTS9-Harmony House/St. Cuthbert House, Melrose) and 84.203 $kgCO_2e/kg/m^2$ (NTS1-Newhailes Estate, Stable Block) across National Trust for Scotland's sample properties. In comparison, the values at the City of Edinburgh Council's sample properties were 15.426 $kgCO_2e/kg/m^2$ (CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and 52.409 $kgCO_2e/kg/m^2$ (20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh) respectively.

Overall comparisons show that the lowest average normalised embodied carbon expenditure within ‘cradle-to-site’ and the selected maintenance periods of 2001 to 2010 were at CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) (15.426 $kgCO_2e/kg/m^2$) compared to the highest at NTS1-Newhailes Estate, Stable Block (84.203 $kgCO_2e/kg/m^2$). These results indicate that less embodied carbon was expended in repairing every m^2 wall of the former compared to the latter. Additionally, the former is more efficient than the latter in terms of embodied carbon expenditure. Research results show that the lower the value of normalised embodied carbon ($kgCO_2e/kg/m^2$), the more efficient the repair in terms of embodied carbon expenditure. Appendix N provides more detailed results on the normalised embodied carbon expenditure ($kgCO_2e/kg/m^2$) for stone masonry wall repair within ‘cradle-to-site’ and the 2001 to 2010 maintenance periods across all selected sample properties.

5.10 Percentage of Embodied Carbon Expenditure in Stone Masonry Wall Repair

Table 5.22: Percentage (%) of embodied carbon expenditure within the 2001 to 2010 maintenance periods

Repair Techniques	**Percentage (%) of Embodied Carbon Expenditure Within 2001-2010 Maintenance Periods**					
	Within 'cradle-to-gate'			**Within 'gate-to site'**		
	Minimum ($kgCO_2e/kg$)/Sample Properties	**Maximum ($kgCO_2e/kg$)/Sample Properties**	**Average ($kgCO_2e/kg$)**	**Minimum ($kgCO_2e/kg$)/Sample Properties**	**Maximum ($kgCO_2e/kg$)/Sample Properties**	**Average ($kgCO_2e/kg$)**
1. Natural stone replacement						
a. Indenting + lime mortar grout mix	56.72%/CEC7	78.74%/HS2	69.90%	21.26%/HS2	43.28%/CEC7	30.07%
b. Indenting + dowels + lime grout mix	0.00%/CEC5-Stone Type B	88.78/NTS9	77.43%	0.00%/CEC Stone Type B	25.59%/HS8	15.26%
c. Dowels + epoxy resin	0.00%/CEC5-Stone Type B	97.78%/NTS9	80.73%	0.00%/CEC Stone Type B	20.77%/HS8	11.89%
2. Repointing						
Lime mortar repointing	75.59%/NTS9	87.37%/HS8	79.19%	12.63%/HS8	24.41%/NTS9	20.81%
3. Pinning and consolidation						
a. Dowels + lime grout mix	98.08%/NTS4	99.06%/HS8	98.54%	0.94%/HS8	1.92%/NTS4	1.46%
b. Dowels + epoxy resin	99.02%/CEC1	99.47%/HS8	99.39%	0.53%/HS8	0.98%/CEC1	0.61%
4. Plastic repair						
a. Lime based mortar with aggregates	0.00%/CEC5-Stone Type A	86.72%/HS8	72.47%	0.00%/CEC Stone Type A	25.34%/NTS5	19.91%
b. Lime based mortar (multi-layer plastic repair)	0.00%/CEC5-Stone Type B	98.20%/HS8	86.55%	0.00%/CEC5-Stone Type B	60.17%/NTS1	7.01%

Source: Author, 2012.

Note:

HS2-Melrose Abbey, HS8-Jedburgh Abbey, NTS1-Newhailes Estate, Stable Block, NTS4-Falkland Palace, NTS5-House of the Binns, NTS9-Harmony House/St. Cuthbert House, Melrose, CEC1-15 Hillside Crescent & 30-32 Hillside Street, Edinburgh, CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A) and CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and CEC7- 4-11 Elm Row, Edinburgh.

Table 5.22 shows the percentage contribution of embodied carbon expenditure for each selected stone masonry wall repair technique across all sample properties within the 2001 to 2010 maintenance periods. The percentage contribution is based on total embodied carbon expenditure (see Appendix J) expended within 'cradle-to-gate' and 'gate-to-site' respectively. It must be noted that the minimum, maximum and average percentage contributions within 'cradle-to-gate' are commonly influenced by the embodied carbon coefficient value of repair materials and their profiles. In comparison, kg/km emissions factors (mode of transport), the mass in kilogrammes of materials transported, the resourcing location and transportation distance are all factors that influence the percentage contribution of embodied carbon expenditure within the 'gate-to-site' boundary. Commonly, the higher the embodied carbon coefficient value and mass (kg) of materials used for repair, the greater the percentage of contribution within the former boundary. Meanwhile, the greater the value of mass (kg) of materials transported and the longer transportation distance needed for their delivery to the building site commonly results in the latter having a greater percentage of embodied carbon expenditure.

Within the 'cradle-to-gate' boundary, research results show that the highest average contribution (99.39%) of embodied carbon expenditure was from the use of stainless dowels and epoxy resin in the pinning and consolidation techniques. This is higher than the percentage contribution of stone indenting, particularly considering the lowest normalised average of 69.90%. Within the same boundary, the use of secondary fixing materials (with a high embodied coefficient) for the former technique led to it having a greater percentage contribution of embodied carbon expenditure compared to the latter. In general, more maintenance interventions are required when using the former technique due to its lower longevity of repair (shorter life expectancy). In comparison, the lowest percentage contribution for the latter is relatively dependent on the generally lower number of interventions as repair longevity is superior.

Table 5.22 also shows that the highest percentage contributions of embodied carbon expenditure within the 'cradle-to-gate' boundary range from 99.02% (CEC1-15 Hillside Crescent and 30-32 Hillside Street, Edinburgh) to a maximum of 99.47% (HS8-Jedburgh Abbey) where stainless dowels and epoxy resin in the pinning and consolidation techniques were used. This is approximately double the value of the range of the percentage contribution of embodied carbon expended on stone indenting using lime grout mix, the lowest range of which was from 56.72% (CEC7- 4-11 Elm Row, Edinburgh) to 78.74% (HS2- Melrose Abbey). It was also found that the use of lime mortar materials with a high embodied carbon coefficient value, namely secondary fixing materials and a large amount of imported materials requiring greater transportation distances, caused it to have the highest range of embodied carbon expenditure. In comparison, the lowest percentage contribution range of embodied carbon expenditure for the former technique within the same boundary and maintenance periods is mainly due to the use of low carbon materials such as lime mortar grout mix. It must be noted that the minimum 0% embodied carbon expenditure within the 'cradle-to-gate' boundary for CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A and Type B) was due to no intervention being undertaken using relevant techniques within the selected maintenance periods.

In comparison, research results show that within the 'gate-to-site' boundary and the 2001 to 2010 maintenance periods, the lowest average percentage of embodied carbon expenditure was produced by the pinning and consolidation techniques using stainless dowels and epoxy resin repair techniques (0.61%) compared to the highest (30.07%) for the indenting of stone using lime mortar grout mix. The percentage was higher for the latter due to the usage of stone (high mass in kg) that resulted in more embodied carbon being emitted due to the transportation of heavier materials to the building site (see Appendix O).

Table 5.22 also shows that the highest percentage contribution of embodied carbon expenditure within the 'gate-to-site' boundary ranges from 0% (CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) to a maximum of 60.17% (NTS1-Newhailes Estate, Stable Block) multi-layer patch using plastic repair techniques. This is approximately 61 times greater than the range in percentage contribution of embodied carbon expenditure expended during pinning and consolidation using stainless dowels and epoxy resin. The lowest range was from 0.53% (HS8-Jedburgh Abbey) to 0.98% (CEC1-15 Hillside Crescent & 30-32 Hillside Street, Edinburgh). It was also found that the use of locally sourced secondary fixing materials resulted in lower carbon emissions during transportation. These contrast between these results and those of the former is mainly due to the use of high mass kg of the same secondary fixing materials and imported lime mortar materials. It must be noted that the minimum figure of 0% of embodied carbon expenditure within this boundary at CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type A and Type B respectively) was due to no intervention being undertaken using relevant techniques within the selected maintenance periods.

Appendix O provides more detailed results on the embodied carbon expenditure percentage contribution for stone masonry wall repair within the 2001 to 2010 maintenance periods across all selected sample properties within ‘cradle-to-gate’ and ‘gate-to-site’ respectively.

Table 5.23: Average percentage embodied carbon expenditure

	Average Percentage of Embodied Carbon Expenditure Comparison Within 2001-2010 Maintenance Periods							
	Replacement		**Repointing**		**Pinning & Consolidation**		**Plastic Repair**	
Collaborative Partners	cradle-to-gate (%)	gate-to-site (%)	cradle-to-gate (%)	gate-to-site (%)	cradle-to-gate (%)	gate-to-site (%)	cradle-to-gate (%)	gate-to-site (%)
Historic Scotland	79.44%	20.56%	81.04%	18.96%	99.05%	0.95%	88.95%	11.05%
National Trust for Scotland (NTS)	82.20%	17.80%	78.33%	21.67%	98.92%	1.08%	84.80%	15.20%
The City of Edinburgh Council (CEC)	74.44%	18.86%	77.26%	22.74%	98.94%	1.06%	78.12%	11.88%

Source: Author, 2012.

Table 5.23 illustrates the average percentage embodied carbon expenditure across the collaborative partners for the 2001 to 2010 maintenance periods. Research results show that emissions within ‘cradle-to-gate’ are generally higher compared to ‘gate-to-site’. It was found that the highest average percentage of embodied carbon expenditure (99.05%) was expended within the former boundary compared to the lowest figure of 0.95% expended within the latter boundary using pinning and consolidation undertaken by Historic Scotland. It must be noted that the average percentage contribution of embodied carbon expenditure within the former boundary is commonly influenced by the embodied carbon coefficient value of repair materials and their profiles. Meanwhile, kg/km emissions factors (mode of transport), the mass in kilogrammes of materials transported, the resourcing location and transportation distance are considered as the main influencing factors on the percentage contribution of embodied carbon expenditure within the latter boundary. It may be concluded that the higher the value of the influencing factors, the greater the average percentage contribution of embodied carbon expenditure within both boundaries.

5.10.1 Percentage of Embodied Carbon Expenditure

It is found that average percentage contribution of embodied carbon expenditure within the ‘cradle-to-gate’ boundary is commonly influenced by the embodied carbon coefficient value of repair materials and their profiles. On the other hand, kg/km emissions factors (mode of transport), the mass in kilogrammes of materials transported, the resourcing location and transportation distance are considered as the main influencing factors on the percentage contribution of embodied carbon expenditure within ‘gate-to-site’ boundary.

Research results show that the higher the value of the influencing factors, the greater the average percentage contribution of embodied carbon expenditure within both boundaries. This trend occurred across all the collaborative partners (see Table 5.23).

5.11 Testing the ‘Green Maintenance’ Model

5.11.1 Association With Embodied Carbon Expenditure Per 1m^2 Repaired Wall (kgCO$_2$e/kg/m^2)

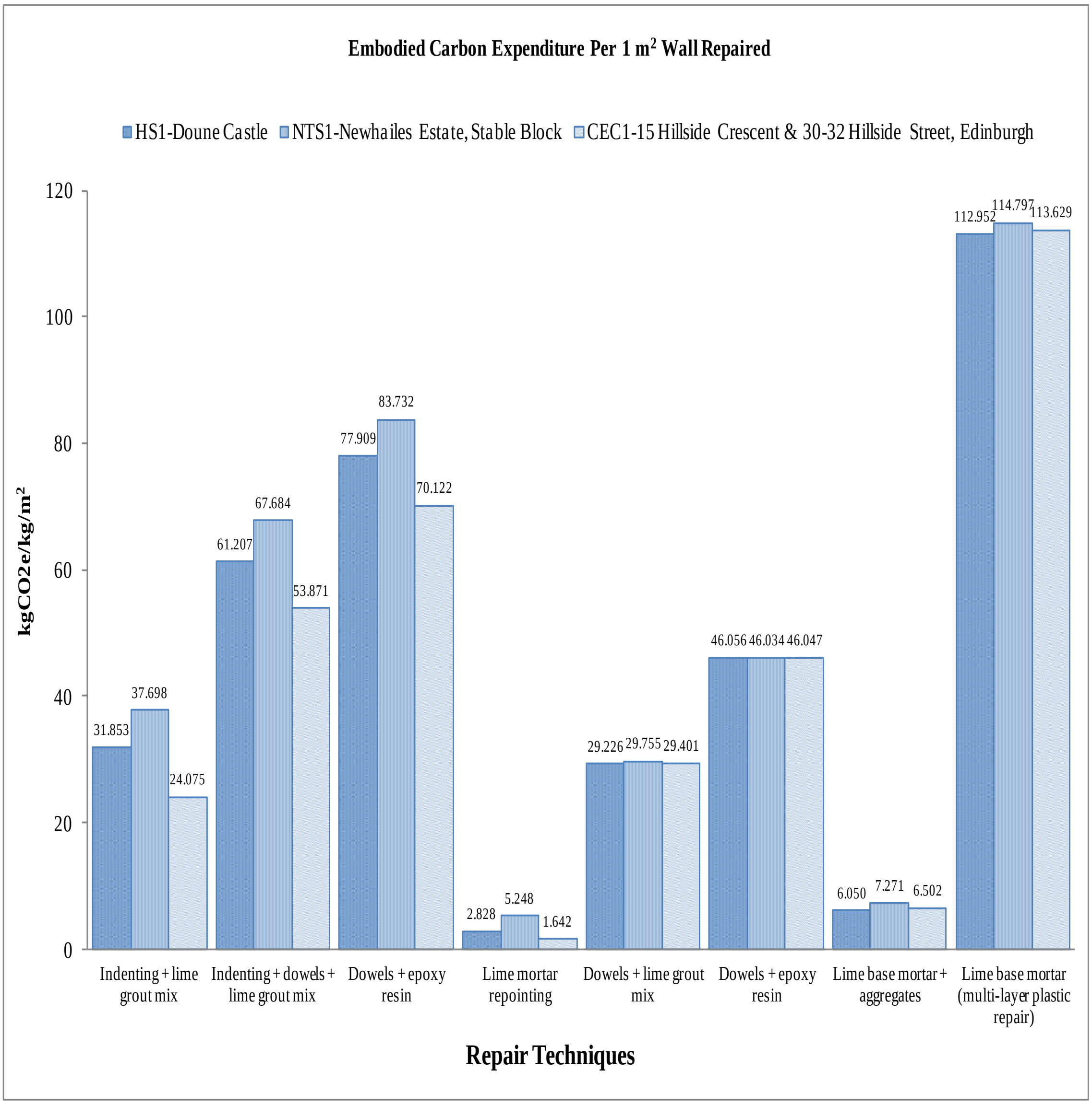


Figure 5.1: Total embodied carbon expenditure per 1m^2 repaired wall (kgCO$_2$e/kg/m^2) for typical selected sample properties

Source: Author, 2012.

Figure 5.1 presents a typical comparison of embodied carbon expenditure for $1m^2$ of repaired wall across selected stone masonry wall repair techniques within the 'cradle-to-site' boundary and the 2001 to 2010 maintenance periods for HS1, NTS1 and CEC1 respectively. Within the same boundary and maintenance periods, research results show that the highest total embodied carbon across typical sample properties occurred in using the multi-layer plastic repair techniques with an expenditure of 112.952 $kgCO_2e/kg/m^2$, 114.797 $kgCO_2e/kg/m^2$ and 113.629 $kgCO_2e/kg/m^2$ respectively. Meanwhile, lime mortar repointing contributes to the lowest figures of 2.828 $kgCO_2e/kg/m^2$, 5.428 $kgCO_2e/kg/m^2$ and 1.642 $kgCO_2e/kg/m^2$ respectively. Total embodied carbon expenditure is highly influenced by the embodied carbon expended in every $1m^2$ of wall repaired or the $kgCO_2e/kg/m^2$ value. The higher the value of $kgCO_2e/kg/m^2$, the greater the total embodied carbon expenditure within the same boundary and maintenance periods (see also Appendix J).

In comparison, the lower the total $kgCO_2e/kg/m^2$ expended within the same boundary and maintenance periods, the more efficient stone masonry wall techniques are in terms of embodied carbon expenditure. However, it must be noted that the lower embodied $kgCO_2e/kg/m^2$ for lime mortar repointing varies depending on the area of stone masonry wall repaired (more repointing is needed for the commonly larger delaminated surface of exposed wall and loose joints). In contrast, the lower $kgCO_2e/kg/m^2$ figure resulting from plastic repair using lime-based mortar and aggregates is due to the usage of low carbon materials (lime materials). Meanwhile, the lower $kgCO_2e/kg/m^2$ for pinning and consolidation using stainless dowels and epoxy resin is mainly influenced by the resourcing location (less carbon is emitted for locally sourced materials). Despite the higher $kgCO_2e/kg/m^2$ expended for natural stone replacement, the application has the highest longevity of repair (in this case 100 years for natural stone replacement). Based on the 'Green Maintenance' model, this technique is to be encouraged (it contributes to lower total embodied carbon expenditure) when compared to other repair techniques with a shorter longevity of repair, for which the average life expectancy ranges from 25 to 30 years.

5.11.2 Association With Total Embodied Carbon Expenditure (Total $kgCO_2e/kg$)

The total approximate embodied carbon ($kgCO_2e/kg$) expended during processing and manufacturing and the transportation of repair materials used to repair $1m^2$ of stone masonry wall to historic masonry building sites for each selected technique within ‘cradle-to-site’ was generated using Equation No. (12) and No. (14), as shown in Chapter 4:

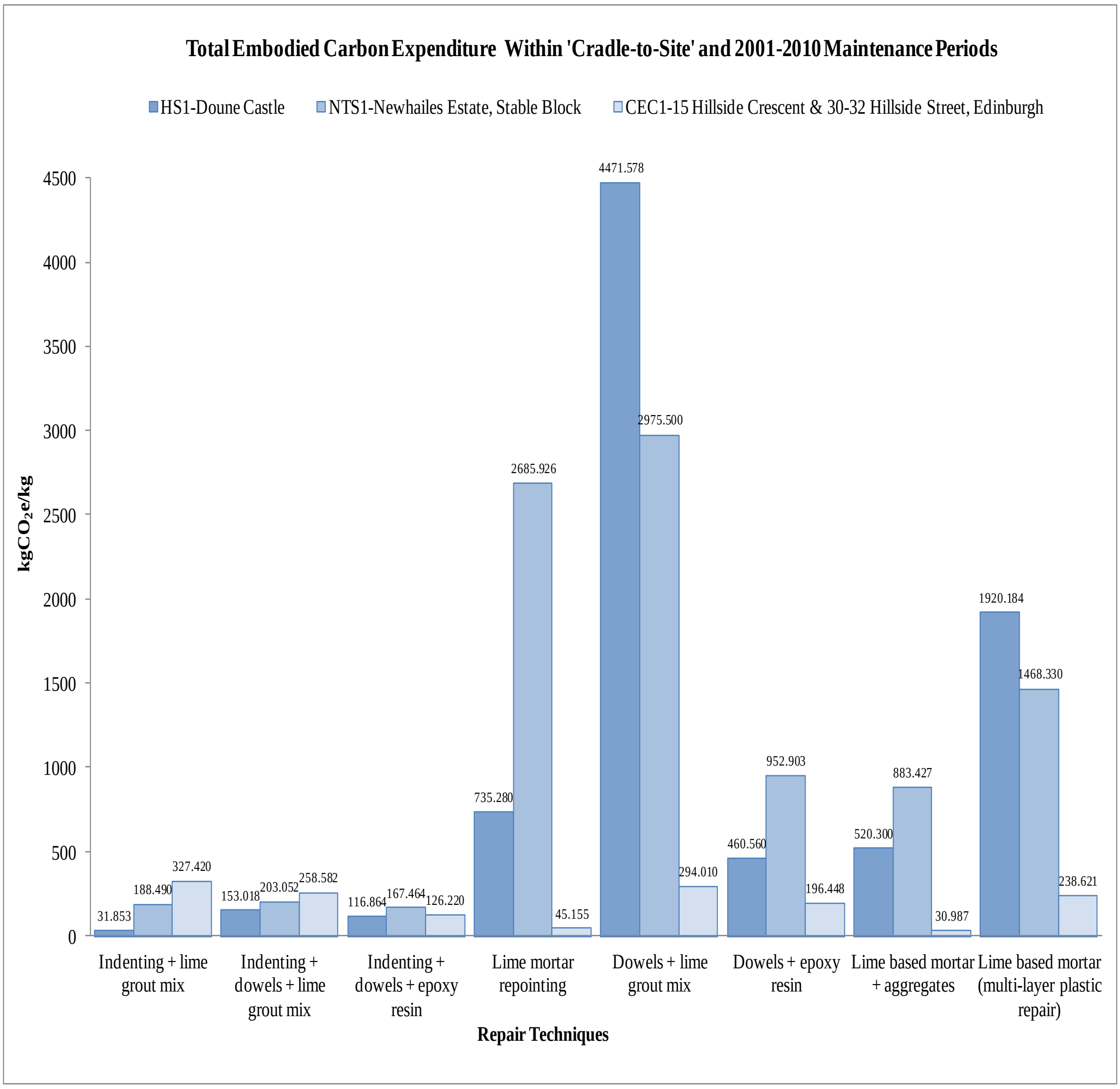


Figure 5.2: Total embodied carbon expenditure for typical selected sample properties

Source: Author, 2012.

Figure 5.2 represents a comparison of total embodied carbon expenditure across selected stone masonry wall repair techniques within the ‘cradle-to-site’ boundary and the 2001 to 2010 maintenance periods for HS1, NTS1 and CEC1 respectively (see also Appendix M). Research results show that the highest total embodied carbon expenditure across typical sample properties arose from the use of stainless dowels and lime grout mix in the pinning and consolidation technique (4471.578 $kgCO_2e/kg$, 2975.500 $kgCO_2e/kg$ and 294.010 $kgCO_2e/kg$ respectively).

In contrast, natural stone replacement had the lowest total embodied carbon expenditure (between 31.853 $kgCO_2e/kg$ and 327.420 $kgCO_2e/kg$ for stone indenting using lime grout mix for HS1). It must be emphasised that total embodied carbon expenditure is highly influenced by the embodied carbon expended in every $1m^2$ of wall repaired or the ($kgCO_2e/kg/m^2$) value. The higher the value of $kgCO_2e/kg/m^2$, the greater the total embodied carbon expenditure within the same boundary and maintenance periods. In comparison, the lower the total $kgCO_2e/kg$ expended within the same boundary and maintenance periods for the latter technique indicates its superior efficiency in terms of embodied carbon expenditure. This is mainly due to the greater longevity of repair (the least number of maintenance interventions (n), and lower m^2 total wall repaired area) for the latter (in this case 100 years) as opposed to the former (approximately 20 years, greater (n) and m^2). The model 'Green Maintenance' shows that the natural stone replacement techniques are environmentally effective and should be recommended for repair as opposed to other repair techniques as they have the lowest total embodied carbon expenditure.

5.11.3 Association With Cumulative Embodied Carbon Expenditure ($kgCO_2e/kg$)

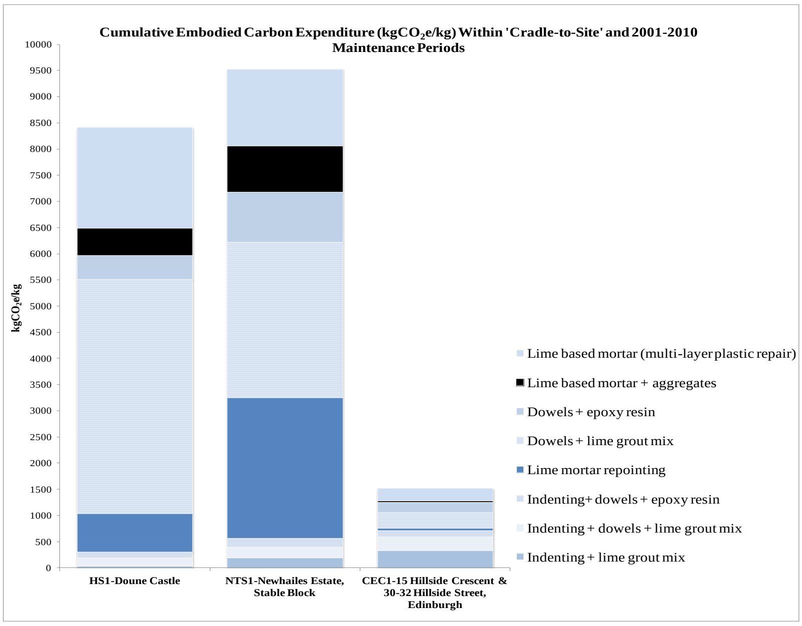


Figure 5.3: Cumulative embodied carbon expenditure for typical selected sample properties

Source: Author, 2012.

Figure 5.3 presents a typical comparison of the cumulative embodied carbon expenditure across selected stone masonry wall repair techniques within the ‘cradle-to-site’ boundary and the 2001 to 2010 maintenance periods for HS1, NTS1 and CEC1 respectively (see also Appendix M) with expenditure of 9525.092 kgCO$_2$e/kg, 8409.637 kgCO$_2$e/kg and 1517.443 kgCO$_2$e/kg respectively. Across selected typical sample properties, the use of stainless dowels and lime grout mix in pinning and consolidation generally had the highest final cumulative embodied carbon expenditure. Within the same boundary and maintenance periods, natural stone replacement commonly had the lowest cumulative embodied expenditure. This is mainly due to the latter’s high longevity of repair (commonly at least 100 years, the lowest number of maintenance interventions (n), and lesser m^2 total wall repaired area) compared to the former (approximately 20 years, greater (n) and m^2). Results from ‘Green Maintenance’ models show that a repair technique with the lowest cumulative embodied carbon expenditure should be undertaken. The low cumulative expenditure for repair techniques reflects their greater efficiency in terms of embodied carbon expenditure.

5.11.4 Association With Normalised Embodied Carbon Expenditure [(Total kgCO$_2$e/kg)/(Total m^2)]

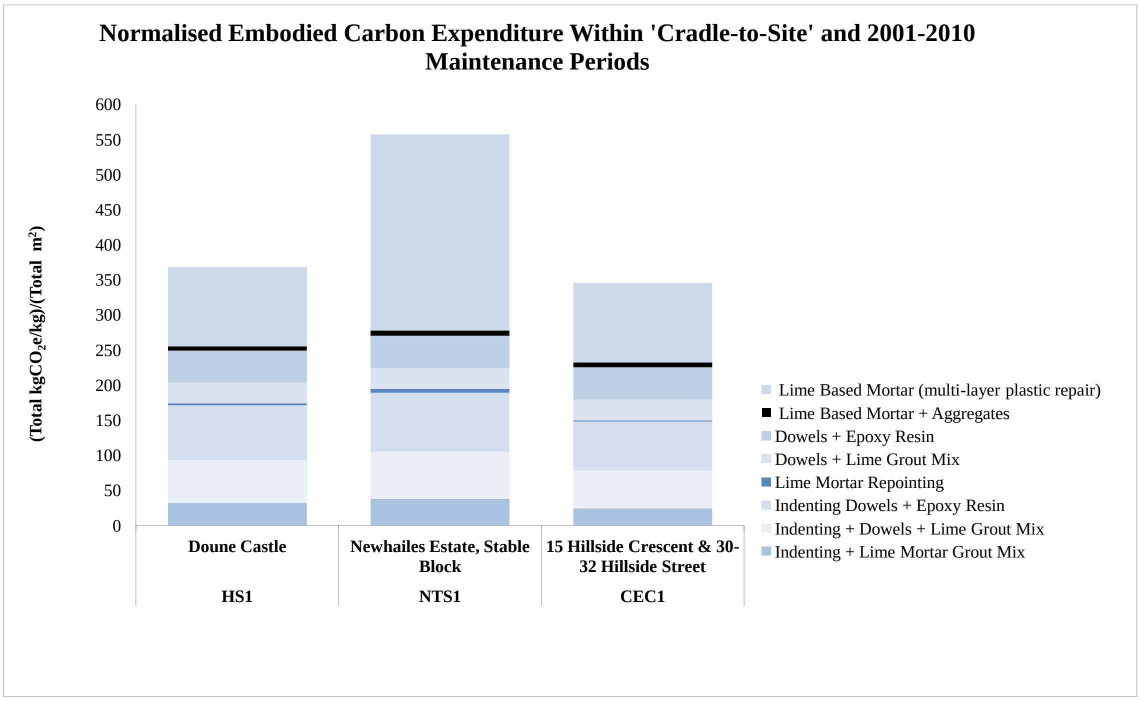


Figure 5.4: Normalised embodied carbon expenditure [(Total kgCO$_2$e/kg)/(Total m^2)]
Source: Author, 2012.

Figure 5.4 shows that the lowest normalised embodied carbon expenditures of 6.050 $kgCO_2e/kg/m^2$, 7.271 $kgCO_2e/kg/m^2$ and 6.593 $kgCO_2e/kg/m^2$ were expended for HS1, NTS1 and CEC1 respectively as a result of the use of stainless dowels and epoxy resin in pinning and consolidation techniques within 'cradle-to-site' and the 2001 to 2010 maintenance periods. Meanwhile, the highest figures of 112.952 $kgCO_2e/kg/m^2$, 279.982 $kgCO_2e/kg/m^2$ and 113.629 $kgCO_2e/kg/m^2$ occurred at the properties within the same boundary and maintenance periods using multi-layer plastic repair techniques.

Across typical selected properties, the minimum average normalised embodied carbon expenditure of 15.246 $kgCO_2e/kg/m^2$ was for CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) as opposed to the maximum of 84.203 $kgCO_2e/kg/m^2$ for NTS1-Newhailes Estate, Stable Block within the same boundary and maintenance periods (see Appendix N). Research results show that normalised embodied carbon expenditure is highly influenced by the total embodied carbon expenditure ($kgCO_2e/kg$) and total area of repaired wall (m^2). In general, the greater the total embodied carbon expenditure ($kgCO_2e/kg$) and the smaller the area (m^2) of wall repaired, the lower the normalised embodied carbon expenditure ($kgCO_2e/kg/m^2$) value for repair and vice versa.

Across all selected stone masonry wall repair techniques, it was also found that lime mortar repointing had the lowest normalised embodied carbon expenditure (with an average of 2.985 $kgCO_2e/kg/m^2$) compared to other repair techniques (see Appendix N). This is due to a lower mass (in kg) of lime mortar used. In addition, this technique commonly required the lowest quantity of materials (lowest mass (kg) of lime mortar used for repointing loose and broken joints) in every $1m^2$ area of wall repaired. Repair techniques with the lowest normalised average are not necessarily the most efficient in terms of embodied carbon expenditure. Despite the lowest normalised embodied carbon expenditure, lime mortar repointing is highly dependent on the larger area of delaminated surface wall. As previously discussed, natural stone replacement is the most efficient in terms of embodied carbon expenditure due to the lower number of maintenance interventions (n) and total area of wall repaired (m^2).

5.11.5 Normalised Embodied Carbon Expenditure

The research results show that the normalised embodied carbon expenditure on the stone masonry wall repair value [(Total $kgCO_2e/kg$)/(Total m^2)] for the selected sample properties within the 2001-2010 period is influenced mainly by the total number of interventions and the total area of walls repaired. It must be emphasised that a larger total number of interventions (n) and the larger the area of walls repaired (m^2) does not necessarily result in a greater normalised embodied carbon expenditure. The overall total amount of normalised embodied carbon expenditure on stone masonry wall repairs is also primarily influenced by the longevity of the repairs and the total average of the normalised embodied carbon expenditure for repairing every 1 m^2 of wall (or functional units of $kgCO_2e/kg/m^2$). Table 5.28 shows an average of normalised embodied carbon expenditure [(Total $kgCO_2e/kg$)/(Total m^2)] within 'cradle-to-site' (for 2001-2010 maintenance periods) across selected sample properties for this research.

It was found from this research that the normalised embodied carbon expenditure for stone masonry wall repairs undertaken by Historic Scotland within the ‘cradle-to-site’ boundary and 10-year maintenance periods are within the range between 368.082 $kgCO_2e/kg/m^2$ (HS1-Doune Castle) and 405.198 $kgCO_2e/kg/m^2$ (HS8-Jedburgh Abbey). This result demonstrates that the normalised embodied carbon expenditure value for both sample properties is mainly influenced by the factors discussed previously.

Comparatively, the normalised embodied carbon expenditure across the National Trust for Scotland sample properties within the same boundary and maintenance period also shows the same trend. The overall total of the normalised embodied carbon expenditure value range on a sample of properties in this organisation is between 344.21 $kgCO_2e/kg/m^2$ (NTS9-Harmony House/St. Cuthbert House, Melrose) and 557.104 $kgCO_2e/kg/m^2$ (NTS1-Newehailes Estate, Stable Block).

The lowest overall total of the normalised embodied carbon expenditure on stone used for masonry wall repairs for the former was due to the lowest total number of interventions (eight) (despite having the same number of interventions as NTS6, NTS7, NTS8 and NTS10), and the lowest total area of stone masonry walls repaired (61.52 m^2) for the former, as opposed to the total number of interventions (nine) and the largest area of repaired wall (1706.16 m^2) for the latter.

The highest value of the overall total normalised embodied carbon expenditure, however, was for NTS1-Newhailes Estate, Stable Block repairs (557.104 $kgCO_2e/kg/m^2$), as opposed to NTS5-House of the Binns, which totalled only 392.740 $kgCO_2e/kg/m^2$. This is due to a higher total average of normalised embodied carbon expenditure in every 1 m^2 wall ($kgCO_2e/kg/m^2$) for the former than for the latter. Comparatively, the normalised embodied carbon expenditure average for NTS1 is 62.414 $kgCO_2e/kg/m^2$ compared with 41.588 $kgCO_2e/kg/m^2$ for NTS5.

The results from this research show that the overall total of normalised embodied carbon expenditure for stone masonry wall repairs undertaken by The City of Edinburgh Council is between 108.233 $kgCO_2e/kg/m^2$ (CEC5-131-141 Bruntsfield Place, Edinburgh (Stone Type B) and 403.518 $kgCO_2e/kg/m^2$ (CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh). Within the same maintenance periods, 7 interventions had been undertaken for repairing 765.07 m^2 for the former, compared to 14 interventions and 699.22 m^2 for the latter.

Despite the larger total area of repaired stone masonry walls for the former; i.e. using repointing (212.34 m^2) and plastic repairs using lime-based mortar and aggregates of plastic repairs (532.00 m^2), the lowest overall total normalised embodied carbon expenditure was using these two techniques, due to the lower number of interventions, with three and one intervention, respectively. Comparatively, the lowest total average of normalised embodied carbon expenditure was for the former (12.689 $kgCO_2e/kg/m^2$), compared to the highest (42.675 12.689 $kgCO_2e/kg/m^2$) for the latter within the same boundary and period.

Meanwhile, the overall average of normalised embodied carbon expenditure for the properties owned and managed by Historic Scotland is 40.078 $kgCO_2e/kg/m^2$ (mostly castles, abbeys and churches), by National Trust for Scotland properties is 42.427 $kgCO_2e/kg/m^2$ (spread over private houses, cottages, palaces and estates) and by The City of Edinburgh Council is 35.177 $kgCO_2e/kg/m^2$ (mostly tenement blocks). It could be concluded that the different types and uses of buildings also influence normalised embodied carbon expenditure ($kgCO_2e/kg/m^2$).

Differences in building type and usage also influence the total area of stone masonry wall (and wall surface exposed to weather), degradation rate, orientation, detail, specification, material profiles etc. As shown by the research results, all of these factors influence the total embodied carbon expenditure for selected masonry wall repair techniques (either in a single technique or a combination of techniques in different repair scenarios) within the same boundary of LCA and maintenance periods.

5.11.6 Implications for Annual Embodied Carbon Expenditure

Figure 5.5 shows the minimum annual embodied carbon expenditure for stone masonry wall repair (total $kgCO_2/kg$)/10-year maintenance periods) within 'cradle-to-site' and the 2001 to 2010 maintenance periods was for CEC2 (112.534 $kgCO_2e/kg$) compared to a maximum of 3889.212 $kgCO_2e/kg$ for HS2-Melrose Abbey.

Within the same boundary and maintenance periods, research results show that the annual embodied carbon expenditure within the 'cradle-to-site' boundary and 10-year maintenance periods for pinning and consolidation and plastic repair (particularly multi-layer plastic repairs) contributed to highest annual embodied carbon expenditure value (see Appendix O).

This is due the greater mass (kg) and high embodied coefficient value of the secondary fixing materials such as stainless steel dowels, epoxy resin and non-ferrous tying wire used in this technique. In comparison, natural stone replacement had the lowest value due its high longevity of repair (commonly 100 years and in some cases longer). Additionally, the latter had the lowest number of annual maintenance interventions (n) in natural stone replacement (a lower total area of area in m^2 repaired), resulting in lower annual embodied carbon expenditure.

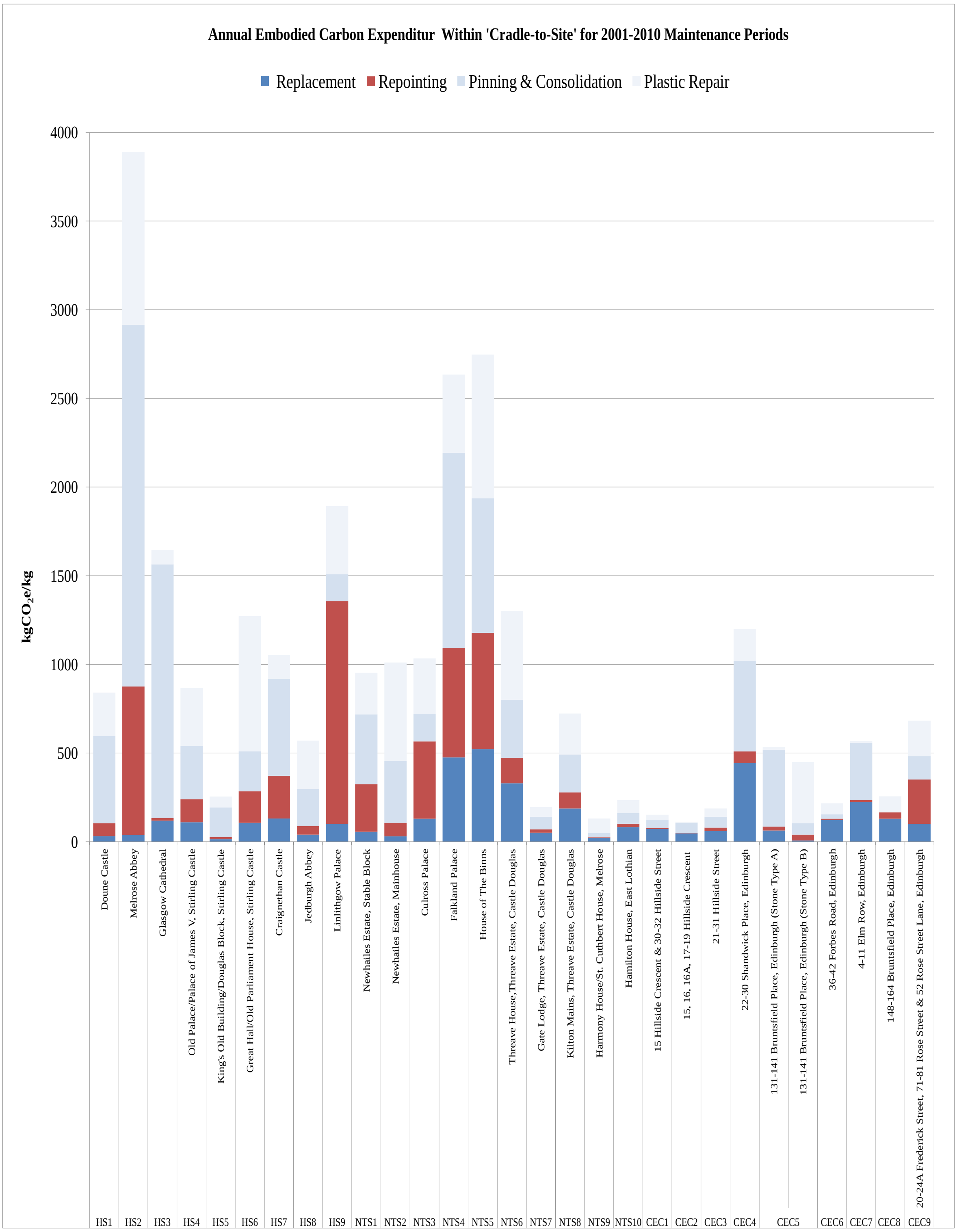


Figure 5.5: Annual embodied carbon expenditure for stone masonry wall repair techniques

Source: Author, 2012.

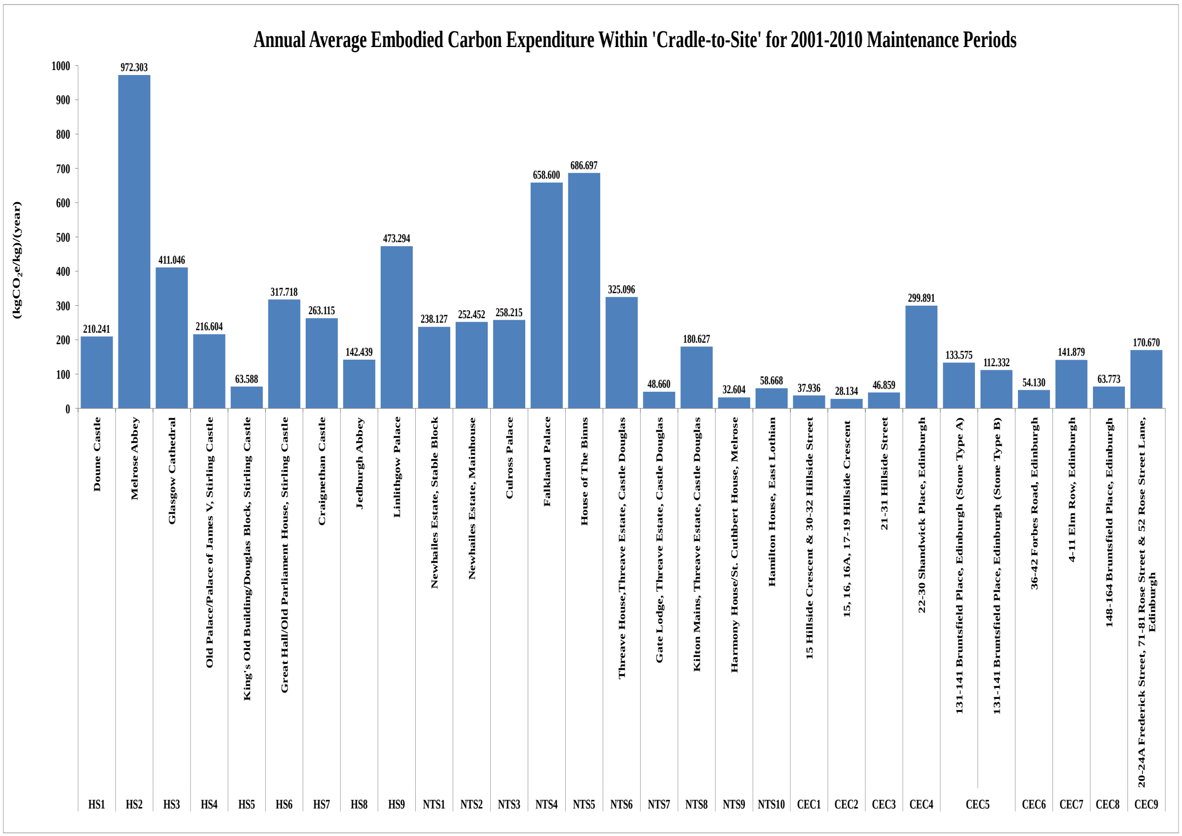


Figure 5.6: Annual average embodied carbon expenditure for selected sample properties.

Source: Author, 2012.

Figure 5.6 shows the annual average embodied carbon expenditure over 10 years across seleceted sample properties. On average, annual embodied carbon expenditure was highly influenced by application of repair techniques. It was found that the lowest annual average of 28.314 (kgCO2e/kg)/(year) was for CEC2-15, 16, 16A, 17-19 Hillside Crescent compared to the highest of 972.303 (kgCO2e/kg)/(year) for HS2-Melrose Abbey. These results indicate that the difference is due to the longevity of repair for repair techniques, the maintenance interventions (n) required and the total area in m^2 of wall repaired.

‘Green Maintenance’ models show that the application of either a single or a combination of repair techniques with the highest longevity of repair results in lower annual average embodied carbon expenditure. The lowest annual average expenditure for selected properties indicates that their repairs were more efficient in terms embodied carbon expenditure. The lower embodied carbon expended for their repair on an annual basis suggests that the repair of the properties was more efficient (see Appendix O).

5.11.7 Annual and Total Embodied Carbon Expenditure

It was found that natural stone replacements have a lower annual embodied carbon expenditure than lime mortar repointing, pinning and consolidation and plastic repair techniques. It was also found that the selected sample properties (in this case historic masonry buildings) with lower annual embodied carbon expenditure commonly exhibited less total embodied carbon expenditure within the same selected maintenance period.

Within this same period, the research reveals that the sample properties with a greater number of natural stone replacement interventions have less total embodied carbon expenditure. This is due to the lower number of interventions for masonry wall repairs using this repair technique on an annual basis, compared with other repair techniques. (see Table 5.24).

Table 5.24: Average cumulative ($kgCO_2e/kg$) within 'cradle-to-site' (for 2001-2010 maintenance periods)

Repair Techniques	**Average cumulative ($kgCO_2e/kg$) within 'cradle-to-site' (for 2001-2010 maintenance periods)**
1. Natural stone replacement	
a. Indenting + lime mortar grout mix	650.956
b. Indenting + dowels + lime grout mix	552.295
c. Dowels + epoxy resin	250.994
2. Repointing	
Lime mortar repointing	2204.475
3. Pinning and consolidation	
a. Dowels + lime grout mix	2908.925
b. Dowels + epoxy resin	1192.305
4. Plastic repair	
a. Lime based mortar with aggregates	600.770
b. Lime based mortar (multi-layer plastic repair)	2182.540

Source: Author, 2012.

5.11.8 Influences of the Profiles of Repair Materials and Resourcing Location

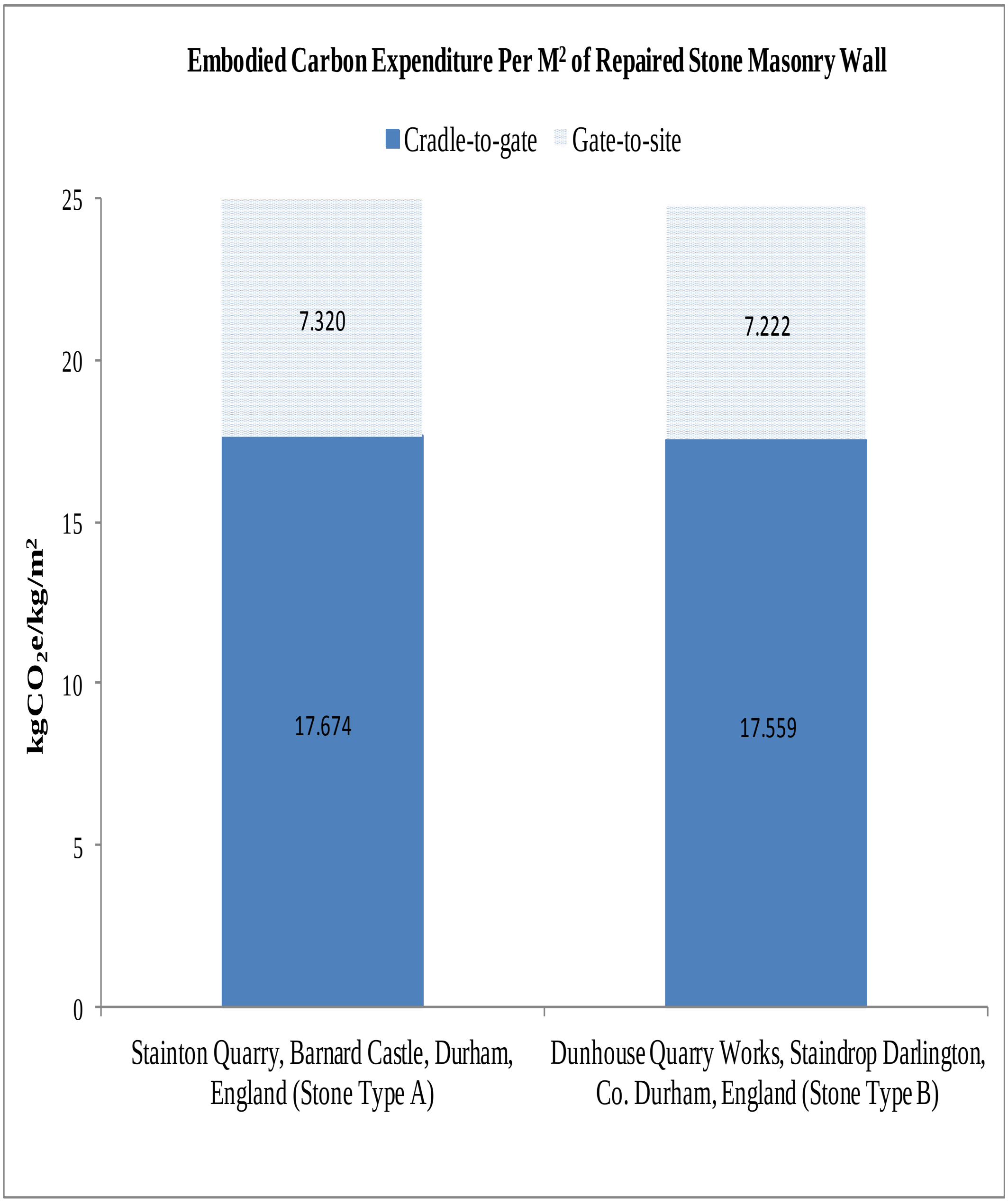


Figure 5.7: Embodied carbon expenditure per m^2 of repaired stone masonry wall ($kgCO_2e/kg$)

Source: Author, 2012.

Note: Sample of indenting and lime grout mix of natural stone replacement techniques undertaken on CEC5- 131-141 Bruntsfield Place, Edinburgh by The City of Edinburgh Council

Figure 5.7 provide information on the impact of two different types of stone procured from two quarries on the embodied carbon expenditure in every 1m^2 (kgCO$_2$e/kg/m^2) of wall repaired for the sample properties.

The comparison of the extent of impact was based on similar repair techniques (stone indenting using for lime grout mix of natural stone replacement techniques) and within the same boundary. It was found that kgCO$_2$e/kg/m^2 values were mainly influenced by the embodied carbon coefficient value of stone, profiles and resourcing locations. The greater the mass, namely in terms of kilogrammes and bulk density, the greater embodied carbon expenditure expended for quarrying and processing.

Meanwhile, it was found that the greater the transportation distance (kilometres) due to the different resourcing locations needed for the delivery of stone to the building site, the higher the total embodied carbon expenditure expended for the same techniques. 'Green Maintenance' models suggest that this pattern is similar across all selected sample properties.

5.11.9 Longevity and Number of Repairs Influences on Environmental Maintenance Impact (EMI)

To test the model, the estimated embodied carbon expenditure associated with undertaking a series of complete interventions within a 100-year maintenance profile period was generated using Equation No. (13), as shown in Chapter 4.

With regard to stone masonry wall repairs, it may be concluded that natural stone replacement techniques have the lowest embodied carbon expenditure within 100 years. Within the same period, this repair technique also has the lowest number of interventions and embodied carbon expenditure due to the long longevity of repair.

5.11.10 Efficiency of Stone Masonry Wall Repair Techniques Efficiency in Terms of Embodied Carbon Expenditure and Environmental Maintenance Impact (EMI)

Research results show that the average values of embodied carbon expenditure for stone masonry wall repair across three selected sample properties. It was found that the replacement of natural stone had the highest average embodied carbon expenditure compared to the other three repair techniques. However, natural stone replacement also had the longest longevity of repair with only one intervention within a 100-year maintenance profile. This technique appears to produce on average less carbon compared to the other three repair techniques due to the lower number of interventions within the same maintenance period.

5.11.11 *Total Environmental Maintenance Impact (EMI) of Stone Masonry Wall Repair Techniques*

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 5.25 were entered into Equation No. (13), as shown in Chapter 4. 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.

Table 5.25: Total Environmental Maintenance Impact (EMI)

	Total Environmental Maintenance Impact (EMI) $\sum ECE_{cradle\text{-}to\text{-}site}$ kgCO$_2$e/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 & 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: Author, 2012.

Note:

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

Table 5.25 represents the total Environmental Maintenance Impact (EMI) expended for stone masonry wall repair at three different selected sample properties. It was found that the EMI for replacing natural stone was lower than the other three repair techniques within ‘cradle-to-site’ and 100-year maintenance profile periods. This is due to the higher longevity of repair for this technique, which requires only one intervention within the same maintenance profile period (different repair scenarios are shown in Chapter 4, Figure 4.3). Within the same period and selected sample properties, natural stone replacement appears to have the lowest total embodied carbon expenditure compared to re-pointing, pinning and consolidation and plastic repair. Despite the lowest EMI resulting from lime mortar repointing, this repair technique is subject to the total area of delaminated surface wall to be repaired. A larger area of total wall was generally repaired using this technique.

5.12 Comparative Embodied Carbon Expenditure

The research results show that there are high functional units ($kgCO_2e/kg/m^2$) in making repairs using the natural stone replacement technique. Within a 100-year maintenance profile period, however, only one intervention is undertaken with this technique, compared to three, four and five interventions for plastic repairs, repointing and pinning and consolidation, respectively. This is due to the natural stone replacement technique having the longest longevity of repairs within the same period. It can be concluded that the higher the longevity of repair (the fewer interventions undertaken) using the selected repair techniques, the less carbon expended on repairs.

Research results show that natural stone replacement has the lowest embodied carbon and energy expenditure within the 100-year maintenance profiles. Comparatively, within the 10-year selected maintenance period of historic masonry buildings, natural stone replacement commonly requires the lowest number of interventions (n) of all the techniques. In addition, the total area repaired using this technique is generally smaller than with the other repair techniques. These research 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.

The typical research results from HS1-Doune Castle show that 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 $kgCO_2e/kg$). 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.

Table 5.26 summarises the EMI, evaluated in terms of embodied carbon expenditure, over the 100-year maintenance period for different repair scenarios at the same sample properties (in this case CEC4-22-30, Shandwick Place of Edinburgh).

Table 5.26**:** 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: Author, 2012.

Note:

Materials data are derived from Crishna et al., (2001) and Hammond and Jones, (2008a and 2008b); 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). 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 * distance (km); sample taken from CEC4-22-30 Shandwick Place of Edinburgh.

Table 5.27: Embodied carbon expenditure associated with alternative repair scenarios undertaken on 1m^2 of stone masonry wall based on average normalised (kgCO$_2$e/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$_2$e/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$_2$e/m^2	-	1.641	-	-	-
	Number of intervention (n)	-	4	-	-	-
	Total Average EMI	**-**	**6.564**			
Pinning and consolidation	kgCO$_2$e/m^2	-		37.725		-
	Number of intervention (n)	-		1		-
	Total Average EMI			**37.725**		
Plastic repair	kgCO$_2$e/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: Author, 2012.

Note:

Materials data are derived from Crishna et al., (2001) and Hammond and Jones, (2008a and 2008b); 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).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 * distance (km); sample taken from CEC4-22-30 Shandwick Place of Edinburgh.

From the data shown in Table 5.27, 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. Research results also revealed that 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 highly subject to the generally high number of interventions (n) and the large area (m^2) of delaminated stone masonry wall surface repaired. Additionally, the transport of materials has a major impact on the EMI results (as noted by Crishna et al., 2011). Research results show that transportation accounts for more than one-fifth (for Scenarios 1, 2 and 3) and nearly one-fifth (for Scenarios 4 and 5) of the EMIs (compared to one-quarter of the EMI as noted by Forster et al. 2011). This research 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).

5.13 Concluding Comments

Research results 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. Additionally, the number of intervention (n) and total area repaired (m^2) assessed is also critical.

Research results shows that the variation in the number of maintenance interventions (n) undertaken by collaborative partners is an indicator of their philosophical attitude towards stone masonry wall repair and their broader repair strategies. It must emphasise that number of maintenance intervention undertaken may also be related in certain cases by enforced repair works. Ultimately, research results show that by using the proposed mathematical framework and calculation, 'Green Maintenance' model can evaluate the efficiency of stone masonry wall repair in terms of embodied carbon expenditure. A correlation between research results and the efficiency of stone masonry wall repairs in terms of embodied carbon expenditure will be discussed in Chapter 6.

Chapter 6: Discussion

This chapter discusses the research findings regarding 'Green Maintenance' modelling and the testing results for historic masonry buildings. It discusses these factors within the context of life cycle assessment (LCA) that forms a principle component of the work. This chapter also evaluates the relative efficiency of stone masonry wall repair in terms of embodied carbon expenditure.

6.1 The Maintenance of Historic Masonry Buildings and Embodied Carbon Expenditure

Building maintenance forms a large component of the construction sector. It is therefore clear that maintenance has a substantial potential capacity to reduce carbon emissions through repair intervention and the selection of materials and techniques. Masonry repair is an integral part of the maintenance sector and appropriate techniques can reduce carbon expenditure, whilst inappropriate techniques can increase carbon.

In order to achieve a good environmental outcome (with low embodied carbon expenditure and less CO_2 emissions); and in order to fulfil building conservation philosophical defensibility, this research shown that appropriate LCA could be adopted to evaluate embodied carbon expenditure for historic masonry buildings maintenance through stone masonry wall repair. The selected LCA boundary and the associated inputs, and maintenance periods and longevity are essential in determining the embodied carbon expenditure or how "green" the interventions are. The concept of 'green' maintenance provides benefits for those involved in the building maintenance decision making process enabling rational selection of repair, not solely based on cost.

6.2 The Life-Cycle Assessment (LCA) for Historic Masonry Buildings

To date, various LCA methods have been developed across a range of disciplines in the built environment. However, this research found that a concerted effort is required in order to establish a unified global LCA database. The accuracy of the current fragmented databases for modelling the Environmental Maintenance Impact (EMI) of repair to historic masonry buildings during the maintenance phase (use stage) would appear to remain variable. This lack of consistency reduces easy practical application of any model or evaluation method. In recent years, there have been a significant number of LCA publications which have documented the environmental impact of different materials used in the building industry (such as the application of Sima Pro and Gabi4) by SISTech. The adoption of these LCA results have, however, not to date been comprehensively incorporated into historic masonry building repair or been widely published (see examples from Alshboul and Alzoubi, 2008 and Venkitachalam, 2008).

The literature review of this research found that previous LCA studies were prone to varying scope, different terms, diverse interpretation, unclear origins, vague timelines and unjustified guidelines. To date, there has been no clear evaluation on how these issues cause variations in embodied carbon expenditure. Additionally, there has been no consensus regarding the definition of LCA boundaries for historic masonry building maintenance, particularly for their stone masonry wall repair. Therefore, the extent of the impact of these problems regarding embodied carbon expenditure expended in historic masonry buildings repair remains unclear.

Despite all of these issues, a significant number of previous studies which have attempted to achieve standardisation in LCA. This is clearly encouraging. However, the role of these studies in evaluating the aforementioned issues, particularly with regards to the maintenance and repair of historic masonry buildings remain unclear. This has been due to the difficulties in achieving comprehensive data, particularly for embodied carbon coefficient value of materials used in historic masonry buildings repair. In addition, there have been no informed comparisons in the ISO 14041 documents that sets minimum requirement of embodied carbon expenditure for these buildings.

To date, it has been globally recognised that *'Green Procurement'* and the evaluation of embodied carbon is becoming more prevalent. When we apply these concepts to within a context of repair of historic masonry buildings it is clear that that as the number of repairs increase during the maintenance phase (use stage), there is a correlated rise in the expended embodied carbon. Maintenance record data relating to repairs to the elements of historic masonry buildings (such as the walls) provided ideal information (such as the different volume of work, longevity of repair, and number of interventions). This information was utilised to evaluate the efficiency of repairs in terms of embodied carbon expenditure within selected boundaries and maintenance period. This has been demonstrated by the 'Green Maintenance' model through the adoption of appropriate approaches to the LCA method.

6.3 Lime Versus Cement Materials and Their Environmental Impact

Comparatively, lime based materials are much better than general cement in terms of their flexibility, breathability and compatibility with traditional masonry substrates. Additionally, lime mortars are well known for their ability to sequester carbon. This capability and physical characteristics give lime material better environmental and performance credentials when compared with OP (Ordinary Portland) cement. Research results show that lime mortar repointing is more durable compared to cement mortar repointing. Higher longevity of repair for lime mortar materials contributes to less maintenance intervention i.e. less embodied carbon expenditure and less quantity in mass (kg). Due to this factor lime materials in stone masonry wall repair are to be encouraged.

Research results also show that different mixes and volumes of lime mortar, lime grout mix and lime plaster materials contribute accordingly to the mass (kg) of the materials which are used for stone masonry wall repair. Additionally, different embodied carbon coefficient values associated with these materials contributes towards different measurement values. It was found that the differences in embodied carbon expenditure for repair can be correlated with the mix proportions and the mass of kg of lime mortar materials used. The lower the number of maintenance intervention (n) and mass (kg) of lime mortar materials used will reduce the embodied carbon expended for the repair. However it must be emphasised that the proportion of lime materials mixes which are used in stone masonry walls need to adhere to building conservation guidelines and philosophical frameworks. This is applied to all materials which are used in stone masonry wall repair including high embodied carbon materials such as secondary fixing materials.

6.4 High Embodied Carbon Coefficient of Secondary Fixing Materials Impact

Research results show that the grade, length and diameter of stainless steel dowels which are used for stone masonry wall repair have mainly been based on common specifications produced by their respective manufacturers. It must be emphasised that their total number and the mass (kg) are dependent upon their minimum spacing (in millimetres). This research found that stainless steel dowels had a high embodied carbon coefficient value (refer to ICE, Version 2011). This was mainly due to the high energy that was expended in steel production. Due to this, their use in stone masonry wall repair has contributed towards high embodied carbon expenditure for most repair techniques which uses them as one of the fixing materials. To reduce embodied carbon expenditure for repair, alternative options such as greater depth of ‘cutting-back’ sections of decayed natural stone could be undertaken. This alternative would therefore become relatively more environmentally effective. Alternatively, the use of nylon rod dowels could be adopted for pinning and consolidation techniques. Meanwhile, it would be practical to use wire frame and ceramic T section (0.70 $kgCO_2e/kg$) for plastic repair techniques (particularly for multi-layer plastic repair).

The research results showed that the epoxy resin was normally used in natural stone replacement, pinning and consolidation and multi-layer plastic repair. In general, the embodied carbon coefficient values for this material is moderately high (5.72 $kgCO_2e/kg$). Due to this factor, the embodied carbon expenditure of stone masonry wall repair techniques that use this material is considerably higher. Alternatively, the use of lime based grouts and other adhesive materials with lower embodied carbon coefficient such as rubber based materials (2.85 $kgCO_2e/kg$) and plastic (3.31 $kgCO_2e/kg$) could be used to reduce embodied carbon expenditure.

Comparatively, the use of non-ferrous tying wire has quite a similar impact to stainless steel dowels as both materials are commonly produced and manufactured at similar plants. Commonly, both materials have a high embodied carbon coefficient value. This contributes to high embodied carbon expenditure in multi-layer plastic repair which use non-ferrous tying wire materials. Research results show that the high embodied carbon coefficient of secondary fixing materials has contributes to the high embodied carbon expenditure for repair. Therefore, alternative repair techniques and materials are to be encouraged to achieve reduced embodied carbon expenditure.

6.5 Low Embodied Carbon Materials Impact

A preference for using low embodied carbon materials for building maintenance is commonly accepted wisdom. However, the benefits potentially derived from the use locally available materials of similar durability for historic masonry buildings needs to be considered. The use of low carbon materials commonly contribute to lower embodied carbon expenditure. Recycling may seem to be an ideal solution for the scarcity of traditional materials in stone masonry wall repair. However, the sorting, cleaning and disposing process of these materials may contribute towards additional embodied carbon expenditure. Therefore, it must be emphasised that the use of recycled materials may contribute towards the additional value of the Environmental Maintenance Impact (EMI).

6.6 Resourcing Location Impact

It has been found that, different types of stone used in repair are derived from alternative quarries, from different locations. Different resourcing locations for stone (commonly quarry) contributes towards variation in transportation distances between the quarry and the building site. Research results show that the greater the distance of the stone resourcing location, the greater the CO_2 that is emitted during stone transportation within the 'gate-to-site' boundary. Therefore, the use of locally sourced materials for repair is to be encouraged when evaluating the selection of materials.

It also has been found that the resourcing location for materials is determined based on where they are being produced, processed and manufactured. This research has ascertained that each stone masonry wall repair material has a different resourcing location as they have a different nature of procurement: stones (quarry); sand (mining quarry); all limes - Jurra Kalk and aggregates - (quarry and processing plant) and brick dust/fire clay/fly ash, stainless steel dowels, epoxy resin and non-ferrous tying wire (processing plant).

6.7 Other Research Parameters Influences

To achieve consistent and comparable results for this research, relevant resourcing location of repair materials used were accordingly addressed. For this research, it was unfeasible to make assumptions as qualities of LCA varied. Therefore, the nature and scale of the LCA data in other countries (other than UK) was also considered for the evaluation of the embodied carbon expenditure.

Meanwhile, the mass or volume of each substance from relevant energy and industries associated with stone masonry wall repair materials was explained accordingly wherever applicable. In addition, it must be noted that the measurement of annual CO_2 emissions from the heating of carbon containing minerals by Integrated Pollution Control (IPC) of UK) and relevant discharges from stone masonry wall repair materials were not considered for this research as they were not utilised to evaluate embodied carbon expenditure and EMI.

This research has revealed that there are differences with regard to the building site location the materials resourcing, and transportation distance. With regards to the delivery of repair materials to the building site, these parameters have contributed towards divergent embodied carbon expenditure for stone masonry wall repair.

It must be noted that CO_2 emissions for the whole plant which processed stone repair materials were not considered for this research. It was not possible to collect all relevant data regarding CO_2 emissions in accordance with the duration of this research. Other factors included the negative emissions of substances (such as sequestration of CO_2 by growing plants or re-carbonation of lime); as well as relevant emissions and air, water and land discharges. In this research, other research parameters which influenced the research results were considered accordingly.

Additionally, technological development and advancement as well as constant changes in the mode of transportation have also influenced the embodied carbon expenditure in quarrying, mining, processing and manufacturing and the transportation of repair materials respectively.

6.8 'Green Maintenance': Development, Results and Testing

The 'Green Maintenance' maintenance model in this research was developed using generated LCA data of embodied carbon expenditure (kgCO_2e/kg). This was applied to stone masonry wall repair techniques on historic masonry buildings. Primarily, this model was set to improve the efficiency of stone masonry wall repair in terms of embodied carbon expenditure for historic masonry buildings. It must be emphasised that the application of this model is also be relevant to different types of repairs interventions, to both modern and historic buildings alike.

For this work, assumptions were made regarding the longevity of repair, but these were directed from previous LCA studies and The Building Research Establishment (BRE) Stone List. This was a vital component required for the 'Green Maintenance' model.

In addition, it must be emphasised that this model can operate in a realistic and accurate manner and will improve as the LCA data inputs are enhanced over time. Improvement will also be noted if greater synthesis of theoretical calculation and procedures occur.

6.8.1 Collaborative Efforts and Calculations Procedures: Results and Contribution

It must be emphasised that the collaborative partners for this research were selected from the organisations that were responsible for maintaining historic masonry buildings. Using the calculation procedures of the 'Green Maintenance' model it has demonstrated that the Environmental Maintenance Impact (EMI) for single or a combination of stone masonry wall repair techniques with different repair scenarios can be generated within selected boundaries of LCA and maintenance periods. Assumptions in the LCA have been previously highlighted and are not believed to debase the research. This research shows that by evaluating the embodied carbon expenditure and longevity of each selected stone masonry wall repair technique could yield how "Green" the maintenance intervention was and therefore tested the model's ability to operate.

For this research, relevant formulaic expressions were used for the theoretical calculation of the 'Green maintenance' model in order to evaluate the embodied carbon expenditure expended on stone masonry wall repair. In order to minimise the inaccuracy of LCA for this research, the selected scope was defined by taken into account; geographical coverage, the nature of the transportation and its impact on embodied carbon in kg/km.

6.8.2 Number of Maintenance Interventions (n) and Its Impact on Total Embodied Carbon Expenditure for Stone Masonry Wall Repair

Longevity of repair for stone masonry wall repair techniques is determined by their durability. When this information is combined with the respective embodied carbon expenditure this can be fed into the ‘Green maintenance’ model with greater effect.

From this research, it was found that the number of interventions (n) within the selected maintenance periods (such as 10 years period for this research) was very much related to repair techniques durability and stone masonry wall exposure. This research showed that the highest embodied carbon expenditure in every 1 m^2 of repaired stone masonry ($kgCO_2e/kg/m^2$) was associated with natural stone replacement techniques. However, natural stone replacement was also the most effective repair technique as it contributed to the lowest total embodied carbon expenditure over the life cycle within the same selected boundary of LCA and maintenance period.

The research results showed that the total embodied carbon which was expended on stone masonry wall repair over the selected 10 years maintenance period was highly influenced by repointing, pinning and consolidation techniques and plastic repair and not by natural stone replacement techniques. Commonly, the lowest embodied carbon expenditure per 1 m^2 wall ($kgCO_2e/kg/m^2$) was expended for repointing technique. It must be emphasised that, in reality, the number of maintenance intervention (n) and total area repaired (m^2) undertaken using this technique is normally the highest. This is due to lower durability and larger wall areas to be repointed. Therefore, total embodied carbon expenditure expended on this type of repair technique is usually higher than alternatives within the same boundary and maintenance periods.

It was also determined that the total embodied carbon expenditure associated with pinning and consolidation, plastic repair techniques was comparatively higher when compared to natural stone replacement. This was due to the higher embodied carbon coefficient value of repair materials (particularly for secondary fixing materials) which was used for these two techniques. By contrast, if stainless steel dowels were not used in plastic repair techniques (particularly in multi-layer plastic repair technique) the embodied carbon expenditure expended could be significantly reduce. Additionally, significant reduction in embodied carbon expenditure for plastic repair (particularly multi-layer plastic repair patch) can be achieved by using lower embodied carbon coefficient materials such as wire frames (ceramic T section and nylon rod) as opposed to stainless steel dowels. In addition, both pinning and consolidation and plastic repair technique had a greater embodied carbon expenditure per 1 m^2 wall ($kgCO_2e/kg/m^2$) when compared to other techniques. This is mainly due to the use of high embodied carbon materials associated with the secondary fixing techniques. From the research results, it can be concluded that the greater the value of the functional unit ($kgCO_2e/kg/m^2$) and overall total embodied carbon expended on selected masonry wall repair techniques, the poorer they are in terms of their carbon expenditure.

The research results also showed that generally, the greater the cumulative embodied carbon expenditure for stone masonry wall repair, the greater the number of maintenance interventions within the evaluated period (in this research is 10 years). It must however, be emphasise that, the cumulative embodied carbon expenditure could be greater in the case of less number of maintenance intervention within the same periods. In the case of HS2-Melrose Abbey, the highest of cumulative value of 38892.117 $kgCO_2/kg$ (see Appendix M) has been expended for its repair despite only 13 maintenance interventions being undertaken within the same period (refer Table 5.14). This is mainly due to single major intervention of multi-layer plastic repair (with total 60 m^2 wall) undertaken on this property. In addition, the high value of cumulative embodied carbon expenditure for stone masonry wall repair on HS5-King's Old Building, HS9-Linlithgow Palace and NTS4-Falkland Palace was highly influenced by the repair type undertaken and the materials adopted. Comparatively, the low cumulative value of embodied carbon expenditure on masonry wall repairs on 15, 16, 16A, 17-19 Hillside Crescent, Edinburgh, was influenced by natural stone replacement. It could be concluded that natural stone replacement highest longevity of repair and this has contributed to reduced embodied carbon expenditure as opposed to other repair techniques.

This research has also shown the occurrence of a higher the number of interventions associated with repointing, and pinning and consolidation and plastic repair techniques. It is found that these repair techniques contribute to the greater value of embodied carbon expenditure within the same 10 year maintenance period as opposed to natural stone replacement. This trend occurred across all collaborative partners. Additionally, despite similar numbers of maintenance interventions which were undertaken on stone masonry walls on the same selected historic buildings, it was also found that these three repair techniques remained poor in terms of their embodied carbon expenditure as opposed to natural stone replacement. Conversely, natural stone replacement consumed less carbon when compared to other techniques. This is due to the highest longevity of repair compared to other techniques. This occurred across most of the selected samples of historic masonry buildings for this research.

Research results show that annual embodied carbon expenditure for stone masonry wall repair was greatly influenced by the total repaired stone masonry wall area. However, research results also confirmed that the higher the total area of the stone masonry wall did not automatically contribute to greater normalised annual embodied carbon expenditure ($kgCO_2e/kg/yr/m^2$). It was found that, normalised annual embodied carbon expenditure was unlikely to be determined by a higher total masonry wall area (m^2). For example, buildings with the lowest $kgCO_2e/kg/yr/m^2$ including HS8-Jedburgh Abbey, NTS10-Hamilton House and CEC5-131-141 Bruntsfield Place, Edinburgh had a high total stone masonry wall area. This was due to the lowest value for embodied carbon expended on every 1 m^2 of repaired wall ($kgCO_2e/m^2$), and the lower number of maintenance interventions (n) undertaken with the greatest number of repairs with the lowest longevity within the selected maintenance periods.

In contrast, HS5-King’s Old Building, NTS7-Gate Lodge, and CEC2-15, 16, 16A and 17-19 Hillside Street had the lowest total area of stone masonry wall expending slightly higher normalised annual embodied carbon. In these cases, the normalised annual embodied carbon expenditure on stone masonry wall repair value was dependent on the number of maintenance interventions (n) of repointing, pinning and consolidation and plastic repair (as also shown in NTS4-Falkland Palace) and their respective longevity.

The research results showed that normalised cumulative embodied carbon expenditure for stone masonry wall repair was influenced by the number of maintenance interventions of natural stone replacement. In this regard natural stone replacement had the lower number of interventions undertaken over the same period, and therefore, had a lower normalised cumulative embodied carbon expenditure (example of HS3-Glasgow

Cathedral). In contrast, the greater the number of repointing, pinning and consolidation, plastic repair techniques that had been undertaken within the same periods, resulted in greater normalised values of embodied carbon (example from HS2-Melsrose Abbey). This was due to the lowest longevity of repair for these respective techniques.

With regards to NTS10-Harmony House, it had the lowest increment of normalised cumulative embodied carbon expenditure for masonry wall repair within the same maintenance periods. The research results would also suggest that the lower number of stone masonry wall repairs that were undertaken within the same maintenance periods, the lower the value for cumulative embodied carbon expenditure and vice versa. For example, the higher normalised cumulative carbon expenditure for NTS4-Falkland Palace was due to higher interventions for each repointing, pinning consolidation and plastic repair techniques. In general, the greater the number of interventions for repointing, pinning and consolidation and plastic repair techniques which have been undertaken on stone masonry walls of National Trust for Scotland, the greater the value of normalised cumulative embodied carbon expenditure.

In the case of The City of Edinburgh Council, natural stone replacement contributed to the lowest embodied carbon expenditure on stone masonry wall repair with the lowest normalised incremental cumulative carbon expenditure (see CEC7-4-11 Elm Row). This was due to highest longevity of repair for this technique (higher number of maintenance interventions). In contrast, the other three repair techniques were the main contributor to the higher normalised cumulative carbon expenditure (despite the same number of interventions with natural stone replacement) (example from CEC-21-31 Hillside Street).

6.8.3 Total Area Repaired (m^2) and Its Impact on Total Embodied Carbon Expenditure for Stone Masonry Wall Repair

The research results showed that there were differences in the embodied carbon expended when repairing the same area of building elements (in this case the stone masonry wall surface area in m^2). This was due to differences in the embodied carbon expenditure for different repair techniques. Research results show that the higher the total area repaired, the higher the total embodied carbon expended for repair.

From this research, it is found that total area of repaired wall (m^2) is determined by different life expectancies of repair techniques. The lower the longevity of repair the greater the multiple or repeat number of interventions. This contributes to a higher level of maintenance interventions (n) with correspondingly higher embodied carbon expenditure. LCA evaluation of this research indicates that longevity of repair for stone masonry wall repair techniques contribute to significant results in embodied carbon expenditure particularly during the maintenance phase (use stage) of buildings.

6.8.4 Impact of Different Stone Masonry Wall Repair Techniques on Total Embodied Carbon Expenditure

It was previously determined that the longevity of repair of different stone masonry wall repair techniques would obviously influence the embodied carbon expenditure over time between maintenance interventions (in this research 10 years of maintenance periods over the period 2001-2010). Despite the high embodied carbon expenditure in every 1 m^2 for natural stone replacement when compared to repointing, pinning and consolidation and plastic repair, its total Environmental Maintenance Impact (EMI) was commonly lower within 100 years. This indicates that, the most durable natural stone replacement not only contributes less maintenance interventions, but also contribute to less total embodied carbon expenditure within the same maintenance period.

6.9 'Green Maintenance' Model Test Results

The 'Green Maintenance' model results show that the longevity of repairs has a significant influence on the embodied carbon expenditure. The impact of the longevity of the repairs on the embodied carbon expenditure has been proven using EMI. In this research, 'Green Maintenance' has been tested using EMIs for a single stone masonry wall repair technique or a combination of techniques in different repair scenarios within the 'cradle-to-site' boundary of the LCA and maintenance profiles of 100 years. Based on the typical EMI results, it was found that natural stone replacement contributes to the lowest EMI compared to the other three techniques (see Table 6.1). This trend was common across all selected properties forming the basis of the research.

Table 6.1: Environmental Maintenance Impact (EMI) for alternative repair scenarios within 100 years

	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 @ 49.965 $kgCO_2e/m^2$	**49.965**	**-**	**39.972**	**-**	**34.976**
Repointing @ 1.641 $kgCO_2e/m^2$	**-**	**6.564**	**-**	**-**	**-**
Pinning and consolidation @37.725 $kgCO_2e/m^2$	**-**	**-**	**37.725**	**-**	**-**
Plastic repair @ 60.049 $kgCO_2e/m^2$	**-**	**-**	**-**	**199.963**	**60.049**
Overall Total Average EMI	**49.965**	**6.564**	**77.697**	**199.963**	**95.025**

Source: Author, 2012.

Note: Sample taken from CEC4-22-30 Shandwick Place of Edinburgh.

It could be concluded that the repair techniques with the lowest EMI are the most efficient in terms of embodied carbon expenditure, and their application is to be encouraged. This research also shows that the 'Green Maintenance' model is universal and is applicable to all repair types and building forms.

6.9.1 'Green Maintenance' Model Testing

Within the selected boundary of LCA and maintenance periods, the research results show that the efficiency of single or a combination of repairs undertaken in different scenarios could be compared using their Environmental Maintenance Impact (EMI) results. It was found that the average value of embodied carbon expenditure for replacing natural stone replacement was the highest compared to the other repair techniques. Additionally, this repair technique had the highest longevity with only one intervention within 100 years. Overall, natural stone replacement techniques would also appear to have expended less embodied carbon compared to repointing, pinning and consolidation and plastic repair respectively. This was due to their lowest number of interventions (n) over time (selected maintenance periods). Due to these factors, the research results also showed that a natural stone replacement technique had the lowest Environmental Maintenance Impact (EMI). Therefore, replacing natural stone should be encouraged as it was the 'greenest' repair technique in terms of the embodied carbon expenditure over longer time frames.

6.10 'Green Maintenance' for Historic Masonry Buildings: Looking Ahead

Previous LCA works have shown that the quantification of historic masonry buildings maintenance in terms of environmental outcomes and sustainability have encountered difficulties. The results of this particular research have shown that stone masonry wall repair techniques are not only able to provide benefits in terms of building conservation philosophical and could also be tailored to fulfil environmental outcomes (correlated with low embodied carbon expenditure or less CO_2 emissions).

To date, methods to evaluate the environmental impact requirements in buildings such as the scoring systems by the Building Research Establishment Environmental Assessment Method (BREEAM) and cost-effective "green" building products selection i.e. The Building for Environmental and Economic Sustainability (BEES) as proposed by Lippiatt (1999). However, the application of these methods on historic masonry buildings repair has not been undertaken.

Based on the generated LCA results within the 'cradle-to-site' boundary and EMI test results, the 'Green Maintenance' model has demonstrated its ability to achieve embodied carbon expenditure (CO_2 emissions) reduction. This research also found that complex prioritisation and varying parameters in historic masonry buildings repair had a significant influence on environmental sustainability.

This research showed that the 'Green Maintenance' model was able to provide added value not only for building maintenance but also for achieving a good environmental outcome as well achieving well considered building conservation.

The most effective maintenance interventions are not only those which suitably accommodate all priorities and parameters which are set out in building conservation philosophy but are also those which are able to provide sustainable solutions for environmental issues. However, the 'Green Maintenance' model testing results have shown that natural stone replacement has the highest embodied carbon expenditure. However, when this is placed in context of 100 years of maintenance period, it has the lowest Environmental Maintenance Impact (EMI) as it has the longest life expectancy compared to other interventions. The benefits are clearly enhanced if the stone quarry is located near to the building site. Therefore, locally sourced stone is to be encouraged as it will reduce CO_2 emissions associated with haulage. It is clear that reopening of stone quarries would aid in significant carbon dioxide reduction especially for major projects. This would also achieve secondary economic benefits in terms of use of local employment.

6.10.1 Target Audience and Intended Use of 'Green Maintenance' Model

This work will benefit those individuals or organisations entrusted with the conservation of historic masonry buildings. The principle focus of the work was large companies with substantial historic buildings portfolios. This research should not be solely seen within a UK context and has value for any country wishing to enhance the environmental maintenance impact. Clearly, those organisations that are driven by government abatement targets to reduce CO_2 from their existing building stock will benefit from this model. The development of 'Green Maintenance' and its formulated formulaic expressions adopted not only help those entrusted with building repair to make rational decisions relating to durability and longevity of repair but also helps them to attain lower embodied carbon expenditure for repair as well as philosophical defensibility (Forster et al., 2011).

The data generated from the 'Green Maintenance' model is intended to improve the performance of buildings i.e. achieving efficacy in terms of reduce embodied carbon expenditure from repair. The LCA for this research would hopefully enable the aforementioned target audience to better understand the influences and impact of the decisions made relating to the maintenance and repair for building elements (in this case stone masonry walls). This should also help the targeted audience to optimise the overall performance of their own buildings, particularly during the maintenance phase (use stage).

6.10.2 Skills Requirement for the 'Green Maintenance' Model

To date, the proportion of those employed in the building industry, particularly those who are involved in maintaining buildings are not comprehensively fulfilling the present demands of the 'Green Maintenance' concept. However, as society is all to aware it is vital that carbon is reduced. This work has shown that the use of 'green procurement' and low carbon materials is an important component in fulfilling this.

(Forster et al., 2011). The concept of ‘Green Maintenance’ will help to promote these changes and reduce CO_2 from traditional building stock.

6.11 Research Contribution

As our society starts to move towards a low carbon economy, the use of ‘green procurement’ and increased use of ‘green materials’ implementation strategies such as ‘Green maintenance’ will become ever more important. This research has shown that embodied carbon expenditure for repairs to stone masonry walls for historic buildings can be reduced by the application of the developed model.

Research results have also shown that the embodied carbon expenditure for historic masonry buildings repairs can be converted into a supplementary stimulus for suitable repair uptake. This research gives validity to an environmentally driven repair strategies agenda.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

The initial research question aimed to evaluate whether a 'Green Maintenance' model for historic masonry buildings can be developed and tested based on the evaluation of the efficiency of stone masonry wall repair techniques in terms of embodied carbon expenditure? It has been successfully demonstrated that this has been achieved and the following chapter establishes the main findings of the research and underpin the initial aims and objectives established in the introduction of the work.

- The 'Green Maintenance' model has demonstrated the theoretical capability to cumulative reduce embodied carbon dioxide in traditionally masonry buildings. This is especially important as these structures are considered as being 'hard to treat' and are associated with energy inefficiency. Traditional approaches to energy conservation focus on reducing heat loss, conserving energy and encouraging the use of renewable energy. The 'Green Maintenance' model has shifted this current paradigm 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. An evaluation of cumulative embodied carbon has been practically tested using the 'Green Maintenance' model. The test results determined the Environmental Maintenance Impact (EMI) for buildings derived from a broad portfolio associated with 3 major organisations.

- 'Green Maintenance' can be seen as being synonymous with environmentally efficient repairs that are a function of higher longevity and lower embodied carbon (less CO_2 emission). In broader sense, this model is not simply confined to masonry and will be of use to those entrusted with the repair of other elements and building components. It is a pioneering evaluation system for the selection of masonry repair techniques. It has been shown to aid in the rational determination of repairs, highlighting those techniques with the greatest ability to reduce carbon dioxide, set against longevity. Clearly, the higher the longevity of repair, the better the technique is to be considered in terms of the embodied carbon expenditure.

Conversely a lower number of interventions undertaken within selected maintenance period contribute to reduced embodied carbon expenditure. The ability of the model to enable rational environmental comparisons and analysis of repair techniques to be made is to be welcomed by practitioners.

- The introduction and application of ‘Green Maintenance’ should highlight the relative importance of factoring carbon into the selection process. This should raise the profile of environmental concerns confronting society. That said, the adoption of ‘Green Maintenance’ has benefits beyond the environmental. It is clear that as carbon accounting becomes more prevalent then an additional financial cost can be evaluated and factored into the true cost of repair (carbon + financial cost). The traditional financial drive for cost reduction should lead to a response with attempts to attain carbon savings as a monetary value will be attached.

- The data inputs for the model will be enhanced over the long term as carbon accounting becomes more prevalent. The accuracy in the models ability to determine and predict the relative efficacy of repairs will therefore be correspondingly enhanced. The determination of efficacy [in terms of Environmental Maintenance Impact (EMI)] has been shown to be appropriate for the evaluation of single or multiple repair techniques adopting different repair scenarios. The ability of the model to aid decisions that underpin long term repair strategies will enable the property holders to substantiate the potential for real carbon reduction for ‘hard to treat’ building stock, over broader time frames. That said, the prediction of repair determinants (EMI) must be adjusted to take into consideration factors such as local exposure levels, the building detailing, design form and the quality of repairs undertaken. All of these factors can have a positive or negative influence upon the longevity of the repair, which is fundamental to the accuracy of the model.

- The ‘Green Maintenance’ model sets a benchmark of environmental profiling for specific masonry repair materials and techniques. The factors utilised for the profiling are composed in part of embodied carbon coefficients. It is evident that emissions (kgkm) associated with haulage is an important determinant in the evaluation of a repairs efficacy relating specifically to its final location. Whilst haulage distance is an important factor to consider the processing energy prior to delivery to site is critical. Obviously a material procured with a high energy input, with low transport distance adopting an efficient haulage system may fair worse than a material transported a greater distance with efficient processing.

- The 'Green Maintenance' model illustrates the importance of transportation of materials with regional sourcing playing and ever increasing role in the significance of CO_2 reduction. The model has illustrated that the local sourcing of regional materials is often environmentally the best option. The use of locally sourced materials compared against imported materials can significantly minimise CO_2 associated with transportation. Clearly, resourcing next to the proposed project location will yield greater results in terms of lower CO_2 emissions. The shorter the transportation distance, the lower the embodied carbon expended on the locally sourced materials delivery. In addition, the appointment of regional companies to undertake the repair work would also be beneficial. This has the simultaneous benefit of stimulating the local economy and repair of hard to treat buildings (including historic masonry buildings) with generally, speaking the most historically accurate materials available. These materials are also often the most physically and aesthetically most compatible. The use of local craft skills also pay dividends in terms of reducing carbon and would hopefully, in the longer term embed the concept of local sourcing and procurement from management tendering for projects through to the operatives undertaking the repairs.

- The ability to give reasoned advice on the environmental appropriateness of materials is a pivotal factor of the work. Repointing using lime-based mortar has been determined as the most appropriate and effective method not only it allows stone masonry walls to breathe but also ensure their appearance and finished work matches the original wall. Theoretically, lime-based mortar pointing is more durable (as compared to cement mortar pointing) as it minimises the deterioration of the masonry substrate. The 'Green Maintenance' model has demonstrated that the use of secondary fixing materials (stainless dowels, epoxy resin and non-ferrous tying wire) with associated high embodied carbon are extremely detrimental in terms of the EMI. These are used in both pinning and consolidation and multi-layer plastic repair techniques. Alternative techniques and materials should be encouraged to achieve CO_2 reduction for similar types of repairs and it is clear that replacing locally sourced natural stone that has a low LCA 'cradle to gate' value will be beneficial.

- Based on the EMI results, it has been shown that 'Green Maintenance' has ability to provide guidance for the flexible selection of maintenance options that minimise embodied carbon expenditure. This promotes sustainable solutions for the repair of existing buildings. The concept of 'Green Maintenance' complements the growth in 'green procurement' that is now being accepted as a tangible developing market area. It must be emphasised that the 'Green Maintenance' model would benefit from agreed cross party definitions for all organisations responsible for the maintenance of buildings.

- If implemented, 'Green Maintenance' could be beneficial to both national and international economies, and should be viewed as an important tool for attaining carbon reduction targets. The protection of historic buildings should not simply be viewed from a cultural perspective, but also from an economic and Environmental Maintenance Impact (EMI).

- The emergence of the 'Green Maintenance' model can be seen as a driver for the promotion and aid in the achievement of low carbon reduction targets for organisations, contractors, as well as practitioners. In the longer term it is hoped that this research will inform government policy for the repair of traditional buildings, enabling advice for all relevant parties to be given and influencing and stimulating appropriate, well considered maintenance strategies.

7.2 Recommendations for Further Research

Whilst the research has established an innovative framework for 'Green Maintenance', further complementary work would be beneficial. The following issues should be investigated;

- A wide scale evaluation of all materials and techniques should be undertaken. This should ultimately be used to generate a formalised inventory for repair techniques. A repair techniques 'carbon hand book' could be developed that could ideally integrate into the building cost information systems. This could potentially, unify the 2 principle measures of cost, both monetary and carbon.

- The Green Maintenance model should be utilised to form the basis of a primary decision making process framework for organisation and practices. The protocol required for practical implementation and long term monitoring would require investigation.
- A feedback system is required to determine the accuracy of the model and associated interventions. Large scale evaluation of practice based case studies should be established.
- Whole building integration of the EMI should be tested. This would enable comparability for structures of a similar nature or used in terms of evaluating refurbishment work.
- Work into unifying data and measurement of LCA is required to enhance the accuracy of inputs that are required for the model.

Appendix A: Embodied Carbon Coefficient Profile for Common Stone Masonry Wall Repair Materials

Table A.1: Embodied Carbon Coefficient Profile-Stone

Material Profile: Stone

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

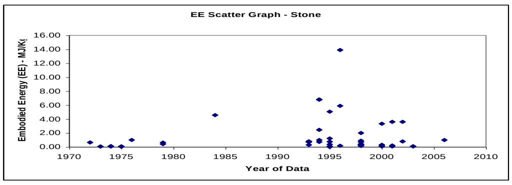
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Stone	**54**	**1.26**	**2.35**	**0.02**	**13.90**	None
Stone, General	18	1.23	1.74	0.02	6.80	
Predominantly Recycled	1	0.40	0.40	0.40	-	
Unspecified	10	1.47	2.12	0.10	6.80	
Virgin	7	1.00	1.24	0.02	3.60	
Stone, Granite	5	4.10	6.01	0.10	13.90	
Unspecified	5	4.10	6.01	0.10	13.90	
Stone, Limestone	18	0.41	0.58	0.03	2.45	
Unspecified	17	0.42	0.60	0.03	2.45	
Virgin	1	0.37	0.37	0.37	-	
Stone, Marble	3	1.88	1.52	0.30	3.33	
Unspecified	3	1.88	1.52	0.30	3.33	
Stone, Slate	1	0.03	0.03	0.03	-	
Virgin	1	0.03	0.03	0.03	-	
Stone, Slate	9	1.40	1.97	0.08	5.06	
Unspecified	7	1.07	1.58	0.10	4.57	
Virgin	2	2.57	3.52	0.08	5.06	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General Stone	1.26 (?)	0.079 (?)	Cradle to Gate	0.1	3.6	The data range is too wide and there is at present not enough data to estimate the data for a 'typical' stone product. Therefore the ICE database average was selected, this is not a typical selection process within the ICE database.
Granite	11	0.7	Cradle to Gate	-	-	Estimated from Ref. 116.
Limestone	1.5	0.090	Cradle to Gate	-	-	Estimated from Ref. 188.
Marble	2	0.130		Not enough data for accurate range. Estimated range +/- 30%		
Marble tile	3.33	0.210	Cradle to grave			Ref. 40.
Sandstone	1.0 (?)	0.06 (?)	Cradle to Gate	-	-	Uncertain estimate based on Ref. 262, awaiting improved data.
Shale	0.03	0.002	Cradle to Gate	-	-	
Slate	0.1 to 1.0	0.007 to 0.063	Cradle to Gate	-	-	Large data range

Comments	Several values were selected based on single sources of data, but because of the importance of stone in construction it was decided that these values should be used if they were from a quality data source. Data on stone was generally poor.

Material Scatter Graph



Embodied Energy & Embodied Carbon Split

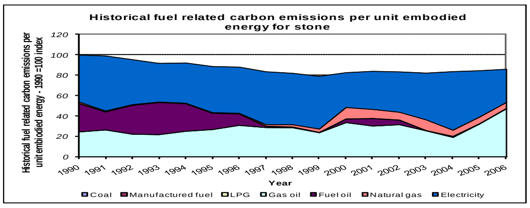
Energy source	% of Embodied Energy from energy source	% of embodied carbon from source
Coal	0.0%	0.0%
LPG	0.0%	0.0%
Oil	50.5%	54.8%
Natural gas	9.0%	7.2%
Electricity	40.5%	38.0%
Other	0.0%	0.0%
Total	**100.0%**	**100.0%**

Comments:

The embodied carbon was estimated by using the UK typical fuel split in this industry.

Note Space

Historical embodied carbon per unit fuel use



Material Properties (CIBSE Data)

Material	Condition	Thermal conductivity (W-m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M ^2 S-1)
stone chippings for roofs		0.96	1800	1000	5.33333E-07
basalt		3.49	2880	840	1.44263E-06
gneiss		3.49	2880	840	1.44263E-06
granite		3.49	2880	840	1.44263E-06
granite, red		2.9	2650	900	1.21593E-06
hard stone (unspecified)		3.49	2880	840	1.44263E-06
		2.9	2750	840	1.25541E-06
limestone		1.5	2180	720	9.55657E-07
		2.9	2750	840	1.25541E-06
	At 50'C	1.8	2420	840	8.85478E-07
		2.9	2750	840	1.25541E-06
	Dry	2.91	2750	840	1.25974E-06
	Moist	3.49	2750	840	1.51082E-06
marble, white		2	2500	880	9.09091E-07
petit granit (blue stone)	Dry	2.91	2700	840	1.28307E-06
	Moist	3.49	2700	840	1.5388E-06
porphyry		3.49	2880	840	1.44263E-06
sandstone		1.83	2200	710	1.17157E-06
		3	2150	840	1.66113E-06
		1.3	2150	840	7.19823E-07
		5	2150	840	2.76855E-06
sandstone tiles	Dry	1.2	2000	840	7.14286E-07
slate		1.44	1600	1470	6.12245E-07
	At 50°C	1.72	2750	840	7.44589E-07
slate shale		2.1	2700	840	9.25926E-07
white calcareous stone	Firm, moist	2.09	2350	840	1.05876E-06
	Firm, dry	1.74	2350	840	8.81459E-07
	hard, moist	2.68	2550	840	1.25117E-06
	Hard, dry	2.21	2550	840	1.03175E-06
tufa, soft	Dry	0.35	1300	840	3.20513E-07
	Moist	0.5	1300	1260	3.0525E-07

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.2: Embodied Carbon Coefficient Profile-Cement

Material Profile: Cement

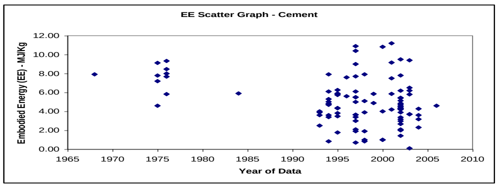
Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Cement	**116**	**5.20**	**2.70**	**0.10**	**14.20**	There was a large sample of data.
Cement Mortar	11	1.54	0.91	0.10	3.49	
Unspecified	9	1.30	0.70	0.10	2.10	
Virgin	2	2.63	1.22	1.77	3.49	
Cement, Fibre Cement	1	4.60	4.60	4.60		
Virgin	1	4.60	4.60	4.60		
Cement, Fibre Cement	8	10.15	1.93	7.60	14.20	
Unspecified	8	10.15	1.93	7.60	14.20	
Cement, General	94	5.32	2.05	1.42	11.73	
Market Average	7	5.02	0.66	4.29	6.20	
Unspecified	65	5.46	2.27	1.42	11.73	
Virgin	22	4.88	1.07	3.00	6.50	
Cement, Soil-Cement	2	0.85	0.21	0.70	1.00	
Unspecified	2	0.85	0.21	0.70	1.00	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General (UK weighted average)	4.51	0.74	Cradle to Gate	(+/- 30%)		Weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. This data has been estimated from the Mineral Products Association (MPA) factsheets (see Ref. 59). 23% cementitious additions on average.
Average CEM I Portland Cement, 94% Clinker	5.50	0.95				This is a standard cement with no cementitious additions (i.e. Fly ash or blast furnace slag). Composition 94% clinker, 5% gypsum, 1% minor additional constituents (mac's). This data has been estimated from the MPA factsheets (see Ref. 59).
6-20% Fly Ash (CEM II/A-V)	5.28 to 4.51	0.89 (@ 6%) to 0.76 (@ 20%)				Fly ash has a lower embodied carbon than blast furnace slag, however the upper threshold of fly ash content that can be used in a stable mixture is lower than for blast furnace slag. This data has been estimated from the MPA factsheets (see Ref. 59) and the ICE data for fly ash.
21-35% Fly Ash (CEM II/B-V)	4.45 to 3.68	0.75 to 0.62				
21-35% GGBS (CEM II/B-S)	4.77 to 4.21	0.77 to 0.65				GGBS = ground granulated blast furnace slag. Blast furnace slag has a higher embodied carbon than fly ash, however the upper threshold of blast furnace slag content is higher than for fly ash. This data has been estimated from the British Cement Association's factsheets (see Ref. 59) and the ICE data for GGBS.
36-65% GGBS (CEM III/A)	4.17 to 3.0	0.64 to 0.39				
66-80% GGBS (CEM II/B)	2.96 to 2.4	0.38 to 0.26				
Fibre Cement Panels - Uncoated	10.4	1.09 CO2 only		Estimated range +/- 30%		Few data points. Selected data modified from Ref. 107. An example application are facade panels.
Fibre Cement Panels - (Colour) Coated	15.3	1.28 CO2 only		Estimated range +/- 30%		
Mortar (1:3 cement:sand mix)	1.33	0.221		(+/- 30%)		Estimated from the ICE Cement, Mortar & Concrete Model and mix proportions.
Mortar (1:4)	1.11	0.182				
Mortar (1:5)	0.97	0.156				
Mortar (1:6)	0.85	0.136				
Mortar (1:½:4½ Cement:Lime:Sand mix)	1.34	0.213				
Mortar (1:1:6 Cement:Lime:Sand mix)	1.11	0.174				
Mortar (1:2:9 Cement:Lime:Sand mix)	1.03	0.155				
Cement stabilised soil @ 5%	0.68	0.061				Assumed 5% cement content.
Cement stabilised soil @ 8%	0.83	0.084				Assumed 8% stabiliser contents (6% cement and 2% quicklime)
Comments	The high range is due to the fact that the embodied energy is highly dependent upon the clinker content of cement, manufacturing technology and if additions have been added, such as fly ash, slag…etc. Cement is an important building material and is important in the manufacture of concrete. There are a wide range of cement types with a large variation in the embodied energy and carbon, but the typical cement (general category above) provides a reasonable value to use in the absence of knowing the specific type of cement. This typical value is consistent with the database statistics and modern sources of data. The scatter graph shows a large amount of relatively modern data.					

Material Scatter Graph



Embodied Energy & Embodied Carbon Split

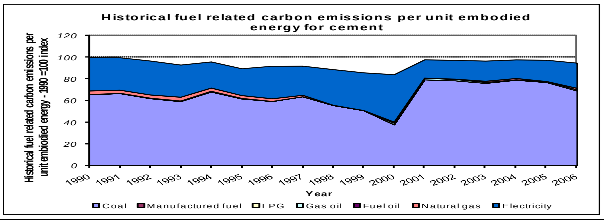
Energy source	% of Embodied Energy from energy source	% of embodied carbon from source
Coal	63.4%	32.0%
LPG	0.0%	0.0%
Oil	1.4%	0.5%
Natural gas	2.4%	0.7%
Electricity	32.8%	10.9%
Other	0.0%	55.9% (Non-fuel emissions)
Total	**100.0%**	**100.0%**

Comments:

0.52 KgCO2/Kg clinker is released by de-carbonation in the manufacture of clinker, which is the main constituent of cement. This has been represented in the row labelled 'other' above.

Note Space

Historical embodied carbon per unit fuel use



Material Properties (CIBSE Data)

Material	Condition	Thermal conductivity (W-m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M ^2 S-1)
cement		0.72	1860	840	4.60829E-07
cement blocks, cellular		0.33	520	2040	3.11086E-07
cement fibreboard, magnesium oxysulphide binder		0.082	350	1300	1.8022E-07
Cement mortar		0.72	1650	920	4.74308E-07
cement mortar	Dry	0.93	1900	840	5.82707E-07
cement mortar	Moist	1.5	1900	840	9.3985E-07
cement/lime plaster		0.8	1600	840	5.95238E-07
cement panels, wood fibres A	Dry	0.08	350	1890	1.20937E-07
cement panels, wood fibres B	Moist	0.12	350	3040	1.12782E-07
cement panels, wood fibres C		0.12	400	1470	2.04082E-07
cement panels, wood fibres D	Dry	0.35	1650	840	2.52525E-07
Cement Screed		1.4	2100	650	1.02564E-06

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.3: Embodied Carbon Coefficient Profile-Lime

Material Profile: Lime

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

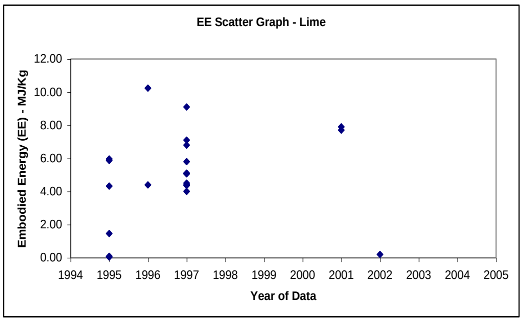
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Lime	**39**	**4.57**	**2.79**	**0.04**	**10.24**	
Lime, General	39	4.57	2.79	0.04	10.24	None
Unspecified	4	6.51	4.36	0.20	10.24	
Virgin	35	4.24	2.40	0.04	9.10	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General Lime	5.3	0.78	Cradle to Gate	4	9.1	Wide range, dependent upon manufacturing technology. Although the embodied energy was higher than for cement the UK lime industry mix of fuels were cleaner thank cement, as such its embodied carbon was lower.

Comments	Lime is often chosen as an environmentally friendly material. It was therefore surprising to learn that the embodied energy of lime was slightly higher than for cement. This was observed from the respectable sample size of 39 data records. Lime is fired in the kiln to a lower temperature than cement, which is often misconceived as proof for a lower embodied energy. The present authors suggest that yield, density, and time in the kiln are all vital parameters to total energy consumption and that firing temperature may not be used as a proxy for embodied energy. This is presented as a possibility for its higher embodied energy. It should be noted that embodied energy is, in itself, not evidence to discredit limes environmental credentials. Due to a more favourable fuel mix and slightly lower process related carbon dioxide emissions lime has a lower embodied carbon than cement. An additional benefit of using lime based mortar includes the increased ability for deconstruction, rather than demolition. The re-carbonation that occurs over the lifetimes of both cement and lime based mortars (when exposed to air) will reduce the embodied carbon impact of the materials. Its understood that this process is not undesirable for lime (unlike cement). Examination of lime's full carbon cycle, cradle-to-grave, is therefore

Material Scatter Graph



Embodied Energy & Embodied Carbon Split

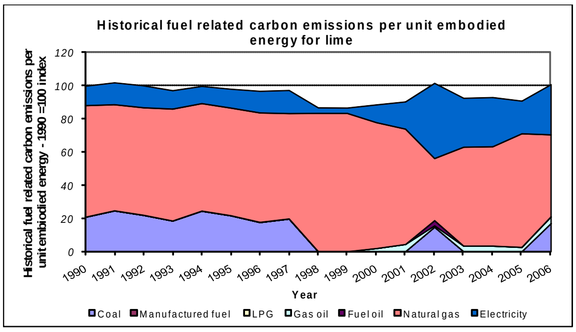
Energy source	% of Embodied Energy from energy source	% of embodied carbon from energy source
Coal	10.8%	6.2%
LPG	0.0%	0.0%
Oil	3.4%	1.5%
Natural gas	56.4%	18.1%
Electricity	29.4%	11.1%
Other	0.0%	63.1%
Total	**100.0%**	**100.0%**

Comments:

The fuel split was taken from the typical UK fuel use in UK lime industry. Lime releases approximately 0.48 kg CO2/kg lime produced. This is a process related emission and is additional to the fuel related CO2.

Note Space

Historical embodied carbon per unit fuel use



Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.4: Embodied Carbon Coefficient Profile-Sand

Material Profile: Sand

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

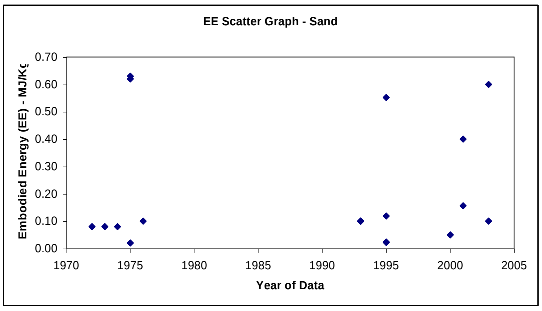
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Sand	**18**	**0.21**	**0.23**	**0.02**	**0.63**	
Sand, General	18	0.21	0.23	0.02	0.63	These statistics were obscured by a few high values (See scatter chart)
Unspecified	12	0.24	0.24	0.02	0.63	
Virgin	6	0.15	0.22	0.02	0.55	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General Sand	0.0081	0.0051	Cradle to Gate	0.05	0.15	Estimated from UK industrial fuel consumption data.

Comments	Transport is a significant contributor to the cradle to gate embodied energy of sand. The impacts of transporting the sand must be added to these values.

Material Scatter Graph



Embodied Energy & Embodied Carbon Split

Energy source	% of Embodied Energy from energy source	% of embodied carbon from source
Coal	0.0%	0.0%
LPG	0.0%	0.0%
Oil	26.5%	29.8%
Natural gas	8.0%	6.6%
Electricity	65.5%	63.6%
Other	0.0%	0.0%
Total	**100.0%**	**100.0%**

Comments:

The embodied carbon was estimated by using the UK typical fuel split in this industry.

Note Space

Historical embodied carbon per unit fuel use

Material Properties (CIBSE Data)

Material	Condition	Thermal conductivity (W-m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M^2 S-1)
sand		1.74	2240	840	9.24745E-07

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.5: Embodied Carbon Coefficient Profile-Clay (including Bricks)

Material Profile: Clay (including Bricks)

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

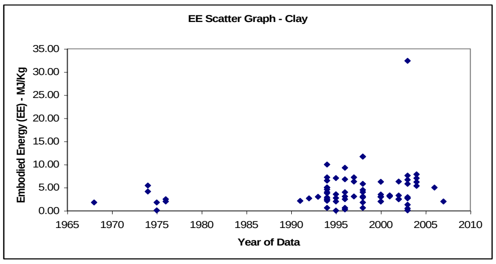
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Clay	**80**	**4.30**	**4.12**	**0.02**	**32.40**	There was a good sample size
Clay, General	80	4.30	4.12	0.02	32.40	
Unspecified	58	4.53	4.57	0.07	32.40	
Virgin	22	3.59	2.22	0.02	7.60	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General simple baked clay products	3	0.24	Cradle to Gate	1	5	None
Tile	6.5	0.48		2.88	11.7	
Vitrified clay pipe DN 100 & DN 150	6.2	0.46		Estimated range +/- 30%		
Vitrified clay pipe DN 200 & DN 300	7.0	0.50				
Vitrified clay pipe DN 500	7.9	0.55				
General Clay Bricks	3.0	0.24		0.63	6	
EXAMPLE: Single Brick	6.9 MJ per brick	0.55 kgCO2 per brick		-	-	Assuming 2.3 kg per brick (Brick Development Association estimate)
Limestone Bricks	0.85	?	Cradle to Gate	0.7	1.01	

Comments	Clay products release process related carbon dioxide emissions during their manufacturing. This is dependent upon the type of clay product. There was a large data range associated with all ceramic and brick products.

Material Scatter Graph



Embodied Energy & Embodied Carbon Split (Bricks)

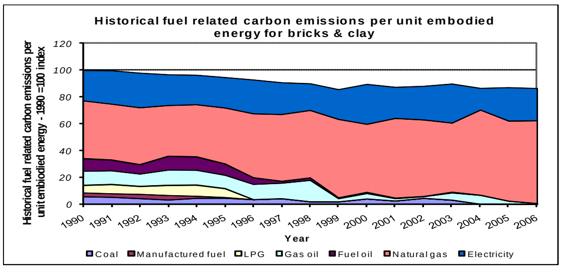
Energy source	% of Embodied Energy from energy source	% of embodied carbon from energy source
Coal	0.0%	0.0%
LPG	0.0%	0.0%
Oil	0.4%	0.2%
Natural gas	74.6%	49.5%
Electricity	25.0%	17.3%
Other	0.0%	33.0%
Total	**100.0%**	**100.0%**

Comments:

The embodied carbon was estimated by using the UK typical fuel split in this industry.

Note Space

Historical embodied carbon per unit fuel use



Material Properties (CIBSE Data)

Material	Thermal conductivity (W-m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M^2 S-1)	Comments
clay tiles	0.85	1900	840	5.32581E-07	
clay tiles, burnt	1.3	2000	840	7.7381E-07	
clay tile, hollow, 10.2mm. 1 cell	0.52	1120	840	5.52721E-07	
Clay tile, hollow, 20.3mm, 2 cells	0.623	1120	840	6.62202E-07	
Clay tile, hollow, 32.5mm, 3 cells	0.693	1120	840	7.36607E-07	
clay tile, pavior	1.803	1920	840	1.11793E-06	
BRICKS					
Brick A	0.72	1920	840	4.46429E-07	The CISBE guide presented multiple values for brick
Brick B	1.31	2080	921	6.8383E-07	
aerated	0.3	1000	840	3.57143E-07	
brickwork, inner leaf	0.62	1700	800	4.55882E-07	
brickwork, outer leaf	0.84	1700	800	6.17647E-07	
burned A	0.75	1300	840	6.86813E-07	
burned B	0.85	1500	840	6.74603E-07	
burned C	1	1700	840	7.0028E-07	
mud	0.75	1730	880	4.92643E-07	
paviour	0.96	2000	840	5.71429E-07	
reinforced	1.1	1920	840	6.82044E-07	
tile	0.8	1890	880	4.81E-07	

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.6: Embodied Carbon Coefficient Profile-Aggregate

Material Profile: Aggregate

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

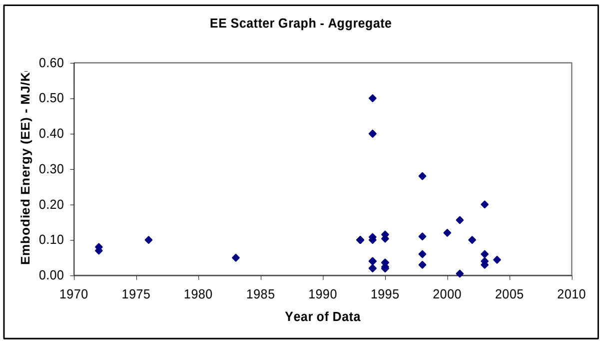
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Aggregate	**37**	**0.11**	**0.12**	**0.01**	**0.50**	None
Aggregate, General	37	0.11	0.12	0.01	0.50	
Predominantly Recycled	3	0.25	0.21	0.10	0.40	
Unspecified	17	0.11	0.07	0.02	0.28	
Virgin	17	0.10	0.15	0.01	0.50	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General Aggregate	0.083	0.0052	Cradle to Gate	0.05	0.25	Estimated from UK industrial fuel consumption data.

Comments	It should be noted that the scatter graph does not display all of the data necessary to select a 'best' embodied energy/carbon coefficient, for example the boundary conditions are missing (cradle to site, cradle to gate...etc). These are stored in the full database and were considered during the selection process. Transport is often considered to be a significant contributor for aggregates.

Material Scatter Graph



Embodied Energy & Embodied Carbon Split

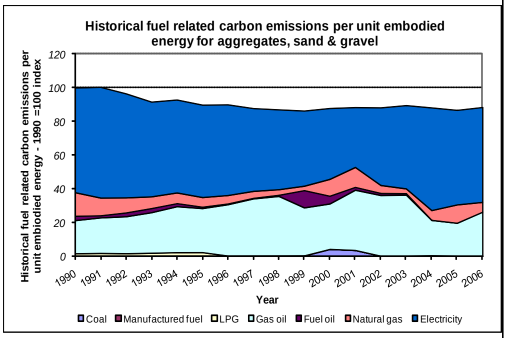
Energy source	% of Embodied Energy from energy source	% of embodied carbon from source
Coal	0.0%	0.0%
LPG	0.0%	0.0%
Oil	26.5%	29.8%
Natural gas	8.0%	6.6%
Electricity	65.5%	63.6%
Other	0.0%	0.0%
Total	**100.0%**	**100.0%**

Comments:

The embodied carbon was estimated by assuming the UK typical fuel split in this industry, the resulting value is in agreement with other results in the literature.

Note Space

Historical embodied carbon per unit fuel use



Material Properties (CIBSE Data)

Material	Condition	Thermal conductivity (W-m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M^2 S-1)
aggregate	Undried	1.8	2240	840	9.5663E-07
aggregate (sand, gravel or stone)	Oven dried	1.3	2240	920	6.3082E-07

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.7: Embodied Carbon Coefficient Profile-Steel

Material Profile: Steel

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Steel	**180**	**31.25**	**16.50**	**6.00**	**95.70**	None
Steel, General	154	29.36	13.45	6.00	77.00	
50% Recycled	2	32.75	20.86	18.00	47.50	
Market Average	11	25.68	5.92	18.20	36.00	
Other Specification	2	19.40	0.71	18.90	19.90	
Predom. Recycled	33	13.60	4.86	6.00	23.40	
Unspecified	49	31.96	10.61	12.50	77.00	
Virgin	57	37.48	12.07	12.00	63.42	
Steel, Stainless	21	45.68	28.84	8.20	95.70	
Market Average	3	48.36	6.22	40.20	51.48	
Predom. Recycled	2	11.00	0.00	11.00	11.00	
Unspecified	8	43.10	32.21	8.20	95.70	
Virgin	8	57.80	28.76	12.00	81.77	
Steel, Structural	5	30.91	3.74	25.50	35.90	
Unspecified	2	28.67	4.48	25.50	31.83	
Virgin	3	32.40	3.10	30.00	35.90	

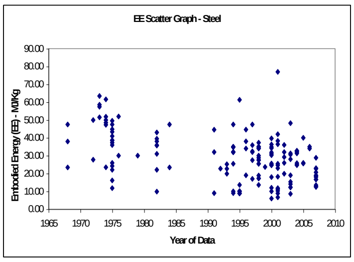
Selected Embodied Energy & Carbon Coefficients and Associated Data

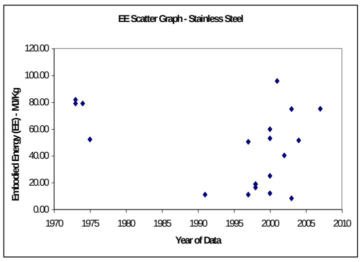
Material	Embodied Energy - MJ/Kg					Embodied Carbon - Kg CO2e/Kg					Boundaries	Best EE Range - MJ/Kg		Specific Comments
	UK Typical - EU 59% Recy.	R.O.W. Typical - 35.5% Recy.	World Typical - World 39% Recy.	Primary (100% hypothetical virgin)	Secondary	UK Typical - EU 59% Recy.	R.O.W. Typical - 35.5% Recy.	World Typical - World 39% Recy.	Primary (100% hypothetical virgin)	Secondary		Low EE	High EE	
General Steel	20·1	26·2	25·3	35·4	9·40	1.46	2.03	1.95	2.89	0.47	Cradle to Gate	(+/- 30%)		Estimated from UK's consumption mixture of types of steel (excluding stainless). Doesn't include the final cutting of the steel products to the specified dimensions. Estimated from World Steel Association (Worldsteel) data.
Bar & rod	17.4	22.3	21.6	29.2	8·8	1.40	1.95	1.86	2.77	0.45				Doesn't include the final cutting of the bar/rod to length. Estimated from Worldsteel data.
Coil (Sheet)	18·8	24·4	23·5	32·8	*NTMR*	1.38	1.92	1.85	2.74	*NTMR*				NTMR = Not Typical Manufacturing Route. Data doesn't include the cutting of the coil into sheets. Data is as leaves the coil manufacturer. Estimated from Worldsteel data.
Coil (Sheet) - Galvanised	22·6	29·5	28·5	40·0	*NTMR*	1.54	2.12	2.03	3.01	*NTMR*				NTMR = Not Typical Manufacturing Route. Data doesn't include the cutting of the coil into sheets. Data is as leaves the coil manufacturer. Estimated from Worldsteel data.
Engineering steel	-	-	-	-	13·1	-	-	-	-	0.72				Estimated from Worldsteel data.
Pipe	19·8	25·8	24·9	34·7	*NTMR*	1.45	2.01	1.94	2.87	*NTMR*				NTMR = Not Typical Manufacturing Route. Estimated from Worldsteel data.
Plate	25·1	33·2	32·0	45·4	*NTMR*	1.66	2.31	2.21	3.27	*NTMR*				NTMR = Not Typical Manufacturing Route. Doesn't include the final cutting of the plate. Estimated from Worldsteel data.
Section	21·5	28·1	27·1	38·0	10·0	1.53	2.12	2.03	3.03	0.47				Data doesn't include final fabrication stage (cutting of the section). Estimated from Worldsteel data.
Wire	36 (?)					3.02 (?)								Uncertain data.
Stainless	56.7					6.15 CO2 only					Cradle to Gate	11	82	World average data from the Institute of Stainless Steel Forum (ISSF) life cycle inventory data. Selected data is for the most popular grade (304). Stainless steel does not have separate primary and recycled material production routes.

Comments

Please read the recycling methodology guide (Annex on recycling methods) before using this data, which also contains guidance on end of life issues for steel. The above data is '*cradle to gate*', which excludes the important end of life stage (see Annex on recycling methods). The majority of this data has been derived from the World Steel Association (Formerly International Iron & Steel Institute [IISI]) life cycle inventory (LCI) data, which is the most complete and detailed steel LCI to date and can be obtained free of charge from the IISI website (www.worldsteel.org). Some of the IISI data has been modified to fit within the ICE framework and methodology (e.g. converted to Gross Calorific Value). It should be noted that the data for 'primary steel' is a purely hypothetical 100% primary steel, this enables the recycled content approach to be easily implemented. In practise all steel contains at least a small recycled content, even if sourced from a 'primary production route' (Blast Furnace), on average blast furnace steel has a recycled content of approx 13% (*e.g. general steel @13% recycled content = BF route = 31 MJ/kg*). On the other hand a 100% recycled steel is realistic. **Only steel PRODUCTION WITHIN the EU 27 countries may apply the EU 27 3-year average recycled content of 59%. If applying this recycled content a 'rest of the world' recycled content should be applied to non-EU 27 steel (for consistency within the same project), the 3-year average ROTW recycled content is 35.5%. Alternatively the 3-year world average recycled content of 39% may be applied for all steel products, but this cannot be mixed with the EU 27 average within the same project. For further guidance please see Annex on recycling methods.** There is now new data from Worldsteel, which updates the LCI study to 2010. This data was not used here because we were not able to process the data in time (and the Worldsteel methodology report was still being finished). Readers with a strong interest in steel are advised to look at the detailed data from Worldsteel, which is available through their website.

Material Scatter Graph





Embodied Energy & Embodied Carbon Split

A breakdown of fuel use or carbon emissions was not possible. This is because the steel industry is complicated by the production of by-products (which may be allocated energy or carbon credits), excess electricity production (they produce some of their own electricity) and non-fuel related emissions (from the calcination of lime during the production process).

Material Properties (CIBSE Data)

Material	Condition		Thermal conductivity (W m-1 K-1)	Density (kg m -3)	Specific heat (J kg-1 K-1)	Thermal Diffusivity (M^2 S-1)
stainless steel, 5% Ni			29	7850	480	7.69639E-06
stainless steel, 20% Ni			16	8000	480	4.16667E-06
steel			45	7800	480	1.20192E-05

Source: Hammond and Jones, 2008a; 2008b and 2011.

Table A.8: Embodied Carbon Coefficient Profile-Sealants and Adhesives

Material Profile: Sealants & Adhesives

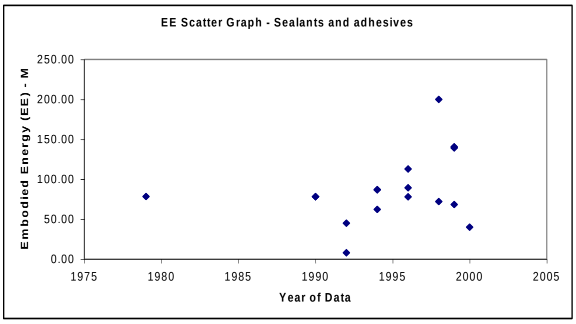
Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Sealants and adhesives	**17**	**83.60**	**44.90**	**8.00**	**200.00**	There were more materials (sealants and adhesives) in the ICE database than have been used for this inventory, as can be observed from these database statistics. limited data from quality resources made selection of coefficients difficult.
Sealants and adhesives, Epoxide Resin	2	139.96	0.91	139.32	140.60	
Market Average	1	139.32	139.32	139.32		
Unspecified	1	140.60	140.60	140.60		
Sealants and adhesives, General Adhesives	2	61.67	23.57	45.00	78.34	
Unspecified	2	61.67	23.57	45.00	78.34	
Sealants and adhesives, General sealants	1	8.00	8.00	8.00		
Unspecified	1	8.00	8.00	8.00		
Sealants and adhesives, Mastic Sealant	2	131.14	97.38	62.28	200.00	
Unspecified	2	131.14	97.38	62.28	200.00	
Sealants and adhesives, melamine resin	2	96.36	23.27	79.90	112.81	
Unspecified	2	96.36	23.27	79.90	112.81	
Sealants and adhesives, Phenol Formaldehyde	3	78.77	16.30	60.00	89.32	
Unspecified	3	78.77	16.30	60.00	89.32	
Sealants and adhesives, Urea Formaldehyde	5	63.74	17.53	40.00	78.20	
Unspecified	5	63.74	17.53	40.00	78.20	

Selected Embodied Energy & Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg	Feedstock Energy (Included) - MJ/Kg	Embodied Carbon - Kg CO2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
					Low EE	High EE	
Epoxide Resin	137	42.6	5.7 CO2 only	Cradle to Gate	(+/- 20%)		Source: www.plasticseurope.org
Mastic Sealant	62 to 200	?	?	Cradle to Gate	-	-	Only two data sources, with large range, data includes an unknown value of feedstock energy.
Melamine Resin	97	18	4.19 CO2 only	Cradle to Gate	(+/- 30%)		Feedstock energy 18 MJ/kg - estimated from Ref. 34.
Phenol Formaldehyde	88	32	2.98 CO2 only	Cradle to Grave	-	-	Feedstock energy 32 MJ/kg - estimated from Ref. 34.
Urea Formaldehyde	70	18	2.76 CO2 only	Cradle to Site	(+/- 30%)		Feedstock energy 18 MJ/kg - estimated from Ref. 34.

Comments	The data on sealants & adhesives was very limited, especially with regards to feedstock energy and carbon emissions.

Material Scatter Graph	**Embodied Energy & Embodied Carbon Split**
	No fuel split or embodied carbon breakdown was available.

Source: Hammond and Jones, 2008a; 2008b and 2011.

Appendix B: CO_2 Emissions Factors Per Tonne km for HGV Road Freight

Table B.1: Updated 2008 CO_2 emission factors per tonne km for HGV road freight (based on UK average vehicle loads in 2005)

Body Type	**Gross Vehicle Weight**	**gCO_2 per tonne km**
Rigid	>3.5-7.5t	591
Rigid	>7.5-17t	336
Rigid	>17t	187
All rigid	**UK average**	**276**
Articulated	>3.5-33t	163
Articulated	>33t	82
All articulated	**UK average**	**86**
ALL HGVs	**UK average**	**132**

Source: Defra/DECC, 2009.

Notes:

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.

Appendix C: Lime Mortar Materials and Mixes

Table C.1: Lime mortar materials and mixes-Historic Scotland

		Mixes (by volumes)								
		Historic Scotland (HS)								
Repair techniques	**Lime mortar/grout/plaster mixes materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace
Natural stone replacement	**(a) Indenting + lime mortar grout mix**									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	2					1	
	Jurra Kalk		1							
	Sand	3	5	7	3	3	3	5	5	6
	Brick Dust/Fire Clay/Fly Ash (Approx.)	1/16			1/16	1/16	1/16			
	(b) Indenting + dowels + lime grout mix									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	2					1	
	Jurra Kalk		1							
	Sand	3	5	7	3	3	3	5	5	6
	Brick Dust/Fire Clay/Fly Ash (Approx.)	1/16			1/16	1/16	1/16			
	(c) Dowels + epoxy resin*	None								
Repointing	(a) Lime mortar									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	2					1	
	Jurra Kalk		1							
	Sand	3	5	7	3	3	3	5	5	6
	Brick Dust/Fire Clay/Fly Ash (Approx.)	1/16			1/16	1/16	1/16			
Pinning and consolidation	(a) Dowels + lime grout									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	1					1	
	Jurra Kalk		1							
	Sand	2	5	4	2	2	2	4	5	3
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	3	6
	(b) Dowels + epoxy resin*	None								
Plastic repair	(a) Lime base mortar + aggregates									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	1					1	
	Jurra Kalk		1							
	Sand	2	3	3	2	2	2	5	3	3
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4
	(b) Lime base mortar (multi-layer plastic repair)									
	Cement (General)	1/16	1		1/16	1/16	1/16		1	1
	Lime Putty	1		1	1	1	1	1		
	Natural Hydraulic Lime (NHL 3.5)							1		1
	Natural Hydraulic Lime (NHL 5)		1	1					1	
	Jurra Kalk		1							
	Sand	2	3	3	2	2	2	5	3	3
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4
Notes: * Use only stainless steel dowels and epoxy resin										

Source: Author, 2012.

Table C.2: Lime mortar materials and mixes-National Trust for Scotland

		Mixes (by volumes)								
		National Trust for Scotland (NTS)								
Repair techniques	**Lime mortar/grout/plaster mixes materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose
Natural stone replacement	**(a) Indenting + lime mortar grout mix**									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	2	2	2	2	2	2	2	2	8
	Brick Dust/Fire Clay/Fly Ash (Approx.)									
	(b) Indenting + dowels + lime grout mix									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	2	2	2	2	2	2	2	2	8
	Brick Dust/Fire Clay/Fly Ash (Approx.)									
	(c) Dowels + epoxy resin*	None								
Repointing	(a) Lime mortar									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	2	2	2	2	2	2	2	2	8
	Brick Dust/Fire Clay/Fly Ash (Approx.)									
Pinning and consolidation	(a) Dowels + lime grout									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	2	2	2	2	2	2	2	2	2
	Crushed limestone/gravel/chippings	1	1	1	1	1	4	4	4	4
	(b) Dowels + epoxy resin*	None								
Plastic repair	(a) Lime base mortar + aggregates									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	3	3	3	3	8	2	2	2	4
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4
	(b) Lime base mortar (multi-layer plastic repair)									
	Cement (General)						1/2	1/2	1/2	
	Lime Putty	0.75	0.75	0.75	0.75	0.75				1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1	1	1	1	1	
	Natural Hydraulic Lime (NHL 5)									2
	Jurra Kalk									
	Sand	3	3	3	3	8	2	2	2	4
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4
Notes: * Use only stainless steel dowels and epoxy resin										

Source: Author, 2012.

Table C.3: Lime mortar materials and mixes-The City of Edinburgh Council

		Mixes (by volumes)									
		The City of Edinburgh Council (CEC)									
Repair techniques	**Lime mortar/grout/plaster mixes materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street, Edinburgh	CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh	CEC3-21-31 Hillside Street, Edinburgh	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh
						Stone Type A	Stone Type B				
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	3	3	3	3	3	3	3	3	3	5
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	(b) Indenting + dowels + lime grout mix										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	3	3	3	3	3	3	3	3	3	5
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	(c) Dowels + epoxy resin*	None									
Repointing	(a) Lime mortar										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	3	3	3	3	3	3	3	3	3	5
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
Pinning and consolidation	(a) Dowels + lime grout										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	3	3	3	3	3	3	3	3	3	3
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4	4
	(b) Dowels + epoxy resin*	None									
Plastic repair	(a) Lime base mortar + aggregates										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	5	5	5	5	5	5	5	3	3	5
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4	4
	(b) Lime base mortar (multi-layer plastic repair)										
	Cement (General)										
	Lime Putty	1	1	1	1	1	1	1	1	1	1
	Natural Hydraulic Lime (NHL 3.5)	1	1	1	1						
	Natural Hydraulic Lime (NHL 5)					1	1	1	1	1	2
	Jurra Kalk										
	Sand	5	5	5	5	5	5	5	3	3	5
	Crushed limestone/gravel/chippings (aggregates)	4	4	4	4	4	4	4	4	4	4
Notes: * Use only stainless steel dowels and epoxy resin											

Source: Author, 2012.

Appendix D: Mass (kg) of Lime and Secondary Fixing Materials Used for Stone Masonry Wall Repair

Table D.1: Mass (kg) of lime and secondary fixing materials used for stone masonry wall repair-Historic Scotland

		Approximate of mass (kg) materials for repairing 1 m^2 stone masonry wall								
		Historic Scotland (HS)								
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace
Natural stone replacement	**(a) Indenting + lime mortar grout mix**									
	Cement (General)	0.560	4.625		0.560	0.560	0.560		5.286	4.625
	Lime Putty	8.970		3.700	8.970	8.970	8.970	5.286		
	Natural Hydraulic Lime (NHL 3.5)							5.286		4.625
	Natural Hydraulic Lime (NHL 5)		4.625	7.400					5.286	
	Jurra Kalk		4.625							
	Sand	26.910	23.125	25.900	26.910	26.910	26.910	26.430	26.430	27.750
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.560			0.560	0.560	0.560			
	Total mass (kg) (Approx.)	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**
	(b) Indenting + dowels + lime grout mix									
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Lime grout mix									
	Cement (General)	0.047	0.383		0.047	0.047	0.047		0.438	0.383
	Lime Putty	0.744		0.307	0.744	0.744	0.744	0.438		
	Natural Hydraulic Lime (NHL 3.5)							0.438		0.383
	Natural Hydraulic Lime (NHL 5)		0.383	0.614					0.438	
	Jurra Kalk		0.383							
	Sand	2.232	1.915	2.149	2.232	2.232	2.232	2.190	2.190	2.298
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.047			0.047	0.047	0.047			
	Total mass (kg) (Approx.)	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**
	(c) Dowels + epoxy resin									
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total Mass (kg)(Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**
Repointing	**(a) Lime mortar**									
	Cement (General)	0.167	1.375		0.167	0.167	0.167		1.571	1.375
	Lime Putty	2.667		1.100	2.667	2.667	2.667	1.571		
	Natural Hydraulic Lime (NHL 3.5)							1.571		1.375
	Natural Hydraulic Lime (NHL 5)		1.375	2.200					1.571	
	Jurra Kalk		1.375							
	Sand	8.001	6.875	7.700	8.001	8.001	8.001	7.855	7.855	8.250
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.167			0.167	0.167	0.167			
	Total mass (kg) (Approx.)	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**11.000[7]**
Pinning and consolidation	**(a) Dowels + lime grout**									
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Lime grout mix									
	Cement (General)	0.027	0.256		0.027	0.027	0.027		0.307	0.279
	Lime Putty	0.434		0.307	0.434	0.434	0.434	0.307		
	Natural Hydraulic Lime (NHL 3.5)							0.307		0.279
	Natural Hydraulic Lime (NHL 5)		0.256	0.307					0.307	
	Jurra Kalk		0.256							
	Sand	0.868	1.280	1.228	0.868	0.868	0.868	1.228	1.535	0.837
	Crushed limestone/gravel/chippings (aggregates)	1.736	1.024	1.228	1.736	1.736	1.736	1.228	0.921	1.674
	Total mass (kg) (Approx.)	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**
	(b) Dowels + epoxy resin									
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**
Plastic repair	**(a) Lime Based Mortar with Aggregates**									
	Cement (General)	0.248	2.800		0.248	0.248	0.248		3.112	3.112
	Lime Putty	3.965		3.112	3.965	3.965	3.965	2.545		
	Natural Hydraulic Lime (NHL 3.5)							2.545		3.112
	Natural Hydraulic Lime (NHL 5)		2.800	3.112					3.112	
	Jurra Kalk		2.800							
	Sand	7.930	8.400	9.336	7.930	7.930	7.930	12.725	9.336	9.336
	Crushed limestone/gravel/chippings (aggregates)	15.860	11.200	12.448	15.860	15.860	15.860	10.180	12.448	12.448
	Total mass (kg) (Approx.)	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**
	(b) Lime base mortar (multi-layer plastic repair)									
	(i) Lime base mortar									
	Cement (General)	0.389	4.400		0.389	0.389	0.389		4.889	4.889
	Lime Putty	6.230		4.889	6.230	6.230	6.230	4.000		
	Natural Hydraulic Lime (NHL 3.5)							4.000		4.889
	Natural Hydraulic Lime (NHL 5)		4.400	4.889					4.889	
	Jurra Kalk		4.400							
	Sand	12.460	13.200	14.667	12.460	12.460	12.460	20.000	14.667	14.667
	Crushed limestone/gravel/chippings (aggregates)	24.920	17.600	19.556	24.920	24.920	24.920	16.000	19.556	19.556
	Total mass (kg) (Approx.)	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**
	(ii) Secondary fixing									
	[1] Stainless steel dowels	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200
	Total mass (kg) (Approx.)	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**
	[2] Epoxy resin	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134
	Total mass (kg) (Approx.)	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**
	[3] Non-ferrous tying wire	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680
	Total mass (kg) (Approx.)	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**

Source: Author, 2012.

Table D.2: Mass (kg) of lime and secondary fixing materials used for stone masonry wall repair-National Trust for Scotland

		Approximate of mass (kg) materials for repairing 1 m^2 stone masonry wall									
		National Trust for Scotland (NTS)									
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										
	Cement (General)						2.715	5.286	5.286		5.286
	Lime Putty	7.400	2.201	7.400	7.400	7.400				1.000	
	Natural Hydraulic Lime (NHL 3.5)	9.867	2.934	9.867	9.867	9.867	5.429	10.571	10.571		10.571
	Natural Hydraulic Lime (NHL 5)									2.000	
	Jurra Kalk										
	Sand	19.734	5.868	19.734	19.734	19.734	10.858	21.142	21.142	8.000	21.142
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**37.000 [1]**	**11.000 [2]**	**37.000 [1]**	**37.000 [1]**	**37.000 [1]**	**19.000 [3]**	**37.000 [1]**	**37.000 [1]**	**11.000[2]**	**37.000 [1]**
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Lime grout mix										
	Cement (General)						0.438	0.438	0.438		0.438
	Lime Putty	0.614	0.614	0.614	0.614	0.614				0.279	
	Natural Hydraulic Lime (NHL 3.5)	0.818	0.818	0.818	0.818	0.818	0.876	0.876	0.876		0.876
	Natural Hydraulic Lime (NHL 5)									0.558	
	Jurra Kalk										
	Sand	1.636	1.636	1.636	1.636	1.636	1.752	1.752	1.752	2.232	1.753
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total Mass (kg)(Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**
Repointing	**(a) Lime mortar**										
	Cement (General)						0.857	1.572	1.572		1.572
	Lime Putty	2.201	0.800	2.201	2.201	2.201				0.364	
	Natural Hydraulic Lime (NHL 3.5)	2.934	1.067	2.934	2.934	2.934	1.714	3.143	3.143		3.143
	Natural Hydraulic Lime (NHL 5)									0.728	
	Jurra Kalk										
	Sand	5.868	2.134	5.868	5.868	5.868	3.428	6.286	6.286	2.912	6.286
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**11.000[7]**	**4.000[8]**	**11.000[7]**	**11.000[7]**	**11.000[7]**	**6.000[9]**	**11.000[7]**	**11.000[7]**	**4.000[8]**	**11.000[7]**
Pinning and consolidation	**(a) Dowels + lime grout**										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Lime grout mix										
	Cement (General)						0.205	0.205	0.205		0.205
	Lime Putty	0.485	0.485	0.485	0.485	0.485				0.341	
	Natural Hydraulic Lime (NHL 3.5)	0.646	0.646	0.646	0.646	0.646	0.409	0.409	0.409		0.409
	Natural Hydraulic Lime (NHL 5)									0.682	
	Jurra Kalk										
	Sand	1.292	1.292	1.292	1.292	1.292	0.818	0.818	0.818	0.682	0.818
	Crushed limestone/gravel/chippings (aggregates)	0.646	0.646	0.646	0.646	0.646	1.636	1.636	1.636	1.364	1.636
	Total mass (kg) (Approx.)	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**	**3.067[5]**
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**	**4.600[4]**
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**	**3.067[6]**
Plastic repair	**(a) Lime Based Mortar with Aggregates**										
	Cement (General)						1.867	1.867	1.867		1.474
	Lime Putty	2.400	2.400	2.400	2.400	1.527				2.545	
	Natural Hydraulic Lime (NHL 3.5)	3.200	3.200	3.200	3.200	2.036	3.734	3.734	3.734		2.947
	Natural Hydraulic Lime (NHL 5)									5.090	
	Jurra Kalk										
	Sand	9.600	9.600	9.600	9.600	16.288	7.468	7.468	7.468	10.180	11.788
	Crushed limestone/gravel/chippings (aggregates)	12.800	12.800	12.800	12.800	8.144	14.936	14.936	14.936	10.180	11.788
	Total mass (kg) (Approx.)	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**	**28.000[10]**
	(b) Lime base mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General)						2.934	2.934	2.934		2.316
	Lime Putty	3.772	3.772	3.772	3.772	2.400				4.000	
	Natural Hydraulic Lime (NHL 3.5)	5.029	5.029	5.029	5.029	3.200	5.867	5.867	5.867		4.632
	Natural Hydraulic Lime (NHL 5)									8.000	
	Jurra Kalk										
	Sand	15.087	15.087	15.087	15.087	25.600	11.734	11.734	11.734	16.000	18.528
	Crushed limestone/gravel/chippings (aggregates)	20.116	20.116	20.116	20.116	12.800	23.468	23.468	23.468	16.000	18.528
	Total mass (kg) (Approx.)	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**	**44.000[11]**
	(ii) Secondary fixing										
	[1] Stainless steel dowels	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200
	Total mass (kg) (Approx.)	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**	**9.200[12]**
	[2] Epoxy resin	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134
	Total mass (kg) (Approx.)	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**	**6.134[13]**
	[3] Non-ferrous tying wire	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680
	Total mass (kg) (Approx.)	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**	**3.680[14]**

Source: Author, 2012.

Table D.3: Mass (kg) of lime and secondary fixing materials used for stone masonry wall repair-The City of Edinburgh Council

		Approximate of mass (kg) materials for repairing 1 m^2 stone masonry wall									
		The City of Edinburgh Council (CEC)									
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street, Edinburgh	CEC2-15, 16, 16A, 17-19 Hillside Crescent, Edinburgh	CEC3-21-31 Hillside Street, Edinburgh	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh
						Stone Type A	Stone Type B				
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										
	Cement (General)										
	Lime Putty	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	4.625
	Natural Hydraulic Lime (NHL 3.5)	2.200	2.200	2.200	2.200						
	Natural Hydraulic Lime (NHL 5)					2.200	2.200	2.200	2.200	2.200	9.250
	Jurra Kalk										
	Sand	6.600	6.600	6.600	6.600	6.600	6.600	6.600	6.600	6.600	23.125
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**11.000**[2]	**37.000** [1]
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]
	(ii) Lime grout mix										
	Cement (General)										
	Lime Putty	0.613	0.613	0.613	0.613	0.613	0.613	0.613	0.613	0.613	0.383
	Natural Hydraulic Lime (NHL 3.5)	0.613	0.613	0.613	0.613						
	Natural Hydraulic Lime (NHL 5)					0.613	0.613	0.613	0.613	0.613	0.766
	Jurra Kalk										
	Sand	1.839	1.839	1.839	1.839	1.839	1.839	1.839	1.839	1.839	1.915
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total Mass (kg)(Approx.)	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]
Repointing	**(a) Lime mortar**										
	Cement (General)										
	Lime Putty	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	1.375
	Natural Hydraulic Lime (NHL 3.5)	0.800	0.800	0.800	0.800						
	Natural Hydraulic Lime (NHL 5)					0.800	0.800	0.800	0.800	0.800	2.750
	Jurra Kalk										
	Sand	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400	6.875
	Brick Dust/Fire Clay/Fly Ash (Approx.)										
	Total mass (kg) (Approx.)	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**4.000**[8]	**11.000**[7]
Pinning and consolidation	**(a) Dowels + lime grout**										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]
	(ii) Lime grout mix										
	Cement (General)										
	Lime Putty	0.341	0.341	0.341	0.341	0.341	0.341	0.341	0.341	0.341	0.307
	Natural Hydraulic Lime (NHL 3.5)	0.341	0.341	0.341	0.341						
	Natural Hydraulic Lime (NHL 5)					0.341	0.341	0.341	0.341	0.341	0.614
	Jurra Kalk										
	Sand	1.023	1.023	1.023	1.023	1.023	1.023	1.023	1.023	1.023	0.921
	Crushed limestone/gravel/chippings (aggregates)	1.364	1.364	1.364	1.364	1.364	1.364	1.364	1.364	1.364	1.228
	Total mass (kg) (Approx.)	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]	**3.067**[5]
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600	4.600
	Total mass (kg) (Approx.)	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]	**4.600**[4]
	(ii) Epoxy resin	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067	3.067
	Total mass (kg) (Approx.)	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]	**3.067**[6]
Plastic repair	**(a) Lime Based Mortar with Aggregates**										
	Cement (General)										
	Lime Putty	2.545	2.545	2.545	2.545	2.545	2.545	2.545	3.112	3.112	2.334
	Natural Hydraulic Lime (NHL 3.5)	2.545	2.545	2.545	2.545						
	Natural Hydraulic Lime (NHL 5)					2.545	2.545	2.545	3.112	3.112	4.668
	Jurra Kalk										
	Sand	12.725	12.725	12.725	12.725	12.725	12.725	12.725	9.336	9.336	11.670
	Crushed limestone/gravel/chippings (aggregates)	10.180	10.180	10.180	10.180	10.180	10.180	10.180	12.448	12.448	9.336
	Total mass (kg) (Approx.)	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]	**28.000**[10]
	(b) Lime base mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General)										
	Lime Putty	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.889	4.889	3.667
	Natural Hydraulic Lime (NHL 3.5)	4.000	4.000	4.000	4.000				4.889		7.334
	Natural Hydraulic Lime (NHL 5)					4.000	4.000	4.000		4.889	
	Jurra Kalk										
	Sand	20.000	20.000	20.000	20.000	20.000	20.000	20.000	14.667	14.667	18.335
	Crushed limestone/gravel/chippings (aggregates)	16.000	16.000	16.000	16.000	16.000	16.000	16.000	19.556	19.556	14.668
	Total mass (kg) (Approx.)	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]	**44.000**[11]
	(ii) Secondary fixing										
	[1] Stainless steel dowels	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200	9.200
	Total mass (kg) (Approx.)	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]	**9.200**[12]
	[2] Epoxy resin	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134	6.134
	Total mass (kg) (Approx.)	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]	**6.134**[13]
	[3] Non-ferrous tying wire	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680	3.680
	Total mass (kg) (Approx.)	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]	**3.680**[14]

Source: Author, 2012.

Notes:

[1] Approximate mass in kilogram of materials in 1 m^2 masonry stone indenting and grouting natural stone replacement with 10 mm joints thickness (http://www.lime-mortars.co.uk/calculators/ mortar) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011a).

[2] Approximate mass in kilogram of lime mortar/grout mix materials in 1 m^2 masonry stone indenting and grouting natural stone replacement with 3mm joints finishes thickness (http://www.lime-mortars.co.uk/calculators/ mortar) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011a).

[3] Approximate mass in kilogram of lime mortar/grout mix materials in 1 m^2 masonry stone indenting and grouting natural stone replacement with 5 mm joints finishes thickness (http://www.lime-mortars.co.uk/calculators/ mortar) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011a).

[4] Stainless steel dowels (assumed to require high grade threaded stainless steel dowels 100mm long and 6mm diameter, inserted at approximate of minimum 100 mm spacing or 100 pieces in 1 m^2 wall @ average 46 g) (http://www.valbruna.co.uk/products/reval/dowel-bar-details) (see Valbruna UK Ltd., 2011a)

[5] Lime grout mix materials (2/3 full of drilled hole or approx. 66mm) http://www.valbruna.co.uk/products/reval/dowel-bar-details) (see Valbruna UK Ltd., 2011a) OR @ 100 holes in 1 m^2 wall @ 100 * 2/3* average 46 g (1g ≈ 1ml) (http://www.convertunits.com/from/grams/to/milliliters)

[6] Epoxy resin (2/3 full of drilled hole or approx. 66 mm) (http://www.valbruna.co.uk/products/reval/dowel-bar-details) (see Valbruna UK Ltd., 2011a) OR @ 100 holes in 1 m^2 wall @ 100 * 2/3* average 46 g (1g ≈ 1ml) (http://www.convertunits.com/from/grams/to/milliliters

[7] Approximate mass in kilogram of lime mortar materials in 1 m^2 masonry wall re-pointing with 10 mm thick and 25 mm depth of joints (http://www.lime-mortars.co.uk/calculators/pointing) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011c)

[8] Approximate mass in kilogram of lime mortar materials in 1 m^2 masonry wall re-pointing with 3 mm thick and 25 mm depth of joints (http://www.lime-mortars.co.uk/calculators/pointing) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011c)

[9] Approximate mass in kilogram of lime mortar materials in 1 m^2 masonry wall re-pointing with 5 mm thick and 25 mm depth of joints (http://www.lime-mortars.co.uk/calculators/pointing) (see Lime Mortar Supplier &Stone Restoration Specialist, 2011c).

[10] Approximate mass in kilogram of lime based mortar with aggregates materials in 1 m^2 masonry wall plastic repair with minimum 15 mm depth of undercut/cutback, approx. 9 mm thick for each layer (base coats) and 6 mm finishes http://www.lime-mortars.co.uk/calculators/plaster (approx. base coats 17 kg and finish 11 kg) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011b).

[11] Approximate mass in kilogram of lime based mortar with aggregates materials in 1 m^2 masonry wall plastic repair with minimum 40 mm depth of undercut/cutback, approx. 9 mm thick for each layer (base coats) and 4 mm finishes http://www.lime-mortars.co.uk/calculators/plaster (approx. base coats 36 kg and finish 8 kg) (see Lime Mortar Supplier & Stone Restoration Specialist, 2011b).

[12] Stainless steel dowels (assumed to require high grade threaded stainless steel dowels 100 mm long and 6 mm diameter, inserted at approximate of minimum 50 mm centres spacing or 200 pieces in 1 m^2 wall @ average 46g) (http://www.valbruna.co.uk/products/reval/dowel-bar-details) (see Valbruna UK Ltd., 2011a)

[13] Epoxy resin (2/3 full of drilled hole or approx. 66 mm) (http://www.valbruna.co.uk/products/reval/dowel-bar-details) (see Valbruna UK Ltd., 2011a) OR @ 200 holes in 1 m^2 wall @ 100 * 2/3* average 46 g (1g ≈ 1ml) (http://www.convertunits.com/from/grams/to/milliliters

[14] Approx. mass (kg) of non-ferrous tying wire 1.4307 (304L) grade with 1.2 mm diameter http://www.valbruna.co.uk/products/reval/tying-wire-details (to wrapped/tie 200 dowels, at 50 mm centres spacing every two dowels in 1 m^2 wall http://www.valbruna.co.uk/products/reval/tying-wiredetails (assumed to require 1.2 mm diameter to wrapped/tie 50 mm centres spacing or 200 pieces in 1 m^2 wall [1.2 mm/12 mm *0.920 kg/m * 40m] (see Valbruna UK Ltd., 2011b).

Appendix E: Resourcing Location of Stone Masonry Wall Repair Materials

Table E.1: Resourcing location of stone masonry wall repair materials-Historic Scotland

		Resourcing Location of Stone Masonry Wall Repair Materials								
		Historic Scotland (HS)								
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace
Natural stone replacement	**(a) Indenting + lime mortar grout mix**									
	(i) Stone	[1]	[2]	[1]	[1]	[1]	[1]	[4]	[5]	[5]
	(ii) Lime mortar grout mix									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]	[18]	[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Brick Dust/Fire Clay/Fly Ash [21]	[21]			[21]	[21]	[21]			
	(b) Indenting + dowels + lime grout mix									
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]		[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Brick Dust/Fire Clay/Fly Ash [21]	[21]			[21]	[21]	[21]			
	(c) Dowels + epoxy resin									
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Repointing	**(a) Lime mortar**									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]		[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Brick Dust/Fire Clay/Fly Ash [21]	[21]			[21]	[21]	[21]			
Pinning and consolidation	**(a) Dowels + lime grout**									
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]		[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Dowels + epoxy resin									
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Plastic repair	**(a) Lime Based Mortar with Aggregates**									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]		[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Lime base mortar (multi-layer plastic repair)									
	(i) Lime base mortar									
	Cement (General) [18]	[18]	[18]		[18]	[18]	[18]		[18]	[18]
	Lime Putty [19]	[19]		[19]	[19]	[19]	[19]	[19]		
	Natural Hydraulic Lime (NHL 3.5) [19]							[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]		[19]	[19]					[19]	
	Jurra Kalk [20]		[20]							
	Sand	[12]	[12]	[13]	[13]	[13]	[13]	[13]	[14]	[15]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(ii) Secondary fixing									
	[1] Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	[2] Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
	[3] Non-ferrous tying wire [25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]

Source: Author, 2012.

Table E.2: Resourcing location of stone masonry wall repair materials-National Trust for Scotland

		Resourcing Location of Stone Masonry Wall Repair Materials									
		National Trust for Scotland (NTS)									
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert	NTS10-Hamilton House, East Lothian
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										
	(i) Stone	[6]	[6]	[6]	[6]	[6]	[6]	[6]	[6]	[6]	[6]
	(ii) Lime mortar grout mix										
	Cement (General) [18]						[18]	[18]	[18]		[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Brick Dust/Fire Clay/Fly Ash [21]										
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix										
	Cement (General) [18]						[18]	[18]	[18]	[18]	[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Brick Dust/Fire Clay/Fly Ash [21]										
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Repointing	**(a) Lime mortar**										
	Cement (General) [18]						[18]	[18]	[18]	[18]	[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Brick Dust/Fire Clay/Fly Ash [21]										
Pinning and consolidation	**(a) Dowels + lime grout**										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix										
	Cement (General) [18]						[18]	[18]	[18]		[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Plastic repair	**(a) Lime Based Mortar with Aggregates**										
	Cement (General) [18]						[18]	[18]	[18]		[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Lime base mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General) [18]						[18]	[18]	[18]		[18]
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]				[19]	
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]		[19]
	Natural Hydraulic Lime (NHL 5) [19]									[19]	
	Jurra Kalk [20]										
	Sand	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]	[16]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(ii) Secondary fixing										
	[1] Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	[2] Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
	[3] Non-ferrous tying wire [25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]

Source: Author, 2012.

Table E.3: Resourcing location of stone masonry wall repair materials-The City of Edinburgh Council

		Resourcing Location of Stone Masonry Wall Repair Materials									
		The City of Edinburgh Council (CEC)									
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh
Natural stone replacement	**(a) Indenting + lime mortar grout mix**					Stone Type A	Stone Type B				
	(i) Stone	[7]	[7]	[7]	[8]	[9]	[8]	[9]	[10]	[9]	[11]
	(ii) Lime mortar grout mix										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Brick Dust/Fire Clay/Fly Ash [21]										
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Brick Dust/Fire Clay/Fly Ash [21]										
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Repointing	**(a) Lime mortar**										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Brick Dust/Fire Clay/Fly Ash [21]										
Pinning and consolidation	**(a) Dowels + lime grout**										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Lime grout mix										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	(ii) Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
Plastic repair	**(a) Lime Based Mortar with Aggregates**										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(b) Lime base mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General) [18]										
	Lime Putty [19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]	[19]
	Natural Hydraulic Lime (NHL 3.5) [19]	[19]	[19]	[19]	[19]						
	Natural Hydraulic Lime (NHL 5) [19]					[19]	[19]	[19]	[19]	[19]	[19]
	Jurra Kalk [20]										
	Sand	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[12]	[17]
	Crushed limestone/gravel/chippings (aggregates) [24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]	[24]
	(ii) Secondary fixing										
	[1] Stainless steel dowels [22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]	[22]
	[2] Epoxy resin [23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]	[23]
	[3] Non-ferrous tying wire [25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]

Source: Author, 2012

Notes:

[1] Cleatleam, Darlington, Co. Durham, England

[2] Staindrop, Darlington, Co. Durham, England

[3] Darlington, Co. Durham, England

[4] Birnie, Elgin, Moray, Scotland

[5] Spittal Quarry, Caithness, Scotland

[6] Barnard Castle, Co. Durham, England

[7] Doddintgton Quarry (near Wooler), Northumberland, Barnard Castle, Durham, England

[8] Dunhouse Quarry Works, Staindrop Darlington, Co. Durham, England

[9] Stainton Quarry, Barnard Castle, Durham, England

[10] Bolehill Quarry, Barnard Castle, Durham, England

[11] Dale View/Palmer's Quarry, Grangemill, Matlock, Derbyshire

[12] Combusmore sand (from, Callander , Perthshire, Scotland)

[13] Newbigging sand (from Canwath, South Lanarkshire, Scotland)

[14] Eckford sand (from Kelso, Scotland)

[15] Perth Wharf Quarry sand (from Perth, Scotland)

[16] Gowrie sand from Luncarty, Perth Scotland)

[17] River Tay sand (from mountcastle, Letham, Scotland)

[18] All cement (general) from Dunbar (near Broxburn), East Lothian, Scotland

[19] All lime (lime putty, NHL 3.5 and NHL 5) from St Astier, Southwest France

[20] All Jurra Kalk (from Canton Jura, Northwest Switzerland)

[21] All brick dust/fire clay/fly ash from Armadale, West Lothian (near Northrigg, Bathgate), Scotland

[22] All stainless steel dowels from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

[23] All epoxy resin from Cowie, Stirling (Hexion Chemicals-biggest and nearest manufacturer in Scotland) (http://ww2.momentive.com/locations_home.aspx?id=293

[24] All crushed limestone/limestone gravel from Hardendale, Shap, Cumbria, England

[25] All Non-ferrous wire from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

Appendix F: Total Transportation Distance for Stone Masonry Wall Repair Materials

Table F.1: Total transportation distance for stone masonry wall repair materials-Historic Scotland

		Transportation Distance of Repair Materials to Building Site* (total in km)									
		Historic Scotland									
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Total (km)**
	(i) Stone	233.31	152.37	210.78	233.31	233.31	233.31	296.06	485.92	405.47	**2483.84**
	(ii) Lime mortar grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**162.41**
	Total (km)	**1916.71**	**3341.89**	**3200.30**	**1942.55**	**1942.55**	**1942.55**	**3614.79**	**2124.20**	**2265.80**	**22291.34**
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	(ii) Lime grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**162.41**
	Total (km)	**2136.40**	**3526.52**	**3403.52**	**2150.24**	**2150.24**	**2150.24**	**3700.73**	**1949.28**	**2306.33**	**23473.50**
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	(ii) Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**437.30**
	Total (km)	475.40	457.00	455.30	450.60	450.60	450.60	445.20	445.00	473.60	**4103.30**
Repointing	**(a) Lime mortar**										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**162.41**
	Total (km)	**1683.40**	**3189.52**	**2989.52**	**1709.24**	**1709.24**	**1709.24**	**3318.73**	**1638.28**	**1860.33**	**19807.50**
Pinning and consolidation	**(a) Dowels + lime grout mix**										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	(ii) Lime grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**1803.57**
	Total (km)	**2329.25**	**3676.52**	**3607.86**	**2342.36**	**2342.36**	**2342.36**	**3874.50**	**2082.34**	**2517.11**	**25114.66**
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	(ii) Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**437.30**
	Total (km)	**475.40**	**457.00**	**455.30**	**450.60**	**450.60**	**450.60**	**445.20**	**445.00**	**473.60**	**4103.30**
Plastic repair	**(a) Lime based mortar with aggregates**										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**1803.57**
	Total (km)	**1876.25**	**3339.52**	**3193.86**	**1901.36**	**1901.36**	**1901.36**	**3492.50**	**1771.34**	**2071.11**	**21448.66**
	(b) Lime based mortar (multi-layer plastic repair)										
	(i) Lime based mortar										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**685.92**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**9095.68**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**3359.60**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**4584.05**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**507.14**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**1803.57**
	(ii) Secondary fixing										
	[1] Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	[2] Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**437.30**
	[3] Non-ferrous tying wire [8]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**3666.00**
	Total (km)	**2804.65**	**4133.52**	**4063.16**	**2792.96**	**2792.96**	**2792.96**	**4319.70**	**2527.34**	**2990.71**	**29217.96**

Source: Author, 2012.

Table F.2: Total transportation distance for stone masonry wall repair materials- National Trust for Scotland

		Transportation Distance of Repair Materials to Building Site * (total in km)										
		National Trust for Scotland (NTS)										
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Total (km)**
	(i) Stone	199.52	199.52	278.36	273.53	275.14	181.82	181.82	181.82	155.91	214.00	**2141.44**
	(ii) Lime mortar grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3662.41**	**3662.41**	**3764.75**	**3826.69**	**3786.14**	**2212.38**	**2202.73**	**2207.55**	**3434.74**	**1978.26**	**30738.06**
	(b) Indenting + dowels + lime grout mix											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	(ii) Lime grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3848.89**	**3848.89**	**3935.39**	**4015.16**	**3928.00**	**2380.56**	**2370.91**	**2375.73**	**3610.83**	**2146.26**	**32460.62**
	(c) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	(ii) Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**975.10**
	Total (km)	**455.90**	**455.90**	**469.30**	**522.20**	**452.20**	**527.00**	**527.00**	**527.00**	**448.00**	**454.60**	**4839.10**
Repointing	**(a) Lime mortar**											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3462.89**	**3462.89**	**3486.39**	**3553.16**	**3511**	**2030.56**	**2020.91**	**2025.73**	**3278.83**	**1764.26**	**28596.62**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	(ii) Lime grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**1910.25**
	Total (km)	**4051.89**	**4051.89**	**4167.09**	**4280.65**	**4169.35**	**2518.45**	**2505.58**	**2512.01**	**3761.75**	**2352.21**	**34370.87**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	(ii) Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**975.10**
	Total (km)	**455.90**	**455.90**	**469.30**	**522.20**	**452.20**	**527.00**	**527.00**	**527.00**	**448.00**	**454.60**	**4839.10**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**1910.25**
	Total (km)	**3665.89**	**3665.89**	**3718.09**	**3818.65**	**3752.35**	**2168.45**	**2155.58**	**2162.01**	**3429.75**	**1970.21**	**30506.87**
	(b) Lime base mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**594.68**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**10131.88**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**15026.45**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**1274.83**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**1910.25**
	(ii) Secondary fixing											
	[1] Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	[2] Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**975.10**
	[3] Non-ferrous tying wire [8]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**3864.00**
	Total (km)	**4507.79**	**4507.79**	**4636.39**	**4802.85**	**4621.55**	**3045.45**	**3032.58**	**3039.01**	**4209.75**	**2806.81**	**39209.97**

Source: Author, 2012

Table F.3: Total transportation distance for stone masonry wall repair materials-The City of Edinburgh Council

		Transportation Distance of Repair Materials to Building Site* (total in km)										
		The City of Edinburgh Council (CEC)										
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	
						Stone Type A	Stone Type B					**Total (km)**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											
	(i) Stone	209.17	209.17	209.17	209.17	214.00	212.39	214.00	428.78	214.00	416.73	**2536.58**
	(ii) Lime mortar grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**6728.83**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**10075.58**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3658.05**	**3658.05**	**3658.05**	**3646.48**	**3656.30**	**3654.69**	**3656.30**	**3873.98**	**3656.30**	**3844.23**	**36962.43**
	(b) Indenting + dowels + lime grout mix											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	(ii) Lime grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**6728.83**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**10075.58**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3859.88**	**3859.88**	**3859.88**	**3852.31**	**3832.30**	**3832.30**	**3833.30**	**3832.20**	**3832.30**	**3816.50**	**38410.85**
	(c) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	(ii) Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**581.20**
	Total (km)	**471.70**	**471.70**	**471.70**	**470.60**	**446.50**	**446.50**	**448.10**	**447.20**	**446.50**	**445.70**	**4566.20**
Repointing	**(a) Lime mortar**											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**6728.83**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**10075.58**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Total (km)	**3448.88**	**3448.880**	**3448.88**	**3437.31**	**3442.30**	**3442.30**	**3442.30**	**3445.20**	**3442.30**	**3427.50**	**34425.85**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	(ii) Lime grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**6728.83**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**10075.58**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**1263.40**
	Total (km)	**3859.88**	**3859.88**	**3859.88**	**4059.87**	**4030.21**	**4030.21**	**4031.21**	**4031.72**	**4030.21**	**3881.18**	**39674.25**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	(ii) Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**581.20**
	Total (km)	**471.70**	**471.70**	**471.70**	**470.60**	**446.50**	**446.50**	**448.10**	**447.20**	**446.50**	**445.70**	**4566.20**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**6728.83**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**10075.58**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**1263.40**
	Total (km)	**3448.88**	**3448.88**	**3448.88**	**3644.87**	**3640.21**	**3640.21**	**3640.21**	**3644.72**	**3640.21**	**3492.18**	**35689.25**
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**16804.41**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80				1681.41			**8410.24**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19		1678.19	1681.41	**8394.17**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**817.03**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**1263.40**
	(ii) Secondary fixing											
	[1] Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	[2] Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**581.20**
	[3] Non-ferrous tying wire [8]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**3985.00**
	Total (km)	**4331.580**	**4331.580**	**4331.580**	**4530.470**	**4476.710**	**4476.710**	**4479.310**	**4478.920**	**4476.710**	**4326.880**	**44240.450**

Source: Author, 2012

Notes:*Distance to building site (nearest in km) with approximate kilometre based on shortest/nearest driving road distance in km using land transportation (including Channel Tunnel between Europe and UK) (Google Map) @ 1 mile ≈1.609 km

[1] All cement (general) from Dunbar (near Broxburn), East Lothian, Scotland

[2] All lime (lime putty, NHL 3.5 and NHL 5) from St Astier, Southwest France

[3] All Jurra Kalk (from Canton Jura, Northwest Switzerland)

[4] All brick dust/fire clay/fly ash from Armadale, West Lothian (near Northrigg, Bathgate), Scotland

[5] All stainless steel dowels from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

[6] All epoxy resin from Cowie, Stirling (Hexion Chemicals-biggest and nearest manufacturer in Scotland) (http://ww2.momentive.com/locations_home.aspx?id=293

[7] All crushed limestone/limestone gravel from Hardendale, Shap, Cumbria, England

[8] All Non-ferrous wire from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

Appendix G: Minimum, Maximum and Average of Transportation Distance of for Stone Masonry Wall Repair Materials

Table G.1: Minimum, Maximum and Average of Transportation Distance of for Stone Masonry Wall Repair Materials-Historic Scotland

		Transportation Distance of Repair Materials to Building Site* (minimum, maximum and average in km)									
		Historic Scotland									
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Average (km)**
	(i) Stone	233.31	152.37	210.78	233.31	233.31	233.31	296.06	485.92	405.47	**275.98**
	(ii) Lime mortar grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**40.60**
	Minimum (km)	**9.81**	**69.99**	**54.70**	**37.97**	**37.97**	**37.97**	**26.71**	**13.35**	**65.65**	**39.35**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**489.90**	**711.52**	**787.07**	**496.24**	**496.24**	**496.24**	**881.25**	**614.24**	**674.17**	**627.43**
	(b) Indenting + dowels + lime grout mix										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	(ii) Lime grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**40.60**
	Minimum (km)	**9.81**	**69.99**	**54.70**	**37.97**	**37.97**	**37.97**	**26.71**	**13.35**	**65.65**	**39.35**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**521.29**	**737.90**	**820.94**	**525.91**	**525.91**	**525.91**	**895.58**	**585.08**	**680.93**	**646.60**
	(c) Dowels + epoxy resin										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	(ii) Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**48.59**
	Minimum (km)	**22.40**	**120.00**	**41.30**	**9.60**	**9.60**	**9.60**	**63.20**	**134.00**	**27.60**	**48.59**
	Maximum (km)	**453.00**	**337.00**	**414.00**	**441.00**	**441.00**	**441.00**	**382.00**	**311.00**	**446.00**	**407.33**
	Average (km)	**237.70**	**228.50**	**165.53**	**225.30**	**225.30**	**225.30**	**222.60**	**222.50**	**236.80**	**221.06**
Repointing	**(a) Lime based mortar**										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Brick Dust/Fire Clay/Fly Ash [4]	48.50			37.97	37.97	37.97				**40.60**
	Minimum (km)	**9.81**	**69.99**	**54.7**	**37.97**	**37.97**	**37.97**	**26.71**	**13.35**	**65.65**	**39.35**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**532.67**	**804.72**	**902.326**	**540.06**	**540.06**	**540.06**	**998.29**	**639.90**	**727.91**	**691.78**
Pinning and consolidation	**(a) Dowels + lime grout mix**										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	(ii) Lime grout mix										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**200.40**
	Minimum (km)	**9.81**	**69.99**	**54.70**	**66.29**	**66.29**	**66.29**	**26.71**	**13.35**	**65.65**	**48.79**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**548.84**	**664.41**	**732.85**	**557.40**	**557.40**	**557.40**	**792.46**	**520.51**	**613.76**	**616.11**
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	(ii) Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**48.59**
	Minimum (km)	**22.40**	**120.00**	**41.30**	**9.60**	**9.60**	**9.60**	**63.20**	**134.00**	**27.60**	**48.59**
	Maximum (km)	**453.00**	**337.00**	**414.00**	**441.00**	**441.00**	**441.00**	**382.00**	**311.00**	**446.00**	**407.33**
	Average (km)	**237.70**	**228.50**	**227.65**	**225.30**	**225.30**	**225.30**	**222.60**	**222.50**	**236.80**	**227.96**
Plastic repair	**(a) Lime Based Mortar with Aggregates**										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**200.40**
	Minimum (km)	**9.81**	**69.99**	**54.70**	**66.29**	**66.29**	**66.29**	**26.71**	**13.35**	**65.65**	**48.79**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**564.81**	**711.18**	**786.00**	**576.80**	**576.80**	**576.80**	**860.87**	**555.43**	**641.73**	**650.05**
	(b) LimeBased Mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General) [1]	122.28	69.99		111.83	111.83	111.83		77.07	81.09	**97.99**
	Lime Putty [2]	1502.81		1467.41	1493.15	1493.15	1493.15	1646.01			**1515.95**
	Natural Hydraulic Lime (NHL 3.5) [2]							1646.01		1713.59	**1679.80**
	Natural Hydraulic Lime (NHL 5) [2]		1568.78	1467.41					1547.86		**1528.02**
	Jurra Kalk [3]		1412.70								**1412.70**
	Sand	9.81	138.05	54.70	66.29	66.29	66.29	26.71	13.35	65.65	**56.35**
	Crushed limestone/gravel/chippings (aggregates) [7]	241.35	150.00	204.34	230.09	230.09	230.09	173.77	133.06	210.78	**200.40**
	(ii) Secondary fixing										
	[1] Stainless steel dowels [5]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	[2] Epoxy resin [6]	22.40	120.00	41.30	9.60	9.60	9.60	63.20	134.00	27.60	**48.59**
	[3] Non-ferrous tying wire [8]	453.00	337.00	414.00	441.00	441.00	441.00	382.00	311.00	446.00	**407.33**
	Minimum (km)	**9.81**	**69.99**	**41.30**	**9.60**	**9.60**	**9.60**	**26.71**	**13.35**	**27.60**	**24.17**
	Maximum (km)	**1502.81**	**1568.78**	**1467.41**	**1493.15**	**1493.15**	**1493.15**	**1646.01**	**1547.86**	**1713.59**	**1547.32**
	Average (km)	**479.70**	**577.23**	**619.10**	**477.30**	**477.30**	**477.30**	**665.82**	**454.28**	**525.77**	**528.20**

Source: Author, 2012.

Table G.2: Minimum, Maximum and Average of Transportation Distance of for Stone Masonry Wall Repair Materials-National Trust for Scotland

		Transportation Distance of Repair Materials to Building Site * (minimum, maximum and average in km)										
		National Trust for Scotland (NTS)										
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Avergage (km)**
	(i) Stone	199.52	199.52	278.36	273.53	275.14	181.82	181.82	181.82	155.91	214.00	**214.14**
	(ii) Lime mortar grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	**87.21**	**87.21**	**68.87**	**35.88**	**70.96**	**181.82**	**181.82**	**181.82**	**141.27**	**34.75**	**107.16**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.52**
	Average (km)	**906.24**	**906.24**	**923.73**	**936.87**	**929.52**	**667.47**	**665.32**	**666.40**	**857.47**	**608.23**	**806.75**
	(b) Indenting + dowels + lime grout mix											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	(ii) Lime grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	**87.21**	**87.21**	**68.87**	**35.88**	**70.96**	**188.25**	**185.04**	**186.64**	**141.27**	**34.75**	**108.61**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.52**
	Average (km)	**937.32**	**937.32**	**952.17**	**968.28**	**953.16**	**696.57**	**693.89**	**695.23**	**886.81**	**636.23**	**835.70**
	(c) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	(ii) Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**97.51**
	Minimum (km)	**69.90**	**69.90**	**20.30**	**60.20**	**35.20**	**177.00**	**177.00**	**177.00**	**116.00**	**72.60**	**97.51**
	Maximum (km)	**386.00**	**386.00**	**449.00**	**462.00**	**417.00**	**350.00**	**350.00**	**350.00**	**332.00**	**382.00**	**386.40**
	Average (km)	**227.95**	**227.95**	**234.65**	**261.10**	**226.10**	**263.50**	**263.50**	**263.50**	**224.00**	**227.30**	**241.96**
Repointing	**(a) Lime mortar**											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	**87.21**	**87.21**	**68.87**	**35.88**	**70.96**	**188.25**	**185.04**	**186.64**	**141.27**	**34.75**	**108.608**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.523**
	Average (km)	**1047.588**	**1047.588**	**1052.804**	**1069.536**	**1060.396**	**765.88**	**762.67**	**764.27**	**997.776**	**687.07**	**925.5586**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	(ii) Lime grout mix											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**191.03**
	Minimum (km)	**87.21**	**87.21**	**68.87**	**35.88**	**70.96**	**137.89**	**134.67**	**136.28**	**141.27**	**34.75**	**93.50**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.52**
	Average (km)	**832.42**	**832.42**	**849.25**	**867.88**	**851.48**	**609.56**	**606.81**	**608.18**	**781.69**	**574.76**	**741.44**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	(ii) Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**97.51**
	Minimum (km)	**69.90**	**69.90**	**20.30**	**60.20**	**35.20**	**177.00**	**177.00**	**177.00**	**116.00**	**72.60**	**97.51**
	Maximum (km)	**386.00**	**386.00**	**449.00**	**462.00**	**417.00**	**350.00**	**350.00**	**350.00**	**332.00**	**382.00**	**386.40**
	Average (km)	**227.95**	**227.95**	**234.65**	**261.10**	**226.10**	**263.50**	**263.50**	**263.50**	**224.00**	**227.30**	**241.96**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**191.03**
	Minimum (km)	**87.21**	**87.21**	**68.87**	**35.88**	**70.96**	**137.89**	**134.67**	**136.28**	**141.27**	**34.75**	**93.50**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.52**
	Average (km)	**906.82**	**906.82**	**915.95**	**935.53**	**923.89**	**652.83**	**649.61**	**651.22**	**856.63**	**606.89**	**800.62**
	(b) Lime Based Mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General) [1]						188.25	185.04	186.64		34.75	**148.67**
	Lime Putty [2]	1687.84	1687.84	1708.76	1758.64	1720.02				1568.78		**1688.65**
	Natural Hydraulic Lime (NHL 3.5) [2]	1687.84	1687.84	1708.76	1758.64	1720.02	1610.61	1607.39	1609.00		1636.35	**1669.61**
	Natural Hydraulic Lime (NHL 5) [2]									1568.78		**1568.78**
	Jurra Kalk [3]											
	Sand	87.21	87.21	68.87	35.88	70.96	231.70	228.48	230.09	141.27	93.16	**127.48**
	Crushed limestone/gravel/chippings (aggregates) [7]	203.00	203.00	231.70	265.49	241.35	137.89	134.67	136.28	150.92	205.95	**191.03**
	(ii) Secondary fixing											
	[1] Stainless steel dowels [5]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	[2] Epoxy resin [6]	69.90	69.90	20.30	60.20	35.20	177.00	177.00	177.00	116.00	72.60	**97.51**
	[3] Non-ferrous tying wire [8]	386.00	386.00	449.00	462.00	417.00	350.00	350.00	350.00	332.00	382.00	**386.40**
	Minimum (km)	**69.90**	**69.90**	**20.30**	**35.88**	**35.20**	**137.89**	**134.67**	**136.28**	**116.00**	**34.75**	**79.08**
	Maximum (km)	**1687.84**	**1687.84**	**1708.76**	**1758.64**	**1720.02**	**1610.61**	**1607.39**	**1609.00**	**1568.78**	**1636.35**	**1659.52**
	Average (km)	**696.170**	**696.170**	**707.272**	**733.041**	**708.530**	**532.661**	**530.516**	**531.588**	**654.948**	**497.546**	**628.844**

Source: Author, 2012.

Table G.3: Minimum, Maximum and Average of Transportation Distance of for Stone Masonry Wall Repair Materials-The City of Edinburgh Council

		Transportation Distance of Repair Materials to Building Site* (minimum, maximum and average in km)										
		The City of Edinburgh Council (CEC)										
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	
						Stone Type A	Stone Type B					**Average (km)**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											
	(i) Stone	209.17	209.17	209.17	209.17	214.00	212.39	214.00	428.78	214.00	416.73	**253.66**
	(ii) Lime mortar grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**1682.21**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1679.26**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	**82.86**	**82.86**	**82.86**	**77.71**	**85.92**	**85.92**	**85.92**	**82.38**	**85.92**	**64.68**	**81.70**
	Maximum (km)	**1683.01**	**1683.01**	**1683.01**	**1679.80**	**1678.19**	**1678.19**	**1678.19**	**1681.41**	**1678.19**	**1681.41**	**1680.44**
	Average (km)	**903.99**	**903.99**	**903.99**	**900.67**	**903.40**	**903.13**	**903.40**	**939.63**	**903.40**	**931.72**	**909.73**
	(b) Indenting + dowels + lime grout mix											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	(ii) Lime grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**1682.21**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1679.26**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Maximum (km)	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Average (km)	**937.63**	**937.63**	**937.63**	**934.97**	**932.74**	**932.74**	**932.90**	**932.67**	**932.74**	**927.10**	**933.87**
	(c) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	(ii) Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**58.12**
	Minimum (km)	**60.70**	**60.70**	**60.70**	**55.60**	**56.50**	**56.50**	**57.10**	**60.20**	**56.50**	**56.70**	**58.12**
	Maximum (km)	**411.00**	**411.00**	**411.00**	**415.00**	**390.00**	**390.00**	**391.00**	**387.00**	**390.00**	**389.00**	**398.50**
	Average (km)	**235.85**	**235.85**	**235.85**	**235.30**	**223.25**	**223.25**	**224.05**	**223.60**	**223.25**	**222.85**	**228.31**
Repointing	**(a) Lime mortar**											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**1682.21**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1679.26**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Brick Dust/Fire Clay/Fly Ash [4]											
	Minimum (km)	82.86	82.860	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Maximum (km)	1683.01	1683.010	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Average (km)	**1042.95**	**1042.950**	**1042.95**	**1038.96**	**1041.28**	**1041.28**	**1041.28**	**1041.80**	**1041.28**	**1034.72**	**1040.95**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	(ii) Lime grout mix											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**1682.21**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1679.26**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**180.49**
	Minimum (km)	**82.86**	**82.86**	**82.86**	**77.71**	**85.92**	**85.92**	**85.92**	**82.38**	**85.92**	**64.68**	**81.70**
	Maximum (km)	**1683.01**	**1683.01**	**1683.01**	**1679.80**	**1678.19**	**1678.19**	**1678.19**	**1681.41**	**1678.19**	**1681.41**	**1680.44**
	Average (km)	**937.63**	**937.63**	**937.63**	**831.05**	**827.76**	**827.76**	**827.90**	**827.93**	**827.76**	**803.90**	**858.69**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	(ii) Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**58.12**
	Minimum (km)	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**58.12**
	Maxiumum (km)											
	Average (km)	**411.00**	**411.00**	**411.00**	**415.00**	**390.00**	**390.00**	**391.00**	**387.00**	**390.00**	**389.00**	**398.50**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80							**1682.21**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1679.26**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**180.49**
	Minimum (km)	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Maximum (km)	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Average (km)	**1042.95**	**1042.95**	**1042.95**	**900.40**	**900.72**	**900.72**	**900.72**	**901.42**	**900.72**	**873.05**	**940.66**
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General) [1]											
	Lime Putty [2]	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Natural Hydraulic Lime (NHL 3.5) [2]	1683.01	1683.01	1683.01	1679.80				1681.41			**1682.05**
	Natural Hydraulic Lime (NHL 5) [2]					1678.19	1678.19	1678.19		1678.19	1681.41	**1678.83**
	Jurra Kalk [3]											
	Sand	82.86	82.86	82.86	77.71	85.92	85.92	85.92	82.38	85.92	64.68	**81.70**
	Crushed limestone/gravel/chippings (aggregates) [7]	210. 00	210. 00	210. 00	207.56	197.91	197.91	197.91	199.52	197.91	64.68	**180.49**
	(ii) Secondary fixing											
	[1] Stainless steel dowels [5]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	[2] Epoxy resin [6]	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**58.12**
	[3] Non-ferrous tying wire [8]	411.00	411.00	411.00	415.00	390.00	390.00	391.00	387.00	390.00	389.00	**398.50**
	Minimum (km)	60.70	60.70	60.70	55.60	56.50	56.50	57.10	60.20	56.50	56.70	**58.12**
	Maximum (km)	1683.01	1683.01	1683.01	1679.80	1678.19	1678.19	1678.19	1681.41	1678.19	1681.41	**1680.44**
	Average (km)	**759.411**	**759.411**	**759.411**	**696.208**	**690.156**	**690.156**	**690.511**	**691.170**	**690.156**	**673.888**	**710.048**

Source: Author, 2012.

Notes:*Distance to building site (nearest in km) with approximate kilometre based on shortest/nearest driving road distance in km using land transportation (including Channel Tunnel between Europe and UK) (Google Map) @ 1 mile ≈1.609 km

[1] All cement (general) from Dunbar (near Broxburn), East Lothian, Scotland

[2] All lime (lime putty, NHL 3.5 and NHL 5) from St Astier, Southwest France

[3] All Jurra Kalk (from Canton Jura, Northwest Switzerland)

[4] All brick dust/fire clay/fly ash from Armadale, West Lothian (near Northrigg, Bathgate), Scotland

[5] All stainless steel dowels from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

[6] All epoxy resin from Cowie, Stirling (Hexion Chemicals-biggest and nearest manufacturer in Scotland) (http://ww2.momentive.com/locations_home.aspx?id=293

[7] All crushed limestone/limestone gravel from Hardendale, Shap, Cumbria, England

[8] All Non-ferrous wire from Scunthorpe, North Lincolnshire (Humberside, Yorkshire) (http://www.tatasteeleurope.com/en/company/european_operations/manufacturing/) and http://www.tatasteeleurope.com/en/contact/addresses/

Appendix H: Approximate Embodied Carbon Expenditure for Repairing 1 m^2 Stone Masonry Wall ($kgCO_2e/kg/m^2$)

Table H.1: Approximate embodied carbon ($kgCO_2e/kg$) per 1 m^2 repaired wall within 'cradle-to-gate'-Historic Scotland

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate' boundaries									
		Historic Scotland (HS)									
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Overall Total**
	(i) Stone***	15.085	13.990	14.093	15.085	15.085	15.085	13.338	17.178	17.178	
	Total (Approx.)	**15.085**	**13.990**	**14.093**	**15.085**	**15.085**	**15.085**	**13.338**	**17.178**	**17.178**	**136.117**
	(ii) Lime mortar grout mix										
	Cement	0.414	3.423		0.414	0.414	0.414		3.912	3.423	**12.414**
	Lime Putty	6.997		2.886	6.997	6.997	6.997	4.123			**34.997**
	Natural Hydraulic Lime (NHL 3.5)							4.123		3.608	**7.731**
	Natural Hydraulic Lime (NHL 5)		3.608	5.772					4.123		**13.503**
	Jurra Kalk		3.608								**3.608**
	Sand	0.137	0.118	0.132	0.137	0.137	0.137	0.135	0.135	0.142	**1.210**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.134			0.134	0.134	0.134				**0.536**
	Total (Approx.)	**7.682**	**10.757**	**8.790**	**7.682**	**7.682**	**7.682**	**8.381**	**8.170**	**7.173**	**73.999**
	Total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**210.116**
	(b) Indenting + dowels + lime grout mix										
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**210.116**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**254.610**
	(iii) Lime grout mix										
	Cement	0.035	0.283		0.035	0.035	0.035		0.324	0.283	**1.030**
	Lime Putty	0.580		0.239	0.580	0.580	0.580	0.342			**2.901**
	Natural Hydraulic Lime (NHL 3.5)							0.342		0.299	**0.641**
	Natural Hydraulic Lime (NHL 5)		0.299	0.479					0.342		**1.120**
	Jurra Kalk		0.299								**0.299**
	Sand	0.011	0.010	0.011	0.011	0.011	0.011	0.011	0.011	0.012	**0.099**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.011			0.011	0.011	0.011				**0.044**
	Total (Approx.)	**0.637**	**0.891**	**0.729**	**0.637**	**0.637**	**0.637**	**0.695**	**0.677**	**0.594**	**6.134**
	Total (Approx.) (b i + b ii)	**28.927**	**29.181**	**29.019**	**28.927**	**28.927**	**28.927**	**28.985**	**28.967**	**28.884**	**260.744**
	Total (Approx.) (b i + b ii + b iii)	**51.694**	**53.928**	**51.902**	**51.694**	**51.694**	**51.694**	**50.704**	**54.315**	**53.235**	**470.860**
	(c) Dowels + epoxy resin										
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**210.116**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**254.610**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**157.338**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**411.948**
	Total (Approx.) (c i + c ii + c iii)	**68.539**	**70.519**	**68.655**	**68.539**	**68.539**	**68.539**	**67.491**	**70.120**	**70.123**	**621.064**
Repointing	**(a) Lime mortar**										
	Cement (General)	0.124	1.018		0.124	0.124	0.124		1.163	1.018	**3.695**
	Lime Putty	2.080		0.858	2.080	2.080	2.080	1.225			**10.403**
	Natural Hydraulic Lime (NHL 3.5)							1.225		1.073	**2.298**
	Natural Hydraulic Lime (NHL 5)		1.073	1.716					1.225		**4.014**
	Jurra Kalk		1.073								**1.073**
	Sand	0.041	0.035	0.039	0.041	0.041	0.041	0.040	0.040	0.042	**0.360**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.040			0.040	0.040	0.040				**0.160**
	Total (Approx.)	**2.285**	**3.199**	**2.613**	**2.285**	**2.285**	**2.285**	**2.490**	**2.428**	**2.133**	**22.003**
Pinning and consolidation	**(a) Dowels + lime grout mix**										
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**254.610**
	(ii) Lime grout mix										
	Cement (General)	0.020	0.189		0.020	0.020	0.020		0.227	0.206	**0.702**
	Lime Putty	0.339		0.239	0.339	0.339	0.339	0.239			**1.834**
	Natural Hydraulic Lime (NHL 3.5)							0.239		0.218	**0.457**
	Natural Hydraulic Lime (NHL 5)		0.200	0.239					0.239		**0.678**
	Jurra Kalk		0.200								**0.200**
	Sand	0.004	0.007	0.006	0.004	0.004	0.004	0.006	0.008	0.004	**0.047**
	Crushed limestone/gravel/chippings (aggregates)	0.156	0.092	0.111	0.156	0.156	0.156	0.111	0.083	0.151	**1.172**
	Total (Approx.)	**0.519**	**0.688**	**0.595**	**0.519**	**0.519**	**0.519**	**0.595**	**0.557**	**0.579**	**5.090**
	Total (Approx.) (a i + a ii)	**28.809**	**28.978**	**28.885**	**28.809**	**28.809**	**28.809**	**28.885**	**28.847**	**28.869**	**259.700**
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**254.610**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**157.338**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**411.948**
Plastic repair	**(a) Lime based mortar with aggregates**										
	Cement (General)	0.184	2.072		0.184	0.184	0.184		2.303	2.303	**7.414**
	Lime Putty	3.093		2.427	3.093	3.093	3.093	1.985			**16.784**
	Natural Hydraulic Lime (NHL 3.5)							1.985			**1.985**
	Natural Hydraulic Lime (NHL 5)		2.184	2.427					2.427	2.427	**9.465**
	Jurra Kalk		2.184								**2.184**
	Sand	0.040	0.043	0.048	0.040	0.040	0.040	0.065	0.048	0.048	**0.412**
	Crushed limestone/gravel/chippings (aggregates)	1.427	1.008	1.120	1.427	1.427	1.427	0.916	1.120	1.120	**10.992**
	Total (Approx.)	**4.744**	**7.491**	**6.022**	**4.744**	**4.744**	**4.744**	**4.951**	**5.898**	**5.898**	**49.236**
	(b) Lime based mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General)	0.288	3.256		0.288	0.288	0.288		3.618	3.618	**11.644**
	Lime Putty	4.859		3.813	4.859	4.859	4.859	3.120			**26.369**
	Natural Hydraulic Lime (NHL 3.5)							3.120		3.813	**6.933**
	Natural Hydraulic Lime (NHL 5)		3.432	3.813					3.813		**11.058**
	Jurra Kalk		3.432								**3.432**
	Sand	0.064	0.067	0.075	0.064	0.064	0.064	0.102	0.075	0.075	**0.650**
	Crushed limestone/gravel/chippings (aggregates)	2.243	1.584	1.760	2.243	2.243	2.243	1.440	1.760	1.760	**17.276**
	Total (Approx.)	**7.454**	**11.771**	**9.461**	**7.454**	**7.454**	**7.454**	**7.782**	**9.266**	**9.266**	**77.362**
	(ii) Secondary fixing										
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**509.220**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**314.676**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**100.026**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**923.922**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**110.112**	**114.429**	**112.119**	**110.112**	**110.112**	**110.112**	**110.440**	**111.924**	**111.924**	**1001.284**

Source: Author, 2012.

Table H.2: Approximate embodied carbon (kgCO$_2$e/kg) per 1 m^2 repaired wall within 'cradle-to-gate'-National Trust for Scotland

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate' boundaries										
		National Trust for Scotland (NTS)										
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Overall Total**
	(i) Stone***	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208	
	Total (Approx.)	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**142.080**
	(ii) Lime mortar grout mix											
	Cement						2.009	3.912	3.912		3.912	**13.745**
	Lime Putty	5.772	1.717	5.772	5.772	5.772				0.78		**25.585**
	Natural Hydraulic Lime (NHL 3.5)	7.696	2.289	7.696	7.696	7.696	4.235	8.245	8.245		8.245	**62.043**
	Natural Hydraulic Lime (NHL 5)									1.56		**1.560**
	Jurra Kalk											
	Sand	0.101	0.030	0.101	0.101	0.101	0.055	0.108	0.108	0.041	0.108	**0.854**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**13.569**	**4.036**	**13.569**	**13.569**	**13.569**	**6.299**	**12.265**	**12.265**	**2.381**	**12.265**	**103.787**
	Total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**245.867**
	(b) Indenting + dowels + lime grout mix											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**245.867**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(iii) Lime grout mix											
	Cement						0.324	0.324	0.324		0.324	**1.296**
	Lime Putty	0.479	0.479	0.479	0.479	0.479				0.218		**2.613**
	Natural Hydraulic Lime (NHL 3.5)	0.638	0.638	0.638	0.638	0.638	0.683	0.683	0.683		0.683	**5.922**
	Natural Hydraulic Lime (NHL 5)									0.435		**0.435**
	Jurra Kalk											
	Sand	0.008	0.008	0.008	0.008	0.008	0.009	0.009	0.009	0.011	0.009	**0.087**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**1.125**	**1.125**	**1.125**	**1.125**	**1.125**	**1.016**	**1.016**	**1.016**	**0.664**	**1.016**	**10.353**
	Total (Approx.) (b i + b ii)	**29.415**	**29.415**	**29.415**	**29.415**	**29.415**	**29.306**	**29.306**	**29.306**	**28.954**	**29.306**	**293.253**
	Total (Approx.) (b i + b ii + b iii)	**57.192**	**47.659**	**57.192**	**57.192**	**57.192**	**49.813**	**55.779**	**55.779**	**45.543**	**55.779**	**539.120**
	(c) Dowels + epoxy resin											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**245.867**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**174.820**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**457.720**
	Total (Approx.) (c i + c ii + c iii)	**73.549**	**64.016**	**73.549**	**73.549**	**73.549**	**66.279**	**72.245**	**72.245**	**62.361**	**72.245**	**703.587**
Repointing	**(a) Lime mortar**											
	Cement (General)						0.634	1.163	1.163		1.163	**4.123**
	Lime Putty	1.717	0.624	1.717	1.717	1.717				0.284		**7.776**
	Natural Hydraulic Lime (NHL 3.5)	2.289	0.832	2.289	2.289	2.289	1.337	2.452	2.452		2.452	**18.681**
	Natural Hydraulic Lime (NHL 5)									0.568		**0.568**
	Jurra Kalk											
	Sand	0.030	0.011	0.030	0.030	0.030	0.017	0.032	0.032	0.015	0.032	**0.259**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**4.036**	**1.467**	**4.036**	**4.036**	**4.036**	**1.988**	**3.647**	**3.647**	**0.867**	**3.647**	**31.407**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(ii) Lime grout mix											
	Cement (General)						0.152	0.152	0.152		0.152	**0.608**
	Lime Putty	0.378	0.378	0.378	0.378	0.378				0.266		**2.156**
	Natural Hydraulic Lime (NHL 3.5)	0.504	0.504	0.504	0.504	0.504	0.319	0.319	0.319		0.319	**3.796**
	Natural Hydraulic Lime (NHL 5)									0.532		**0.532**
	Jurra Kalk											
	Sand	0.007	0.007	0.007	0.007	0.007	0.004	0.004	0.004	0.003	0.004	**0.054**
	Crushed limestone/gravel/chippings (aggregates)	0.058	0.058	0.058	0.058	0.058	0.147	0.147	0.147	0.123	0.147	**1.001**
	Total (Approx.)	**0.947**	**0.947**	**0.947**	**0.947**	**0.947**	**0.622**	**0.622**	**0.622**	**0.924**	**0.622**	**8.147**
	Total (Approx.) (a i + a ii)	**29.237**	**29.237**	**29.237**	**29.237**	**29.237**	**28.912**	**28.912**	**28.912**	**29.214**	**28.912**	**291.047**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**174.820**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**457.720**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General)						1.382	1.382	1.382		1.091	**5.237**
	Lime Putty	1.872	1.872	1.872	1.872	1.191				1.985		**10.664**
	Natural Hydraulic Lime (NHL 3.5)	2.496	2.496	2.496	2.496	1.588	2.913	2.913	2.913		2.299	**22.610**
	Natural Hydraulic Lime (NHL 5)									3.970		**3.970**
	Jurra Kalk											
	Sand	0.049	0.049	0.049	0.049	0.083	0.038	0.038	0.038	0.052	0.060	**0.505**
	Crushed limestone/gravel/chippings (aggregates)	1.152	1.152	1.152	1.152	0.733	1.344	1.344	1.344	0.916	1.061	**11.350**
	Total (Approx.)	**5.569**	**5.569**	**5.569**	**5.569**	**3.595**	**5.677**	**5.677**	**5.677**	**6.923**	**4.511**	**54.336**
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General)						2.171	2.171	2.171		1.714	**8.227**
	Lime Putty	2.942	2.942	2.942	2.942	1.872				3.120		**16.760**
	Natural Hydraulic Lime (NHL 3.5)	3.923	3.923	3.923	3.923	2.496	4.576	4.576	4.576		3.613	**35.529**
	Natural Hydraulic Lime (NHL 5)									6.240		**6.240**
	Jurra Kalk											
	Sand	0.077	0.077	0.077	0.077	0.131	0.060	0.060	0.060	0.082	0.094	**0.795**
	Crushed limestone/gravel/chippings (aggregates)	1.810	1.810	1.810	1.810	1.152	2.112	2.112	2.112	1.440	1.668	**17.836**
	Total (Approx.)	**8.752**	**8.752**	**8.752**	**8.752**	**5.651**	**8.919**	**8.919**	**8.919**	**10.882**	**7.089**	**85.387**
	(ii) Secondary fixing											
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**565.800**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**349.640**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**111.140**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**1026.580**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**111.410**	**111.410**	**111.410**	**111.410**	**108.309**	**111.577**	**111.577**	**111.577**	**113.540**	**109.747**	**1111.967**

Source: Author, 2012.

Table H.3: Approximate embodied carbon ($kgCO_2e/kg$) per 1 m^2 repaired wall within 'cradle-to-gate'-The City of Edinburgh Council

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate' boundaries										
		The City of Edinburgh Council (CEC)										
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	
						Stone Type A	Stone Type B					**Overall Total**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											
	(i) Stone***	13.664	13.664	13.664	14.903	14.208	14.093	14.208	14.144	14.208	14.458	
	Total (Approx.)	**13.664**	**13.664**	**13.664**	**14.093**	**14.208**	**14.093**	**14.208**	**14.144**	**14.208**	**14.458**	**140.404**
	(ii) Lime mortar grout mix											
	Cement											
	Lime Putty	1.716	1.716	1.716	1.716	1.716	1.716	1.716	1.716	1.716	3.608	**19.052**
	Natural Hydraulic Lime (NHL 3.5)	1.716	1.716	1.716	1.716							**6.864**
	Natural Hydraulic Lime (NHL 5)					1.716	1.716	1.716	1.716	1.716	7.215	**15.795**
	Jurra Kalk											
	Sand	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.118	**0.424**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**10.941**	**42.135**
	Total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**182.629**
	(b) Indenting + dowels + lime grout mix											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**182.629**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(iii) Lime grout mix											
	Cement											
	Lime Putty	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.299	**4.601**
	Natural Hydraulic Lime (NHL 3.5)	0.478	0.478	0.478	0.478							**1.912**
	Natural Hydraulic Lime (NHL 5)					0.478	0.478	0.478	0.478	0.478	0.597	**2.987**
	Jurra Kalk											
	Sand	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.010	**0.091**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.906**	**9.591**
	Total (Approx.) (b i + b ii)	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.196**	**292.491**
	Total (Approx.) (b i + b ii + b iii)	**46.385**	**46.385**	**46.385**	**46.814**	**46.929**	**46.814**	**46.929**	**46.865**	**46.929**	**54.595**	**475.030**
	(c) Dowels + epoxy resin											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**182.629**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**174.820**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**457.720**
	Total (Approx.) (c i + c ii + c iii)	**62.902**	**62.902**	**62.902**	**63.331**	**63.446**	**63.331**	**63.446**	**63.382**	**63.446**	**71.171**	**640.259**
Repointing	**(a) Lime mortar**											
	Cement (General)											
	Lime Putty	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	1.073	**6.689**
	Natural Hydraulic Lime (NHL 3.5)	0.624	0.624	0.624	0.624							**2.496**
	Natural Hydraulic Lime (NHL 5)					0.624	0.624	0.624	0.624	0.624	2.145	**5.265**
	Jurra Kalk											
	Sand	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.035	**0.143**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**3.253**	**14.593**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(ii) Lime grout mix											
	Cement (General)											
	Lime Putty	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.239	**2.633**
	Natural Hydraulic Lime (NHL 3.5)	0.266	0.266	0.266	0.266							**1.064**
	Natural Hydraulic Lime (NHL 5)					0.266	0.266	0.266	0.266	0.266	0.479	**1.809**
	Jurra Kalk											
	Sand	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	**0.050**
	Crushed limestone/gravel/chippings (aggregates)	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.111	**1.218**
	Total (Approx.)	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.834**	**6.774**
	Total (Approx.) (a i + a ii)	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**29.124**	**289.674**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**282.900**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**174.820**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**457.720**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General)											
	Lime Putty	1.985	1.985	1.985	1.985	1.985	1.985	1.985	2.427	2.427	1.821	**20.570**
	Natural Hydraulic Lime (NHL 3.5)	1.985	1.985	1.985	1.985							**7.940**
	Natural Hydraulic Lime (NHL 5)					1.985	1.985	1.985	2.427	2.427	3.641	**14.450**
	Jurra Kalk											
	Sand	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.048	0.048	0.060	**0.611**
	Crushed limestone/gravel/chippings (aggregates)	0.916	0.916	0.916	0.916	0.916	0.916	0.916	1.120	1.120	0.840	**9.492**
	Total (Approx.)	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**6.022**	**6.022**	**6.362**	**53.063**
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General)											
	Lime Putty	3.120	3.120	3.120	3.120	3.120	3.120	3.120	3.813	3.813	2.860	**32.326**
	Natural Hydraulic Lime (NHL 3.5)	3.120	3.120	3.120	3.120				3.813		5.721	**22.014**
	Natural Hydraulic Lime (NHL 5)					3.120	3.120	3.120		3.813		**13.173**
	Jurra Kalk											
	Sand	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.075	0.075	0.094	**0.958**
	Crushed limestone/gravel/chippings (aggregates)	1.440	1.440	1.440	1.440	1.440	1.440	1.440	1.760	1.760	1.320	**14.920**
	Total (Approx.)	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**9.461**	**9.461**	**9.995**	**83.391**
	(ii) Secondary fixing											
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**565.800**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**349.640**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**111.140**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**1026.580**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**112.119**	**112.119**	**112.653**	**1109.971**

Source: Author, 2012.

Table H.4: Approximate embodied carbon ($kgCO_2e/kg$) per 1 m^2 repaired wall within 'gate-to-site'-Historic Scotland

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries									
		Historic Scotland (HS)									
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Overall Total**
	(i) Stone*	7.259	4.397	6.127	7.259	7.259	7.259	8.144	17.216	14.365	
	Total (Approx.)	**7.259**	**4.397**	**6.127**	**7.259**	**7.259**	**7.259**	**8.144**	**17.216**	**14.365**	**79.285**
	(ii) Lime mortar grout mix										
	Cement	0.009	0.043		0.008	0.008	0.008		0.054	0.05	**0.180**
	Lime Putty	1.779		0.712	1.768	1.768	1.768	1.149			**8.944**
	Natural Hydraulic Lime (NHL 3.5)							1.149		1.046	**2.195**
	Natural Hydraulic Lime (NHL 5)		0.958	1.433					1.08		**3.471**
	Jurra Kalk		0.862								**0.862**
	Sand	0.035	0.421	0.187	0.235	0.235	0.235	0.093	0.047	0.240	**1.728**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.004			0.003	0.003	0.003				**0.013**
	Total (Approx.)	**1.827**	**2.284**	**2.332**	**2.014**	**2.014**	**2.014**	**2.391**	**1.181**	**1.336**	**17.393**
	Total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**96.678**
	(b) Indenting + dowels + lime grout mix										
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**96.678**
	(ii) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**2.227**
	(iii) Lime grout mix										
	Cement	0.001	0.004		0.001	0.001	0.001		0.004	0.004	**0.016**
	Lime Putty	0.148		0.059	0.147	0.147	0.147	0.095			**0.743**
	Natural Hydraulic Lime (NHL 3.5)							0.095		0.087	**0.182**
	Natural Hydraulic Lime (NHL 5)		0.079	0.119					0.089		**0.287**
	Jurra Kalk		0.071								**0.071**
	Sand	0.003	0.035	0.016	0.020	0.020	0.020	0.008	0.004	0.020	**0.146**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.0003			0.0002	0.0002	0.000				**0.001**
	Total (Approx.) (b ii & iii)	**0.427**	**0.394**	**0.445**	**0.436**	**0.436**	**0.436**	**0.430**	**0.286**	**0.382**	**3.673**
	Total (Approx.) (b i + b ii & iii)	**9.513**	**7.075**	**8.904**	**9.709**	**9.709**	**9.709**	**10.965**	**18.683**	**16.083**	**100.350**
	(c) Dowels + epoxy resin										
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**96.678**
	(ii) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**2.227**
	(iii) Epoxy resin	0.009	0.049	0.017	0.004	0.004	0.004	0.026	0.054	0.011	**0.178**
	Total (Approx.) (c ii & iii)	**0.284**	**0.254**	**0.268**	**0.272**	**0.272**	**0.272**	**0.258**	**0.243**	**0.282**	**2.405**
	Total (Approx.) (c i + c ii & iii)	**9.370**	**6.935**	**8.727**	**9.545**	**9.545**	**9.545**	**10.793**	**18.640**	**15.983**	**99.083**
Repointing	**(a) Lime mortar**										
	Cement (General)	0.003	0.013		0.003	0.003	0.003		0.016	0.015	**0.056**
	Lime Putty	0.529		0.213	0.526	0.526	0.526	0.341			**2.661**
	Natural Hydraulic Lime (NHL 3.5)							0.341		0.311	**0.652**
	Natural Hydraulic Lime (NHL 5)		0.285	0.426					0.321		**1.032**
	Jurra Kalk		0.256								**0.256**
	Sand	0.010	0.125	0.056	0.070	0.070	0.070	0.028	0.014	0.071	**0.514**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.001			0.001	0.001	0.001				**0.004**
	Total (Approx.)	**0.543**	**0.679**	**0.695**	**0.600**	**0.600**	**0.600**	**0.710**	**0.351**	**0.397**	**5.175**
Pinning and consolidation	**(a) Dowels + lime grout mix**										
	(i) Stainless steel dowels	**0.275**	**0.205**	**0.251**	**0.268**	**0.268**	**0.268**	**0.232**	**0.189**	**0.271**	2.227
	(ii) Lime grout mix										
	Cement (General)	0.0004	0.002		0.0004	0.0004	0.0004		0.003	0.003	**0.010**
	Lime Putty	0.086		0.059	0.086	0.086	0.086	0.067			**0.470**
	Natural Hydraulic Lime (NHL 3.5)							0.067		0.063	**0.130**
	Natural Hydraulic Lime (NHL 5)		0.053	0.059					0.063		**0.175**
	Jurra Kalk		0.048								**0.048**
	Sand	0.001	0.023	0.009	0.008	0.008	0.008	0.004	0.003	0.007	**0.071**
	Crushed limestone/gravel/chippings (aggregates)	0.055	0.020	0.033	0.053	0.053	0.053	0.028	0.016	0.047	**0.358**
	Total (Approx.)	**0.142**	**0.146**	**0.160**	**0.147**	**0.147**	**0.147**	**0.166**	**0.085**	**0.120**	**1.262**
	Total (Approx.) (a i + a ii)	**0.417**	**0.351**	**0.411**	**0.415**	**0.415**	**0.415**	**0.398**	**0.274**	**0.391**	**3.487**
	(b) Dowels + epoxy resin										
	(i) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**2.227**
	(ii) Epoxy resin	0.009	0.049	0.017	0.004	0.004	0.004	0.026	0.054	0.011	**0.178**
	Total (Approx.) (b i + b ii)	**0.284**	**0.254**	**0.268**	**0.272**	**0.272**	**0.272**	**0.258**	**0.243**	**0.282**	**2.405**
Plastic repair	**(a) Lime based mortar with aggregates**										
	Cement (General)	0.004	0.026		0.004	0.004	0.004		0.032	0.033	**0.107**
	Lime Putty	0.787		0.603	0.781	0.781	0.781	0.552			**4.285**
	Natural Hydraulic Lime (NHL 3.5)							0.552			**0.552**
	Natural Hydraulic Lime (NHL 5)		0.580	0.603					0.636	0.704	**2.523**
	Jurra Kalk		0.522								**0.522**
	Sand	0.010	0.153	0.067	0.069	0.069	0.069	0.045	0.016	0.081	**0.579**
	Crushed limestone/gravel/chippings (aggregates)	0.505	0.222	0.336	0.482	0.482	0.482	0.234	0.219	0.346	**3.308**
	Total (Approx.)	**1.306**	**1.503**	**1.609**	**1.336**	**1.336**	**1.336**	**1.383**	**0.903**	**1.164**	**11.876**
	(b) Lime based mortar (multi-layer plastic repair)										
	(i) Lime base mortar										
	Cement (General)	0.006	0.041		0.006	0.006	0.006		0.050	0.052	**0.167**
	Lime Putty	1.236		0.947	1.228	1.228	1.228	0.869			**6.736**
	Natural Hydraulic Lime (NHL 3.5)							0.869		1.106	**1.975**
	Natural Hydraulic Lime (NHL 5)		0.911	0.947					0.999		**2.857**
	Jurra Kalk		0.820								**0.820**
	Sand	0.016	0.241	0.106	0.109	0.109	0.109	0.071	0.026	0.127	**0.914**
	Crushed limestone/gravel/chippings (aggregates)	0.794	0.348	0.527	0.757	0.757	0.757	0.367	0.343	0.544	**5.194**
	Total (Approx.)	**2.052**	**2.361**	**2.527**	**2.100**	**2.100**	**2.100**	**2.176**	**1.418**	**1.829**	**18.663**
	(ii) Secondary fixing										
	[1] Stainless steel dowels	0.550	0.409	0.503	0.536	0.536	0.536	0.464	0.378	0.542	
	Total (Approx.)	**0.550**	**0.409**	**0.503**	**0.536**	**0.536**	**0.536**	**0.464**	**0.378**	**0.542**	**4.454**
	[2] Epoxy resin	0.018	0.097	0.033	0.008	0.008	0.008	0.051	0.108	0.022	
	Total (Approx.)	**0.018**	**0.097**	**0.033**	**0.008**	**0.008**	**0.008**	**0.051**	**0.108**	**0.022**	**0.353**
	[3] Non-ferrous tying wire	0.220	0.164	0.201	0.214	0.214	0.214	0.186	0.151	0.217	
	Total (Approx.)	**0.220**	**0.164**	**0.201**	**0.214**	**0.214**	**0.214**	**0.186**	**0.151**	**0.217**	**1.781**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**0.788**	**0.670**	**0.737**	**0.758**	**0.758**	**0.758**	**0.701**	**0.637**	**0.781**	**6.588**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**2.840**	**3.031**	**3.264**	**2.858**	**2.858**	**2.858**	**2.877**	**2.055**	**2.610**	**25.251**

Source: Author, 2012.

Table H.5: Approximate embodied carbon ($kgCO_2e/kg$) per 1 m^2 repaired wall within ‘gate-to-site’-National Trust for Scotland

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries										
		National Trust for Scotland (NTS)										
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian	
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Overall Total**
	(i) Stone*	5.847	5.847	8.157	8.016	8.063	5.328	5.328	5.328	4.569	6.271	
	Total (Approx.)	**5.847**	**5.847**	**8.157**	**8.016**	**8.063**	**5.328**	**5.328**	**5.328**	**4.569**	**6.271**	62.754
	(ii) Lime mortar grout mix											
	Cement						0.067	0.129	0.130		0.024	**0.350**
	Lime Putty	1.649	0.490	1.669	1.718	1.680				0.207		**7.413**
	Natural Hydraulic Lime (NHL 3.5)	2.198	0.654	2.226	2.291	2.240	1.154	2.243	2.245		2.283	**17.534**
	Natural Hydraulic Lime (NHL 5)									0.414		**0.414**
	Jurra Kalk											
	Sand	0.227	0.068	0.179	0.093	0.185	0.332	0.638	0.642	0.149	0.26	**2.773**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**4.074**	**1.212**	**4.074**	**4.102**	**4.105**	**1.553**	**3.010**	**3.017**	**0.770**	**2.567**	28.484
	Total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	91.238
	(b) Indenting + dowels + lime grout mix											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	91.238
	(ii) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**2.348**
	(iii) Lime grout mix											
	Cement						0.011	0.011	0.011		0.002	**0.035**
	Lime Putty	0.136	0.136	0.138	0.143	0.139				0.058		**0.750**
	Natural Hydraulic Lime (NHL 3.5)	0.182	0.182	0.185	0.190	0.186	0.186	0.186	0.186		0.189	**1.672**
	Natural Hydraulic Lime (NHL 5)									0.116		**0.116**
	Jurra Kalk											
	Sand	0.019	0.019	0.015	0.008	0.015	0.054	0.053	0.053	0.042	0.022	**0.300**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.) (b ii & iii)	**0.571**	**0.571**	**0.611**	**0.622**	**0.593**	**0.464**	**0.463**	**0.463**	**0.418**	**0.445**	5.221
	Total (Approx.) (b i + b ii & iii)	**10.492**	**7.630**	**12.842**	**12.740**	**12.761**	**7.345**	**8.801**	**8.808**	**5.757**	**9.283**	96.459
	(c) Dowels + epoxy resin											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	91.238
	(ii) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**2.348**
	(iii) Epoxy resin	0.028	0.028	0.008	0.024	0.014	0.072	0.072	0.072	0.047	0.029	**0.394**
	Total (Approx.) (c ii & iii)	**0.262**	**0.262**	**0.281**	**0.305**	**0.267**	**0.285**	**0.285**	**0.285**	**0.249**	**0.261**	2.742
	Total (Approx.) (c i + c ii & iii)	**10.183**	**7.321**	**12.512**	**12.423**	**12.435**	**7.166**	**8.623**	**8.630**	**5.588**	**9.099**	93.980
Repointing	**(a) Lime mortar**											
	Cement (General)						0.021	0.038	0.039		0.007	**0.105**
	Lime Putty	0.490	0.178	0.496	0.511	0.500				0.075		**2.250**
	Natural Hydraulic Lime (NHL 3.5)	0.654	0.238	0.662	0.681	0.666	0.364	0.667	0.668		0.679	**5.279**
	Natural Hydraulic Lime (NHL 5)									0.151		**0.151**
	Jurra Kalk											
	Sand	0.068	0.025	0.053	0.028	0.055	0.105	0.190	0.191	0.054	0.077	**0.846**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**1.212**	**0.441**	**1.211**	**1.220**	**1.221**	**0.490**	**0.895**	**0.898**	**0.280**	**0.763**	8.631
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels	**0.234**	**0.234**	**0.273**	**0.281**	**0.253**	**0.213**	**0.213**	**0.213**	**0.202**	**0.232**	2.348
	(ii) Lime grout mix											
	Cement (General)						0.005	0.005	0.005		0.0009	**0.016**
	Lime Putty	0.108	0.108	0.109	0.113	0.110				0.071		**0.619**
	Natural Hydraulic Lime (NHL 3.5)	0.144	0.144	0.146	0.150	0.147	0.087	0.087	0.087		0.088	**1.080**
	Natural Hydraulic Lime (NHL 5)									0.141		**0.141**
	Jurra Kalk											
	Sand	0.015	0.015	0.012	0.006	0.012	0.025	0.025	0.025	0.013	0.010	**0.158**
	Crushed limestone/gravel/chippings (aggregates)	0.017	0.017	0.020	0.023	0.021	0.030	0.029	0.029	0.027	0.044	**0.257**
	Total (Approx.)	**0.284**	**0.284**	**0.287**	**0.292**	**0.290**	**0.147**	**0.146**	**0.146**	**0.252**	**0.143**	2.271
	Total (Approx.) (a i + a ii)	**0.518**	**0.518**	**0.560**	**0.573**	**0.543**	**0.360**	**0.359**	**0.359**	**0.454**	**0.375**	4.619
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**2.348**
	(ii) Epoxy resin	0.028	0.028	0.008	0.024	0.014	0.072	0.072	0.072	0.047	0.029	**0.394**
	Total (Approx.) (b i + b ii)	**0.262**	**0.262**	**0.281**	**0.305**	**0.267**	**0.285**	**0.285**	**0.285**	**0.249**	**0.261**	2.742
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General)						0.046	0.046	0.046		0.007	**0.145**
	Lime Putty	0.535	0.535	0.541	0.557	0.346				0.527		**3.041**
	Natural Hydraulic Lime (NHL 3.5)	0.713	0.713	0.722	0.743	0.462	0.794	0.792	0.793		0.637	**6.369**
	Natural Hydraulic Lime (NHL 5)									1.054		**1.054**
	Jurra Kalk											
	Sand	0.111	0.111	0.087	0.045	0.153	0.228	0.225	0.227	0.190	0.145	**1.522**
	Crushed limestone/gravel/chippings (aggregates)	0.343	0.343	0.391	0.449	0.259	0.272	0.266	0.269	0.203	0.320	**3.115**
	Total (Approx.)	**1.702**	**1.702**	**1.741**	**1.794**	**1.220**	**1.340**	**1.329**	**1.335**	**1.974**	**1.109**	15.246
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General)						0.073	0.072	0.072		0.011	**0.228**
	Lime Putty	0.840	0.840	0.851	0.876	0.545				0.828		**4.780**
	Natural Hydraulic Lime (NHL 3.5)	1.120	1.120	1.134	1.167	0.727	1.247	1.245	1.246		1.001	**10.007**
	Natural Hydraulic Lime (NHL 5)									1.657		**1.657**
	Jurra Kalk											
	Sand	0.174	0.174	0.137	0.071	0.240	0.359	0.354	0.356	0.298	0.228	**2.391**
	Crushed limestone/gravel/chippings (aggregates)	0.539	0.539	0.615	0.705	0.408	0.427	0.417	0.422	0.319	0.504	**4.895**
	Total (Approx.)	**2.673**	**2.673**	**2.737**	**2.819**	**1.920**	**2.106**	**2.088**	**2.096**	**3.102**	**1.744**	23.958
	(ii) Secondary fixing											
	[1] Stainless steel dowels	0.469	0.469	0.545	0.561	0.506	0.425	0.425	0.425	0.403	0.464	
	Total (Approx.)	**0.469**	**0.469**	**0.545**	**0.561**	**0.506**	**0.425**	**0.425**	**0.425**	**0.403**	**0.464**	4.692
	[2] Epoxy resin	0.057	0.057	0.016	0.049	0.029	0.143	0.143	0.143	0.094	0.059	
	Total (Approx.)	**0.057**	**0.057**	**0.016**	**0.049**	**0.029**	**0.143**	**0.143**	**0.143**	**0.094**	**0.059**	0.790
	[3] Non-ferrous tying wire	0.188	0.188	0.218	0.224	0.203	0.170	0.170	0.170	0.161	0.186	
	Total (Approx.)	**0.188**	**0.188**	**0.218**	**0.224**	**0.203**	**0.170**	**0.170**	**0.170**	**0.161**	**0.186**	1.878
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**0.714**	**0.714**	**0.779**	**0.834**	**0.738**	**0.738**	**0.738**	**0.738**	**0.658**	**0.709**	7.360
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**3.387**	**3.387**	**3.516**	**3.653**	**2.658**	**2.844**	**2.826**	**2.834**	**3.760**	**2.453**	31.318

Source: Author, 2012.

Table H.6: Approximate embodied carbon ($kgCO_2e/kg$) per 1 m^2 repaired wall within 'gate-to-site'-The City of Edinburgh Council

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries										
		The City of Edinburgh Council (CEC)										
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	
						Stone Type A	Stone Type B					**Overall Total**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											
	(i) Stone*	5.895	5.895	5.895	6.080	6.271	6.173	6.271	12.392	6.271	12.426	
	Total (Approx.)	**5.895**	**5.895**	**5.895**	**6.080**	**6.271**	**6.173**	**6.271**	**12.392**	**6.271**	**12.426**	**73.569**
	(ii) Lime mortar grout mix											
	Cement											
	Lime Putty	0.489	0.489	0.489	0.488	0.487	0.487	0.487	0.488	0.487	1.027	**5.418**
	Natural Hydraulic Lime (NHL 3.5)	0.489	0.489	0.489	0.488							**1.955**
	Natural Hydraulic Lime (NHL 5)					0.487	0.487	0.487	0.488	0.487	2.053	**4.489**
	Jurra Kalk											
	Sand	0.072	0.072	0.072	0.068	0.075	0.075	0.075	0.072	0.075	0.198	**0.854**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**1.050**	**1.050**	**1.050**	**1.044**	**1.049**	**1.049**	**1.049**	**1.048**	**1.049**	**3.278**	**12.716**
	Total (Approx.) (a i + a ii)	**6.945**	**6.945**	**6.945**	**7.124**	**7.320**	**7.222**	**7.320**	**13.440**	**7.320**	**15.704**	**86.285**
	(b) Indenting + dowels + lime grout mix											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**6.945**	**6.945**	**6.945**	**7.124**	**7.320**	**7.222**	**7.320**	**13.440**	**7.320**	**15.704**	**86.285**
	(ii) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	**2.421**
	(iii) Lime grout mix											
	Cement											
	Lime Putty	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.085	**1.309**
	Natural Hydraulic Lime (NHL 3.5)	0.136	0.136	0.136	0.136							**0.544**
	Natural Hydraulic Lime (NHL 5)					0.136	0.136	0.136	0.136	0.136	0.170	**0.850**
	Jurra Kalk											
	Sand	0.020	0.020	0.020	0.019	0.021	0.021	0.021	0.020	0.021	0.016	**0.199**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.) (b ii & iii)	**0.542**	**0.542**	**0.542**	**0.543**	**0.530**	**0.530**	**0.530**	**0.527**	**0.530**	**0.507**	**5.323**
	Total (Approx.) (b i + b ii & iii)	**7.487**	**7.487**	**7.487**	**7.667**	**7.850**	**7.752**	**7.850**	**13.967**	**7.850**	**16.211**	**91.608**
	(c) Dowels + epoxy resin											
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**6.945**	**6.945**	**6.945**	**7.124**	**7.320**	**7.222**	**7.320**	**13.440**	**7.320**	**15.704**	**86.285**
	(ii) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	**2.421**
	(iii) Epoxy resin	0.025	0.025	0.025	0.023	0.023	0.023	0.023	0.024	0.023	0.023	**0.237**
	Total (Approx.) (c ii & iii)	**0.275**	**0.275**	**0.275**	**0.275**	**0.260**	**0.260**	**0.260**	**0.259**	**0.260**	**0.259**	**2.658**
	Total (Approx.) (c i + c ii & iii)	**7.220**	**7.220**	**7.220**	**7.399**	**7.580**	**7.482**	**7.580**	**13.699**	**7.580**	**15.963**	**88.943**
Repointing	**(a) Lime mortar**											
	Cement (General)											
	Lime Putty	0.178	0.624	0.178	0.178	0.177	0.177	0.177	0.178	0.177	0.305	**2.349**
	Natural Hydraulic Lime (NHL 3.5)	0.178	0.624	0.178	0.178							**1.158**
	Natural Hydraulic Lime (NHL 5)					0.177	0.177	0.177	0.178	0.177	0.610	**1.496**
	Jurra Kalk											
	Sand	0.026	0.012	0.026	0.025	0.027	0.027	0.027	0.026	0.027	0.059	**0.282**
	Brick Dust/Fire Clay/Fly Ash (Approx.)											
	Total (Approx.)	**0.382**	**1.260**	**0.382**	**0.381**	**0.381**	**0.381**	**0.381**	**0.382**	**0.381**	**0.974**	**5.285**
Pinning and consolidation	**(a) Dowels + lime grout mix**											
	(i) Stainless steel dowels	**0.250**	**0.250**	**0.250**	**0.252**	**0.237**	**0.237**	**0.237**	**0.235**	**0.237**	**0.236**	**2.421**
	(ii) Lime grout mix											
	Cement (General)											
	Lime Putty	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.068	**0.752**
	Natural Hydraulic Lime (NHL 3.5)	0.076	0.076	0.076	0.076							**0.304**
	Natural Hydraulic Lime (NHL 5)					0.076	0.076	0.076	0.076	0.076	0.136	**0.516**
	Jurra Kalk											
	Sand	0.011	0.011	0.011	0.011	0.012	0.012	0.012	0.011	0.012	0.008	**0.111**
	Crushed limestone/gravel/chippings (aggregates)	0.038	0.038	0.038	0.037	0.036	0.036	0.035	0.036	0.036	0.033	**0.363**
	Total (Approx.)	**0.201**	**0.201**	**0.201**	**0.200**	**0.200**	**0.200**	**0.199**	**0.199**	**0.200**	**0.245**	**2.046**
	Total (Approx.) (a i + a ii)	**0.451**	**0.451**	**0.451**	**0.452**	**0.437**	**0.437**	**0.436**	**0.434**	**0.437**	**0.481**	**4.467**
	(b) Dowels + epoxy resin											
	(i) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	**2.421**
	(ii) Epoxy resin	0.025	0.025	0.025	0.023	0.023	0.023	0.023	0.024	0.023	0.023	**0.237**
	Total (Approx.) (b i + b ii)	**0.275**	**0.275**	**0.275**	**0.275**	**0.260**	**0.260**	**0.260**	**0.259**	**0.260**	**0.259**	**2.658**
Plastic repair	**(a) Lime based mortar with aggregates**											
	Cement (General)											
	Lime Putty	0.565	0.565	0.565	0.564	0.564	0.564	0.564	0.691	0.689	0.518	**5.849**
	Natural Hydraulic Lime (NHL 3.5)	0.565	0.565	0.565	0.564							**2.259**
	Natural Hydraulic Lime (NHL 5)					0.564	0.564	0.564	0.691	0.689	1.036	**4.108**
	Jurra Kalk											
	Sand	0.139	0.139	0.139	0.131	0.144	0.144	0.144	0.102	0.106	0.100	**1.288**
	Crushed limestone/gravel/chippings (aggregates)	0.282	0.282	0.282	0.279	0.266	0.266	0.266	0.328	0.325	0.248	**2.824**
	Total (Approx.)	**1.551**	**1.551**	**1.551**	**1.538**	**1.538**	**1.538**	**1.538**	**1.812**	**1.809**	**1.902**	**16.328**
	(b) Lime based mortar (multi-layer plastic repair)											
	(i) Lime base mortar											
	Cement (General)											
	Lime Putty	0.889	0.889	0.889	0.887	0.886	0.886	0.887	1.085	1.083	0.814	**9.195**
	Natural Hydraulic Lime (NHL 3.5)	0.889	0.889	0.889	0.887				1.085		1.628	**6.267**
	Natural Hydraulic Lime (NHL 5)					0.886	0.886	0.887		1.083		**3.742**
	Jurra Kalk											
	Sand	0.219	0.219	0.219	0.205	0.227	0.227	0.205	0.159	0.166	0.157	**2.003**
	Crushed limestone/gravel/chippings (aggregates)	0.444	0.444	0.444	0.438	0.418	0.418	0.438	0.515	0.511	0.389	**4.459**
	Total (Approx.)	**2.441**	**2.441**	**2.441**	**2.417**	**2.417**	**2.417**	**2.417**	**2.844**	**2.843**	**2.988**	**25.666**
	(ii) Secondary fixing											
	[1] Stainless steel dowels	0.499	0.499	0.499	0.504	0.474	0.474	0.475	0.470	0.474	0.472	
	Total (Approx.)	**0.499**	**0.499**	**0.499**	**0.504**	**0.474**	**0.474**	**0.475**	**0.470**	**0.474**	**0.472**	**4.840**
	[2] Epoxy resin	0.049	0.049	0.049	0.045	0.046	0.046	0.046	0.048	0.046	0.046	
	Total (Approx.)	**0.049**	**0.049**	**0.049**	**0.045**	**0.046**	**0.046**	**0.046**	**0.049**	**0.046**	**0.046**	**0.471**
	[3] Non-ferrous tying wire	0.200	0.200	0.200	0.202	0.189	0.189	0.190	0.188	0.189	0.189	
	Total (Approx.)	**0.200**	**0.200**	**0.200**	**0.202**	**0.189**	**0.189**	**0.190**	**0.188**	**0.189**	**0.189**	**1.936**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**0.748**	**0.748**	**0.748**	**0.751**	**0.709**	**0.709**	**0.711**	**0.707**	**0.709**	**0.707**	**7.247**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**3.189**	**3.189**	**3.189**	**3.168**	**3.126**	**3.126**	**3.128**	**3.551**	**3.552**	**3.695**	**32.913**

Source: Author, 2012.

Appendix I: Minimum, Maximum and Average of Embodied Carbon Expenditure for Repairing 1 m^2 Stone Masonry Wall (kgCO$_2$e/kg/m^2)

Table I.1: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within 'cradle-to-gate'-Historic Scotland

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate' boundaries											
		Historic Scotland (HS)											
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace			
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Minimum**	**Maximum**	**Average**
	(i) Stone***	15.085	13.990	14.093	15.085	15.085	15.085	13.338	17.178	17.178			
	Total (Approx.)	**15.085**	**13.990**	**14.093**	**15.085**	**15.085**	**15.085**	**13.338**	**17.178**	**17.178**	**13.338**	**17.178**	**15.148**
	(ii) Lime mortar grout mix												
	Cement	0.414	3.423		0.414	0.414	0.414		3.912	3.423	**0.414**	**3.912**	**1.860**
	Lime Putty	6.997		2.886	6.997	6.997	6.997	4.123			**2.886**	**6.997**	**5.610**
	Natural Hydraulic Lime (NHL 3.5)							4.123		3.608	**3.608**	**4.123**	**3.866**
	Natural Hydraulic Lime (NHL 5)		3.608	5.772					4.123		**3.608**	**5.772**	**4.577**
	Jurra Kalk		3.608								**3.608**	**3.608**	**3.608**
	Sand	0.137	0.118	0.132	0.137	0.137	0.137	0.135	0.135	0.142	**0.118**	**0.142**	**0.134**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.134			0.134	0.134	0.134				**0.134**	**0.134**	**0.134**
	Total (Approx.)	**7.682**	**10.757**	**8.790**	**7.682**	**7.682**	**7.682**	**8.381**	**8.170**	**7.173**	**7.173**	**10.757**	**8.357**
	Total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**21.719**	**25.348**	**23.380**
	(b) Indenting + dowels + lime grout mix												
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**21.719**	**25.348**	**23.380**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Lime grout mix												
	Cement	0.035	0.283		0.035	0.035	0.035		0.324	0.283	**0.035**	**0.324**	**0.154**
	Lime Putty	0.580		0.239	0.580	0.580	0.580	0.342			**0.239**	**0.580**	**0.465**
	Natural Hydraulic Lime (NHL 3.5)							0.342		0.299	**0.299**	**0.342**	**0.321**
	Natural Hydraulic Lime (NHL 5)		0.299	0.479					0.342		**0.299**	**0.479**	**0.380**
	Jurra Kalk		0.299								**0.299**	**0.299**	**0.299**
	Sand	0.011	0.010	0.011	0.011	0.011	0.011	0.011	0.011	0.012	**0.010**	**0.012**	**0.011**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.011			0.011	0.011	0.011				**0.011**	**0.011**	**0.011**
	Total (Approx.)	**0.637**	**0.891**	**0.729**	**0.637**	**0.637**	**0.637**	**0.695**	**0.677**	**0.594**	**0.594**	**0.891**	**0.693**
	Total (Approx.) (b i + b ii)	**28.927**	**29.181**	**29.019**	**28.927**	**28.927**	**28.927**	**28.985**	**28.967**	**28.884**	**28.884**	**29.181**	**28.983**
	Total (Approx.) (b i + b ii + b iii)	**51.694**	**53.928**	**51.902**	**51.694**	**51.694**	**51.694**	**50.704**	**54.315**	**53.235**	**50.704**	**54.315**	**52.353**
	(c) Dowels + epoxy resin												
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**22.767**	**24.747**	**22.883**	**22.767**	**22.767**	**22.767**	**21.719**	**25.348**	**24.351**	**21.719**	**25.348**	**23.380**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
	Total (Approx.) (c i + c ii + c iii)	**68.539**	**70.519**	**68.655**	**68.539**	**68.539**	**68.539**	**67.491**	**70.120**	**70.123**	**67.491**	**70.519**	**69.007**
Repointing	**(a) Lime mortar**												
	Cement (General)	0.124	1.018		0.124	0.124	0.124		1.163	1.018	**0.124**	**1.163**	**0.554**
	Lime Putty	2.080		0.858	2.080	2.080	2.080	1.225			**0.858**	**2.080**	**1.668**
	Natural Hydraulic Lime (NHL 3.5)							1.225		1.073	**1.073**	**1.225**	**1.149**
	Natural Hydraulic Lime (NHL 5)		1.073	1.716					1.225		**1.073**	**1.716**	**1.361**
	Jurra Kalk		1.073								**1.073**	**1.073**	**1.073**
	Sand	0.041	0.035	0.039	0.041	0.041	0.041	0.040	0.040	0.042	**0.035**	**0.042**	**0.040**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.040			0.040	0.040	0.040				**0.040**	**0.040**	**0.040**
	Total (Approx.)	**2.285**	**3.199**	**2.613**	**2.285**	**2.285**	**2.285**	**2.490**	**2.428**	**2.133**	**2.133**	**3.199**	**2.485**
Pinning and consolidation	**(a) Dowels + lime grout mix**												
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Lime grout mix												
	Cement (General)	0.020	0.189		0.020	0.020	0.020		0.227	0.206	**0.020**	**0.227**	**0.105**
	Lime Putty	0.339		0.239	0.339	0.339	0.339	0.239			**0.239**	**0.339**	**0.302**
	Natural Hydraulic Lime (NHL 3.5)							0.239		0.218	**0.218**	**0.239**	**0.229**
	Natural Hydraulic Lime (NHL 5)		0.200	0.239					0.239		**0.200**	**0.239**	**0.223**
	Jurra Kalk		0.200								**0.200**	**0.200**	**0.200**
	Sand	0.004	0.007	0.006	0.004	0.004	0.004	0.006	0.008	0.004	**0.004**	**0.008**	**0.005**
	Crushed limestone/gravel/chippings (aggregates)	0.156	0.092	0.111	0.156	0.156	0.156	0.111	0.083	0.151	**0.083**	**0.156**	**0.128**
	Total (Approx.)	**0.519**	**0.688**	**0.595**	**0.519**	**0.519**	**0.519**	**0.595**	**0.557**	**0.579**	**0.519**	**0.688**	**0.572**
	Total (Approx.) (a i + a ii)	**28.809**	**28.978**	**28.885**	**28.809**	**28.809**	**28.809**	**28.885**	**28.847**	**28.869**	**28.809**	**28.978**	**28.862**
	(b) Dowels + epoxy resin												
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
Plastic repair	**(a) Lime based mortar with aggregates**												
	Cement (General)	0.184	2.072		0.184	0.184	0.184		2.303	2.303	**0.184**	**2.303**	**1.100**
	Lime Putty	3.093		2.427	3.093	3.093	3.093	1.985			**1.985**	**3.093**	**2.733**
	Natural Hydraulic Lime (NHL 3.5)							1.985			**1.985**	**1.985**	**1.985**
	Natural Hydraulic Lime (NHL 5)		2.184	2.427					2.427	2.427	**2.184**	**2.427**	**2.346**
	Jurra Kalk		2.184								**2.184**	**2.184**	**2.184**
	Sand	0.040	0.043	0.048	0.040	0.040	0.040	0.065	0.048	0.048	**0.040**	**0.065**	**0.047**
	Crushed limestone/gravel/chippings (aggregates)	1.427	1.008	1.120	1.427	1.427	1.427	0.916	1.120	1.120	**0.916**	**1.427**	**1.212**
	Total (Approx.)	**4.744**	**7.491**	**6.022**	**4.744**	**4.744**	**4.744**	**4.951**	**5.898**	**5.898**	**4.744**	**7.491**	**5.588**
	(b) Lime based mortar (multi-layer plastic repair)												
	(i) Lime base mortar												
	Cement (General)	0.288	3.256		0.288	0.288	0.288		3.618	3.618	**0.288**	**3.618**	**1.728**
	Lime Putty	4.859		3.813	4.859	4.859	4.859	3.120			**3.120**	**4.859**	**4.294**
	Natural Hydraulic Lime (NHL 3.5)							3.120		3.813	**3.120**	**3.813**	**3.467**
	Natural Hydraulic Lime (NHL 5)		3.432	3.813					3.813		**3.432**	**3.813**	**3.661**
	Jurra Kalk		3.432								**3.432**	**3.432**	**3.432**
	Sand	0.064	0.067	0.075	0.064	0.064	0.064	0.102	0.075	0.075	**0.064**	**0.102**	**0.074**
	Crushed limestone/gravel/chippings (aggregates)	2.243	1.584	1.760	2.243	2.243	2.243	1.440	1.760	1.760	**1.440**	**2.243**	**1.905**
	Total (Approx.)	**7.454**	**11.771**	**9.461**	**7.454**	**7.454**	**7.454**	**7.782**	**9.266**	**9.266**	**7.454**	**11.771**	**8.781**
	(ii) Secondary fixing												
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580			
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964			
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114			
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**110.112**	**114.429**	**112.119**	**110.112**	**110.112**	**110.112**	**110.440**	**111.924**	**111.924**	**110.112**	**114.429**	**111.439**

Source: Author, 2012.

Table I.2: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within ‘cradle-to-gate’-National Trust for Scotland

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate' boundaries												
		National Trust for Scotland (NTS)												
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian			
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Minimum**	**Maximum**	**Average**
	(i) Stone***	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208	14.208			
	Total (Approx.)	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**	**14.208**
	(ii) Lime mortar grout mix													
	Cement						2.009	3.912	3.912		3.912	**2.009**	**3.912**	**3.278**
	Lime Putty	5.772	1.717	5.772	5.772	5.772				0.78		**0.780**	**5.772**	**4.017**
	Natural Hydraulic Lime (NHL 3.5)	7.696	2.289	7.696	7.696	7.696	4.235	8.245	8.245		8.245	**2.289**	**8.245**	**6.598**
	Natural Hydraulic Lime (NHL 5)									1.56		**1.560**	**1.560**	**1.560**
	Jurra Kalk													
	Sand	0.101	0.030	0.101	0.101	0.101	0.055	0.108	0.108	0.041	0.108	**0.030**	**0.108**	**0.083**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**13.569**	**4.036**	**13.569**	**13.569**	**13.569**	**6.299**	**12.265**	**12.265**	**2.381**	**12.265**	**2.381**	**13.569**	**9.978**
	Total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**16.589**	**27.777**	**24.186**
	(b) Indenting + dowels + lime grout mix													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**16.589**	**27.777**	**24.186**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Lime grout mix													
	Cement						0.324	0.324	0.324		0.324	**0.324**	**0.324**	**0.324**
	Lime Putty	0.479	0.479	0.479	0.479	0.479				0.218		**0.218**	**0.479**	**0.414**
	Natural Hydraulic Lime (NHL 3.5)	0.638	0.638	0.638	0.638	0.638	0.683	0.683	0.683		0.683	**0.638**	**0.683**	**0.658**
	Natural Hydraulic Lime (NHL 5)									0.435		**0.435**	**0.435**	**0.435**
	Jurra Kalk													
	Sand	0.008	0.008	0.008	0.008	0.008	0.009	0.009	0.009	0.011	0.009	**0.008**	**0.011**	**0.009**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**1.125**	**1.125**	**1.125**	**1.125**	**1.125**	**1.016**	**1.016**	**1.016**	**0.664**	**1.016**	**0.664**	**1.125**	**1.012**
	Total (Approx.) (b i + b ii)	**29.415**	**29.415**	**29.415**	**29.415**	**29.415**	**29.306**	**29.306**	**29.306**	**28.954**	**29.306**	**28.954**	**29.415**	**29.302**
	Total (Approx.) (b i + b ii + b iii)	**57.192**	**47.659**	**57.192**	**57.192**	**57.192**	**49.813**	**55.779**	**55.779**	**45.543**	**55.779**	**45.543**	**57.192**	**53.488**
	(c) Dowels + epoxy resin													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**27.777**	**18.244**	**27.777**	**27.777**	**27.777**	**20.507**	**26.473**	**26.473**	**16.589**	**26.473**	**16.589**	**27.777**	**24.186**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
	Total (Approx.) (c i + c ii + c iii)	**73.549**	**64.016**	**73.549**	**73.549**	**73.549**	**66.279**	**72.245**	**72.245**	**62.361**	**72.245**	**62.361**	**73.549**	**69.958**
Repointing	**(a) Lime mortar**													
	Cement (General)						0.634	1.163	1.163		1.163	**0.634**	**1.163**	**0.987**
	Lime Putty	1.717	0.624	1.717	1.717	1.717				0.284		**0.284**	**1.717**	**1.222**
	Natural Hydraulic Lime (NHL 3.5)	2.289	0.832	2.289	2.289	2.289	1.337	2.452	2.452		2.452	**0.832**	**2.452**	**1.997**
	Natural Hydraulic Lime (NHL 5)									0.568		**0.568**	**0.568**	**0.568**
	Jurra Kalk													
	Sand	0.030	0.011	0.030	0.030	0.030	0.017	0.032	0.032	0.015	0.032	**0.011**	**0.032**	**0.025**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**4.036**	**1.467**	**4.036**	**4.036**	**4.036**	**1.988**	**3.647**	**3.647**	**0.867**	**3.647**	**0.867**	**4.036**	**3.026**
Pinning and consolidation	**(a) Dowels + lime grout mix**													
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Lime grout mix													
	Cement (General)						0.152	0.152	0.152		0.152	**0.152**	**0.152**	**0.152**
	Lime Putty	0.378	0.378	0.378	0.378	0.378				0.266		**0.266**	**0.378**	**0.350**
	Natural Hydraulic Lime (NHL 3.5)	0.504	0.504	0.504	0.504	0.504	0.319	0.319	0.319		0.319	**0.319**	**0.504**	**0.420**
	Natural Hydraulic Lime (NHL 5)									0.532		**0.532**	**0.532**	**0.532**
	Jurra Kalk													
	Sand	0.007	0.007	0.007	0.007	0.007	0.004	0.004	0.004	0.003	0.004	**0.003**	**0.007**	**0.005**
	Crushed limestone/gravel/chippings (aggregates)	0.058	0.058	0.058	0.058	0.058	0.147	0.147	0.147	0.123	0.147	**0.058**	**0.147**	**0.101**
	Total (Approx.)	**0.947**	**0.947**	**0.947**	**0.947**	**0.947**	**0.622**	**0.622**	**0.622**	**0.924**	**0.622**	**0.622**	**0.947**	**0.810**
	Total (Approx.) (a i + a ii)	**29.237**	**29.237**	**29.237**	**29.237**	**29.237**	**28.912**	**28.912**	**28.912**	**29.214**	**28.912**	**28.912**	**29.237**	**29.100**
	(b) Dowels + epoxy resin													
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
Plastic repair	**(a) Lime based mortar with aggregates**													
	Cement (General)						1.382	1.382	1.382		1.091	**1.091**	**1.382**	**1.285**
	Lime Putty	1.872	1.872	1.872	1.872	1.191				1.985		**1.191**	**1.985**	**1.730**
	Natural Hydraulic Lime (NHL 3.5)	2.496	2.496	2.496	2.496	1.588	2.913	2.913	2.913		2.299	**1.588**	**2.913**	**2.465**
	Natural Hydraulic Lime (NHL 5)									3.970		**3.970**	**3.970**	**3.970**
	Jurra Kalk													
	Sand	0.049	0.049	0.049	0.049	0.083	0.038	0.038	0.038	0.052	0.060	**0.038**	**0.083**	**0.052**
	Crushed limestone/gravel/chippings (aggregates)	1.152	1.152	1.152	1.152	0.733	1.344	1.344	1.344	0.916	1.061	**0.733**	**1.344**	**1.119**
	Total (Approx.)	**5.569**	**5.569**	**5.569**	**5.569**	**3.595**	**5.677**	**5.677**	**5.677**	**6.923**	**4.511**	**3.595**	**6.923**	**5.405**
	(b) Lime based mortar (multi-layer plastic repair)													
	(i) Lime base mortar													
	Cement (General)						2.171	2.171	2.171		1.714	**1.714**	**2.171**	**2.019**
	Lime Putty	2.942	2.942	2.942	2.942	1.872				3.120		**1.872**	**3.120**	**2.719**
	Natural Hydraulic Lime (NHL 3.5)	3.923	3.923	3.923	3.923	2.496	4.576	4.576	4.576		3.613	**2.496**	**4.576**	**3.873**
	Natural Hydraulic Lime (NHL 5)									6.240		**6.240**	**6.240**	**6.240**
	Jurra Kalk													
	Sand	0.077	0.077	0.077	0.077	0.131	0.060	0.060	0.060	0.082	0.094	**0.060**	**0.131**	**0.082**
	Crushed limestone/gravel/chippings (aggregates)	1.810	1.810	1.810	1.810	1.152	2.112	2.112	2.112	1.440	1.668	**1.152**	**2.112**	**1.758**
	Total (Approx.)	**8.752**	**8.752**	**8.752**	**8.752**	**5.651**	**8.919**	**8.919**	**8.919**	**10.882**	**7.089**	**5.651**	**10.882**	**8.493**
	(ii) Secondary fixing													
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580			
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964			
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114			
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**111.410**	**111.410**	**111.410**	**111.410**	**108.309**	**111.577**	**111.577**	**111.577**	**113.540**	**109.747**	**108.309**	**113.540**	**111.151**

Source: Author, 2012.

Table I.3: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within ‘cradle-to-gate’-The City of Edinburgh Council

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'cradle-to-gate'												
		The City of Edinburgh Council (CEC)												
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh			
						Stone Type A	Stone Type B					**Minimum**	**Maximum**	**Average**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**													
	(i) Stone***	13.664	13.664	13.664	14.903	14.208	14.093	14.208	14.144	14.208	14.458			
	Total (Approx.)	**13.664**	**13.664**	**13.664**	**14.093**	**14.208**	**14.093**	**14.208**	**14.144**	**14.208**	**14.458**	**13.664**	**14.458**	**14.044**
	(ii) Lime mortar grout mix													
	Cement													
	Lime Putty	1.716	1.716	1.716	1.716	1.716	1.716	1.716	1.716	1.716	3.608	**1.716**	**3.608**	**2.031**
	Natural Hydraulic Lime (NHL 3.5)	1.716	1.716	1.716	1.716							**1.716**	**1.716**	**1.716**
	Natural Hydraulic Lime (NHL 5)					1.716	1.716	1.716	1.716	1.716	7.215	**1.716**	**7.215**	**3.091**
	Jurra Kalk													
	Sand	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.118	**0.034**	**0.118**	**0.048**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**3.466**	**10.941**	**3.466**	**10.941**	**4.712**
	Total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**17.130**	**25.399**	**18.763**
	(b) Indenting + dowels + lime grout mix													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**17.130**	**25.399**	**18.763**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Lime grout mix													
	Cement													
	Lime Putty	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.478	0.299	**0.299**	**0.478**	**0.448**
	Natural Hydraulic Lime (NHL 3.5)	0.478	0.478	0.478	0.478							**0.478**	**0.478**	**0.478**
	Natural Hydraulic Lime (NHL 5)					0.478	0.478	0.478	0.478	0.478	0.597	**0.478**	**0.597**	**0.508**
	Jurra Kalk													
	Sand	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.010	**0.009**	**0.010**	**0.009**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.965**	**0.906**	**0.906**	**0.965**	**0.955**
	Total (Approx.) (b i + b ii)	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.255**	**29.196**	**29.196**	**29.255**	**29.245**
	Total (Approx.) (b i + b ii + b iii)	**46.385**	**46.385**	**46.385**	**46.814**	**46.929**	**46.814**	**46.929**	**46.865**	**46.929**	**54.595**	**46.385**	**54.595**	**48.001**
	(c) Dowels + epoxy resin													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**17.130**	**17.130**	**17.130**	**17.559**	**17.764**	**17.559**	**17.674**	**17.610**	**17.674**	**25.399**	**17.130**	**18.160**	**18.160**
	(ii) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(iii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (c i + c ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
	Total (Approx.) (c i + c ii + c iii)	**62.902**	**62.902**	**62.902**	**63.331**	**63.446**	**63.331**	**63.446**	**63.382**	**63.446**	**71.171**	**62.902**	**71.171**	**64.528**
Repointing	**(a) Lime mortar**													
	Cement (General)													
	Lime Putty	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	1.073	**0.624**	**1.073**	**0.699**
	Natural Hydraulic Lime (NHL 3.5)	0.624	0.624	0.624	0.624							**0.624**	**0.624**	**0.624**
	Natural Hydraulic Lime (NHL 5)					0.624	0.624	0.624	0.624	0.624	2.145	**0.624**	**2.145**	**1.004**
	Jurra Kalk													
	Sand	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.035	**0.012**	**0.035**	**0.016**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**1.260**	**3.253**	**1.260**	**3.253**	**1.592**
Pinning and consolidation	**(a) Dowels + lime grout mix**													
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Lime grout mix													
	Cement (General)													
	Lime Putty	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.239	**0.239**	**0.266**	**0.262**
	Natural Hydraulic Lime (NHL 3.5)	0.266	0.266	0.266	0.266							**0.266**	**0.266**	**0.266**
	Natural Hydraulic Lime (NHL 5)					0.266	0.266	0.266	0.266	0.266	0.479	**0.266**	**0.479**	**0.319**
	Jurra Kalk													
	Sand	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	**0.005**	**0.005**	**0.005**
	Crushed limestone/gravel/chippings (aggregates)	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.111	**0.111**	**0.123**	**0.121**
	Total (Approx.)	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.660**	**0.834**	**0.660**	**0.834**	**0.689**
	Total (Approx.) (a i + a ii)	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**28.950**	**29.124**	**28.950**	**29.124**	**28.979**
	(b) Dowels + epoxy resin													
	(i) Stainless steel dowels	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290	28.290			
	Total (Approx.)	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**	**28.290**
	(ii) Epoxy resin	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482	17.482			
	Total (Approx.)	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**	**17.482**
	Total (Approx.) (b i + b ii)	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**	**45.772**
Plastic repair	**(a) Lime based mortar with aggregates**													
	Cement (General)													
	Lime Putty	1.985	1.985	1.985	1.985	1.985	1.985	1.985	2.427	2.427	1.821	**1.821**	**2.427**	**2.068**
	Natural Hydraulic Lime (NHL 3.5)	1.985	1.985	1.985	1.985							**1.985**	**1.985**	**1.985**
	Natural Hydraulic Lime (NHL 5)					1.985	1.985	1.985	2.427	2.427	3.641	**1.985**	**3.641**	**2.510**
	Jurra Kalk													
	Sand	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.048	0.048	0.060	**0.048**	**0.065**	**0.060**
	Crushed limestone/gravel/chippings (aggregates)	0.916	0.916	0.916	0.916	0.916	0.916	0.916	1.120	1.120	0.840	**0.840**	**1.120**	**0.954**
	Total (Approx.)	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**4.951**	**6.022**	**6.022**	**6.362**	**4.951**	**6.362**	**5.365**
	(b) Lime based mortar (multi-layer plastic repair)													
	(i) Lime base mortar													
	Cement (General)													
	Lime Putty	3.120	3.120	3.120	3.120	3.120	3.120	3.120	3.813	3.813	2.860	**2.860**	**3.813**	**3.250**
	Natural Hydraulic Lime (NHL 3.5)	3.120	3.120	3.120	3.120				3.813		5.721	**3.120**	**5.721**	**3.857**
	Natural Hydraulic Lime (NHL 5)					3.120	3.120	3.120		3.813		**3.120**	**3.813**	**3.351**
	Jurra Kalk													
	Sand	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.075	0.075	0.094	**0.075**	**0.102**	**0.095**
	Crushed limestone/gravel/chippings (aggregates)	1.440	1.440	1.440	1.440	1.440	1.440	1.440	1.760	1.760	1.320	**1.320**	**1.760**	**1.500**
	Total (Approx.)	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**7.782**	**9.461**	**9.461**	**9.995**	**7.782**	**9.995**	**8.431**
	(ii) Secondary fixing													
	[1] Stainless steel dowels	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580	56.580			
	Total (Approx.)	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**	**56.580**
	[2] Epoxy resin	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964	34.964			
	Total (Approx.)	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**	**34.964**
	[3] Non-ferrous tying wire	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114	11.114			
	Total (Approx.)	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**	**11.114**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**	**102.658**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**110.440**	**112.119**	**112.119**	**112.653**	**110.440**	**112.653**	**111.089**

Source: Author, 2012.

Table I.4: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within ‘gate-to-site’-Historic Scotland

		Approximate of embodied carbon ($kgCO_2e/kg$) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries											
		Historic Scotland (HS)											
Repair Techniques	**Materials**	HS1-Doune Castle	HS2-Melrose Abbey	HS3-Glasgow Cathedral	HS4-Old Palace/Palace of James V, Stirling Castle	HS5-King's Old Building/Douglas Block, Stirling Castle	HS6-Great Hall/Old Parliament House, Stirling Castle	HS7-Craignethan Castle	HS8-Jedburgh Abbey	HS9-Linlithgow Palace			
Natural stone replacement	**(a) Indenting + lime mortar grout mix**										**Minimum**	**Maximum**	**Average**
	(i) Stone*	7.259	4.397	6.127	7.259	7.259	7.259	8.144	17.216	14.365			
	Total (Approx.)	**7.259**	**4.397**	**6.127**	**7.259**	**7.259**	**7.259**	**8.144**	**17.216**	**14.365**	**4.397**	**17.216**	**9.173**
	(ii) Lime mortar grout mix												
	Cement	0.009	0.043		0.008	0.008	0.008		0.054	0.050	**0.008**	**0.054**	**0.027**
	Lime Putty	1.779		0.712	1.768	1.768	1.768	1.149			**0.712**	**1.779**	**1.429**
	Natural Hydraulic Lime (NHL 3.5)							1.149		1.046	**1.046**	**1.149**	**1.098**
	Natural Hydraulic Lime (NHL 5)		0.958	1.433					1.080		**0.958**	**1.433**	**1.172**
	Jurra Kalk		0.862								**0.862**	**0.862**	**0.862**
	Sand	0.035	0.421	0.187	0.235	0.235	0.235	0.093	0.047	0.240	**0.035**	**0.421**	**0.199**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.004			0.003	0.003	0.003				**0.003**	**0.004**	**0.003**
	Total (Approx.)	**1.827**	**2.284**	**2.332**	**2.014**	**2.014**	**2.014**	**2.391**	**1.181**	**1.336**	**1.181**	**2.391**	**1.906**
	Total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**6.681**	**18.397**	**11.069**
	(b) Indenting + dowels + lime grout mix												
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**6.681**	**18.397**	**11.069**
	(ii) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**0.189**	**0.275**	**0.245**
	(iii) Lime grout mix												
	Cement	0.001	0.004		0.001	0.001	0.001		0.004	0.004	**0.001**	**0.004**	**0.002**
	Lime Putty	0.148		0.059	0.147	0.147	0.147	0.095			**0.059**	**0.148**	**0.119**
	Natural Hydraulic Lime (NHL 3.5)							0.095		0.087	**0.087**	**0.095**	**0.091**
	Natural Hydraulic Lime (NHL 5)		0.079	0.119					0.089		**0.079**	**0.119**	**0.097**
	Jurra Kalk		0.071								**0.071**	**0.071**	**0.071**
	Sand	0.003	0.035	0.016	0.020	0.020	0.020	0.008	0.004	0.020	**0.003**	**0.035**	**0.017**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.000			0.000	0.000	0.000				**0.000**	**0.000**	**0.000**
	Total (Approx.) (b ii & iii)	**0.427**	**0.394**	**0.445**	**0.436**	**0.436**	**0.436**	**0.430**	**0.286**	**0.382**	**0.286**	**0.445**	**0.400**
	Total (Approx.) (b i + b ii & iii)	**9.513**	**7.075**	**8.904**	**9.709**	**9.709**	**9.709**	**10.965**	**18.683**	**16.083**	**7.075**	**18.683**	**11.464**
	(c) Dowels + epoxy resin												
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.086**	**6.681**	**8.459**	**9.273**	**9.273**	**9.273**	**10.535**	**18.397**	**15.701**	**6.681**	**18.397**	**11.069**
	(ii) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**0.189**	**0.275**	**0.245**
	(iii) Epoxy resin	0.009	0.049	0.017	0.004	0.004	0.004	0.026	0.054	0.011	**0.004**	**0.054**	**0.021**
	Total (Approx.) (c ii & iii)	**0.284**	**0.254**	**0.268**	**0.272**	**0.272**	**0.272**	**0.258**	**0.243**	**0.282**	**0.243**	**0.284**	**0.267**
	Total (Approx.) (c i + c ii & iii)	**9.370**	**6.935**	**8.727**	**9.545**	**9.545**	**9.545**	**10.793**	**18.640**	**15.983**	**6.935**	**18.640**	**11.333**
Repointing	**(a) Lime mortar**												
	Cement (General)	0.003	0.013		0.003	0.003	0.003		0.016	0.015	**0.003**	**0.016**	**0.008**
	Lime Putty	0.529		0.213	0.526	0.526	0.526	0.341			**0.213**	**0.529**	**0.425**
	Natural Hydraulic Lime (NHL 3.5)							0.341		0.311	**0.311**	**0.341**	**0.326**
	Natural Hydraulic Lime (NHL 5)		0.285	0.426					0.321		**0.285**	**0.426**	**0.349**
	Jurra Kalk		0.256								**0.256**	**0.256**	**0.256**
	Sand	0.010	0.125	0.056	0.070	0.070	0.070	0.028	0.014	0.071	**0.010**	**0.125**	**0.059**
	Brick Dust/Fire Clay/Fly Ash (Approx.)	0.001			0.001	0.001	0.001				**0.001**	**0.001**	**0.001**
	Total (Approx.)	**0.543**	**0.679**	**0.695**	**0.600**	**0.600**	**0.600**	**0.710**	**0.351**	**0.397**	**0.351**	**0.710**	**0.567**
Pinning and consolidation	**(a) Dowels + lime grout mix**												
	(i) Stainless steel dowels	**0.275**	**0.205**	**0.251**	**0.268**	**0.268**	**0.268**	**0.232**	**0.189**	**0.271**	**0.189**	**0.275**	**0.245**
	(ii) Lime grout mix												
	Cement (General)	0.000	0.002		0.000	0.000	0.000		0.003	0.003	**0.000**	**0.003**	**0.001**
	Lime Putty	0.086		0.059	0.086	0.086	0.086	0.067			**0.059**	**0.086**	**0.077**
	Natural Hydraulic Lime (NHL 3.5)							0.067		0.063	**0.063**	**0.067**	**0.065**
	Natural Hydraulic Lime (NHL 5)		0.053	0.059					0.063		**0.053**	**0.063**	**0.058**
	Jurra Kalk		0.048								**0.048**	**0.048**	**0.048**
	Sand	0.001	0.023	0.009	0.008	0.008	0.008	0.004	0.003	0.007	**0.001**	**0.023**	**0.009**
	Crushed limestone/gravel/chippings (aggregates)	0.055	0.020	0.033	0.053	0.053	0.053	0.028	0.016	0.047	**0.016**	**0.055**	**0.039**
	Total (Approx.)	**0.142**	**0.146**	**0.160**	**0.147**	**0.147**	**0.147**	**0.166**	**0.085**	**0.120**	**0.085**	**0.166**	**0.138**
	Total (Approx.) (a i + a ii)	**0.417**	**0.351**	**0.411**	**0.415**	**0.415**	**0.415**	**0.398**	**0.274**	**0.391**	**0.274**	**0.417**	**0.380**
	(b) Dowels + epoxy resin												
	(i) Stainless steel dowels	0.275	0.205	0.251	0.268	0.268	0.268	0.232	0.189	0.271	**0.189**	**0.275**	**0.245**
	(ii) Epoxy resin	0.009	0.049	0.017	0.004	0.004	0.004	0.026	0.054	0.011	**0.004**	**0.054**	**0.021**
	Total (Approx.) (b i + b ii)	**0.284**	**0.254**	**0.268**	**0.272**	**0.272**	**0.272**	**0.258**	**0.243**	**0.282**	**0.243**	**0.284**	**0.267**
Plastic repair	**(a) Lime based mortar with aggregates**												
	Cement (General)	0.004	0.026		0.004	0.004	0.004		0.032	0.033	**0.004**	**0.033**	**0.016**
	Lime Putty	0.787		0.603	0.781	0.781	0.781	0.552			**0.552**	**0.787**	**0.703**
	Natural Hydraulic Lime (NHL 3.5)							0.552			**0.552**	**0.552**	**0.552**
	Natural Hydraulic Lime (NHL 5)		0.580	0.603					0.636	0.704	**0.580**	**0.704**	**0.635**
	Jurra Kalk		0.522								**0.522**	**0.522**	**0.522**
	Sand	0.010	0.153	0.067	0.069	0.069	0.069	0.045	0.016	0.081	**0.010**	**0.153**	**0.067**
	Crushed limestone/gravel/chippings (aggregates)	0.505	0.222	0.336	0.482	0.482	0.482	0.234	0.219	0.346	**0.219**	**0.505**	**0.367**
	Total (Approx.)	**1.306**	**1.503**	**1.609**	**1.336**	**1.336**	**1.336**	**1.383**	**0.903**	**1.164**	**0.903**	**1.609**	**1.308**
	(b) Lime based mortar (multi-layer plastic repair)												
	(i) Lime base mortar												
	Cement (General)	0.006	0.041		0.006	0.006	0.006		0.050	0.052	**0.006**	**0.052**	**0.025**
	Lime Putty	1.236		0.947	1.228	1.228	1.228	0.869			**0.869**	**1.236**	**1.105**
	Natural Hydraulic Lime (NHL 3.5)							0.869		1.106	**0.869**	**1.106**	**0.988**
	Natural Hydraulic Lime (NHL 5)		0.911	0.947					0.999		**0.911**	**0.999**	**0.953**
	Jurra Kalk		0.820								**0.820**	**0.820**	**0.820**
	Sand	0.016	0.241	0.106	0.109	0.109	0.109	0.071	0.026	0.127	**0.016**	**0.241**	**0.106**
	Crushed limestone/gravel/chippings (aggregates)	0.794	0.348	0.527	0.757	0.757	0.757	0.367	0.343	0.544	**0.343**	**0.794**	**0.576**
	Total (Approx.)	**2.052**	**2.361**	**2.527**	**2.100**	**2.100**	**2.100**	**2.176**	**1.418**	**1.829**	**1.418**	**2.527**	**2.055**
	(ii) Secondary fixing												
	[1] Stainless steel dowels	0.550	0.409	0.503	0.536	0.536	0.536	0.464	0.378	0.542			
	Total (Approx.)	**0.550**	**0.409**	**0.503**	**0.536**	**0.536**	**0.536**	**0.464**	**0.378**	**0.542**	**0.378**	**0.550**	**0.489**
	[2] Epoxy resin	0.018	0.097	0.033	0.008	0.008	0.008	0.051	0.108	0.022			
	Total (Approx.)	**0.018**	**0.097**	**0.033**	**0.008**	**0.008**	**0.008**	**0.051**	**0.108**	**0.022**	**0.008**	**0.108**	**0.043**
	[3] Non-ferrous tying wire	0.220	0.164	0.201	0.214	0.214	0.214	0.186	0.151	0.217			
	Total (Approx.)	**0.220**	**0.164**	**0.201**	**0.214**	**0.214**	**0.214**	**0.186**	**0.151**	**0.217**	**0.151**	**0.220**	**0.196**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**0.788**	**0.670**	**0.737**	**0.758**	**0.758**	**0.758**	**0.701**	**0.637**	**0.781**	**0.637**	**0.788**	**0.728**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**2.840**	**3.031**	**3.264**	**2.858**	**2.858**	**2.858**	**2.877**	**2.055**	**2.610**	**2.055**	**3.264**	**2.779**

Source: Author, 2012.

Table I.5: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within ‘gate-to-site’-National Trust for Scotland

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries												
		National Trust for Scotland (NTS)												
Repair Techniques	**Materials**	NTS1-Newhailes Estate, Stable Block	NTS2-Newhailes Estate, Mainhouse	NTS3-Culross Palace	NTS4-Falkland Palace	NTS5-House of the Binns	NTS6-Threave House, Threave Estate, Castle Douglas	NTS7-Gate Lodge, Threave Estate, Castle Douglas	NTS8-Kilton Mains, Threave Estate, Castle Douglas	NTS9-Harmony House/St. Cuthbert House, Melrose	NTS10-Hamilton House, East Lothian			
Natural stone replacement	**(a) Indenting + lime mortar grout mix**											**Minimum**	**Maximum**	**Average**
	(i) Stone*	5.847	5.847	8.157	8.016	8.063	5.328	5.328	5.328	4.569	6.271			
	Total (Approx.)	**5.847**	**5.847**	**8.157**	**8.016**	**8.063**	**5.328**	**5.328**	**5.328**	**4.569**	**6.271**	**4.569**	**8.157**	**6.290**
	(ii) Lime mortar grout mix													
	Cement						0.067	0.129	0.130		0.024	**0.024**	**0.130**	**0.084**
	Lime Putty	1.649	0.490	1.669	1.718	1.680				0.207		**0.207**	**1.718**	**1.167**
	Natural Hydraulic Lime (NHL 3.5)	2.198	0.654	2.226	2.291	2.240	1.154	2.243	2.245		2.283	**0.654**	**2.291**	**1.862**
	Natural Hydraulic Lime (NHL 5)									0.414		**0.414**	**0.414**	**0.414**
	Jurra Kalk													
	Sand	0.227	0.068	0.179	0.093	0.185	0.332	0.638	0.642	0.149	0.26	**0.068**	**0.642**	**0.290**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**4.074**	**1.212**	**4.074**	**4.102**	**4.105**	**1.553**	**3.010**	**3.017**	**0.770**	**2.567**	**0.770**	**4.105**	**2.780**
	Total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	**5.339**	**12.231**	**9.067**
	(b) Indenting + dowels + lime grout mix													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	**5.339**	**12.231**	**9.067**
	(ii) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**0.202**	**0.281**	**0.236**
	(iii) Lime grout mix													
	Cement						0.011	0.011	0.011		0.002	**0.002**	**0.011**	**0.008**
	Lime Putty	0.136	0.136	0.138	0.143	0.139				0.058		**0.058**	**0.143**	**0.119**
	Natural Hydraulic Lime (NHL 3.5)	0.182	0.182	0.185	0.190	0.186	0.186	0.186	0.186		0.189	**0.182**	**0.190**	**0.186**
	Natural Hydraulic Lime (NHL 5)									0.116		**0.116**	**0.116**	**0.116**
	Jurra Kalk													
	Sand	0.019	0.019	0.015	0.008	0.015	0.054	0.053	0.053	0.042	0.022	**0.008**	**0.054**	**0.030**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.) (b ii & iii)	**0.571**	**0.571**	**0.611**	**0.622**	**0.593**	**0.464**	**0.463**	**0.463**	**0.418**	**0.445**	**0.418**	**0.622**	**0.522**
	Total (Approx.) (b i + b ii & iii)	**10.492**	**7.630**	**12.842**	**12.740**	**12.761**	**7.345**	**8.801**	**8.808**	**5.757**	**9.283**	**5.757**	**12.842**	**9.588**
	(c) Dowels + epoxy resin													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	**9.921**	**7.059**	**12.231**	**12.118**	**12.168**	**6.881**	**8.338**	**8.345**	**5.339**	**8.838**	**5.339**	**12.231**	**9.067**
	(ii) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**0.202**	**0.281**	**0.236**
	(iii) Epoxy resin	0.028	0.028	0.008	0.024	0.014	0.072	0.072	0.072	0.047	0.029	**0.008**	**0.072**	**0.040**
	Total (Approx.) (c ii & iii)	**0.262**	**0.262**	**0.281**	**0.305**	**0.267**	**0.285**	**0.285**	**0.285**	**0.249**	**0.261**	**0.249**	**0.305**	**0.275**
	Total (Approx.) (c i + c ii & iii)	**10.183**	**7.321**	**12.512**	**12.423**	**12.435**	**7.166**	**8.623**	**8.630**	**5.588**	**9.099**	**5.588**	**12.512**	**9.340**
Repointing	**(a) Lime mortar**													
	Cement (General)						0.021	0.038	0.039		0.007	**0.007**	**0.039**	**0.025**
	Lime Putty	0.490	0.178	0.496	0.511	0.500				0.075		**0.075**	**0.511**	**0.355**
	Natural Hydraulic Lime (NHL 3.5)	0.654	0.238	0.662	0.681	0.666	0.364	0.667	0.668		0.679	**0.238**	**0.681**	**0.563**
	Natural Hydraulic Lime (NHL 5)									0.151		**0.151**	**0.151**	**0.151**
	Jurra Kalk													
	Sand	0.068	0.025	0.053	0.028	0.055	0.105	0.190	0.191	0.054	0.077	**0.025**	**0.191**	**0.089**
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	**1.212**	**0.441**	**1.211**	**1.220**	**1.221**	**0.490**	**0.895**	**0.898**	**0.280**	**0.763**	**0.280**	**1.221**	**0.844**
Pinning and consolidation	**(a) Dowels + lime grout mix**													
	(i) Stainless steel dowels	**0.234**	**0.234**	**0.273**	**0.281**	**0.253**	**0.213**	**0.213**	**0.213**	**0.202**	**0.232**	**0.202**	**0.281**	**0.236**
	(ii) Lime grout mix													
	Cement (General)						0.005	0.005	0.005		0.0009	**0.001**	**0.005**	**0.004**
	Lime Putty	0.108	0.108	0.109	0.113	0.110				0.071		**0.071**	**0.113**	**0.100**
	Natural Hydraulic Lime (NHL 3.5)	0.144	0.144	0.146	0.150	0.147	0.087	0.087	0.087		0.088	**0.087**	**0.150**	**0.120**
	Natural Hydraulic Lime (NHL 5)									0.141		**0.141**	**0.141**	**0.141**
	Jurra Kalk													
	Sand	0.015	0.015	0.012	0.006	0.012	0.025	0.025	0.025	0.013	0.010	**0.006**	**0.025**	**0.016**
	Crushed limestone/gravel/chippings (aggregates)	0.017	0.017	0.020	0.023	0.021	0.030	0.029	0.029	0.027	0.044	**0.017**	**0.044**	**0.027**
	Total (Approx.)	**0.284**	**0.284**	**0.287**	**0.292**	**0.290**	**0.147**	**0.146**	**0.146**	**0.252**	**0.143**	**0.143**	**0.292**	**0.225**
	Total (Approx.) (a i + a ii)	**0.518**	**0.518**	**0.560**	**0.573**	**0.543**	**0.360**	**0.359**	**0.359**	**0.454**	**0.375**	**0.359**	**0.573**	**0.463**
	(b) Dowels + epoxy resin													
	(i) Stainless steel dowels	0.234	0.234	0.273	0.281	0.253	0.213	0.213	0.213	0.202	0.232	**0.202**	**0.281**	**0.236**
	(ii) Epoxy resin	0.028	0.028	0.008	0.024	0.014	0.072	0.072	0.072	0.047	0.029	**0.008**	**0.072**	**0.040**
	Total (Approx.) (b i + b ii)	**0.262**	**0.262**	**0.281**	**0.305**	**0.267**	**0.285**	**0.285**	**0.285**	**0.249**	**0.261**	**0.249**	**0.305**	**0.275**
Plastic repair	**(a) Lime based mortar with aggregates**													
	Cement (General)						0.046	0.046	0.046		0.007	**0.007**	**0.046**	**0.033**
	Lime Putty	0.535	0.535	0.541	0.557	0.346				0.527		**0.346**	**0.557**	**0.493**
	Natural Hydraulic Lime (NHL 3.5)	0.713	0.713	0.722	0.743	0.462	0.794	0.792	0.793		0.637	**0.462**	**0.794**	**0.693**
	Natural Hydraulic Lime (NHL 5)									1.054		**1.054**	**1.054**	**1.054**
	Jurra Kalk													
	Sand	0.111	0.111	0.087	0.045	0.153	0.228	0.225	0.227	0.190	0.145	**0.045**	**0.228**	**0.150**
	Crushed limestone/gravel/chippings (aggregates)	0.343	0.343	0.391	0.449	0.259	0.272	0.266	0.269	0.203	0.320	**0.203**	**0.449**	**0.314**
	Total (Approx.)	**1.702**	**1.702**	**1.741**	**1.794**	**1.220**	**1.340**	**1.329**	**1.335**	**1.974**	**1.109**	**1.109**	**1.974**	**1.527**
	(b) Lime based mortar (multi-layer plastic repair)													
	(i) Lime base mortar													
	Cement (General)						0.073	0.072	0.072		0.011	**0.011**	**0.073**	**0.052**
	Lime Putty	0.840	0.840	0.851	0.876	0.545				0.828		**0.545**	**0.876**	**0.775**
	Natural Hydraulic Lime (NHL 3.5)	1.120	1.120	1.134	1.167	0.727	1.247	1.245	1.246		1.001	**0.727**	**1.247**	**1.089**
	Natural Hydraulic Lime (NHL 5)									1.657		**1.657**	**1.657**	**1.657**
	Jurra Kalk													
	Sand	0.174	0.174	0.137	0.071	0.240	0.359	0.354	0.356	0.298	0.228	**0.071**	**0.359**	**0.235**
	Crushed limestone/gravel/chippings (aggregates)	0.539	0.539	0.615	0.705	0.408	0.427	0.417	0.422	0.319	0.504	**0.319**	**0.705**	**0.493**
	Total (Approx.)	**2.673**	**2.673**	**2.737**	**2.819**	**1.920**	**2.106**	**2.088**	**2.096**	**3.102**	**1.744**	**1.744**	**3.102**	**2.400**
	(ii) Secondary fixing	**2.673**	**2.673**	**2.737**	**2.819**	**1.920**	**2.106**	**2.088**	**2.096**	**3.102**	**1.744**	**1.744**	**3.102**	**2.400**
	[1] Stainless steel dowels	0.469	0.469	0.545	0.561	0.506	0.425	0.425	0.425	0.403	0.464			
	Total (Approx.)	**0.469**	**0.469**	**0.545**	**0.561**	**0.506**	**0.425**	**0.425**	**0.425**	**0.403**	**0.464**	**0.403**	**0.561**	**0.471**
	[2] Epoxy resin	0.057	0.057	0.016	0.049	0.029	0.143	0.143	0.143	0.094	0.059			
	Total (Approx.)	**0.057**	**0.057**	**0.016**	**0.049**	**0.029**	**0.143**	**0.143**	**0.143**	**0.094**	**0.059**	**0.016**	**0.143**	**0.079**
	[3] Non-ferrous tying wire	0.188	0.188	0.218	0.224	0.203	0.170	0.170	0.170	0.161	0.186			
	Total (Approx.)	**0.188**	**0.188**	**0.218**	**0.224**	**0.203**	**0.170**	**0.170**	**0.170**	**0.161**	**0.186**	**0.161**	**0.224**	**0.189**
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	**0.714**	**0.714**	**0.779**	**0.834**	**0.738**	**0.738**	**0.738**	**0.738**	**0.658**	**0.709**	**0.658**	**0.834**	**0.738**
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	**3.387**	**3.387**	**3.516**	**3.653**	**2.658**	**2.844**	**2.826**	**2.834**	**3.760**	**2.453**	**2.453**	**3.760**	**3.128**

Source: Author, 2012.

Table I.6: Minimum, maximum and average of embodied carbon expenditure per 1 m^2 repaired wall within ‘gate-to-site’-The City of Edinburgh Council

		Approximate of embodied carbon (kgCO$_2$e/kg) of repair materials for repairing 1 m^2 masonry wall within 'gate-to-site' boundaries												
		The City of Edinburgh Council (CEC)												
Repair Techniques	**Materials**	CEC1-15 Hillside Crescent & 30-32 Hillside Street	CEC2-15, 16, 16A, 17-19 Hillside Crescent	CEC3-21-31 Hillside Street	CEC4-22-30 Shandwick Place, Edinburgh	CEC5-131-141 Bruntsfield Place, Edinburgh		CEC6-36-42 Forbes Road, Edinburgh	CEC7-4-11 Elm Row, Edinburgh	CEC8-148-164 Bruntsfield Place, Edinburgh	CEC9-20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh			
						Stone Type A	Stone Type B					**Maximum**	**Minimum**	**Average**
Natural stone replacement	**(a) Indenting + lime mortar grout mix**													
	(i) Stone*	5.895	5.895	5.895	6.080	6.271	6.173	6.271	12.392	6.271	12.426			
	Total (Approx.)	5.895	5.895	5.895	6.080	6.271	6.173	6.271	12.392	6.271	12.426	5.895	12.426	7.658
	(ii) Lime mortar grout mix													
	Cement													
	Lime Putty	0.489	0.489	0.489	0.488	0.487	0.487	0.487	0.488	0.487	1.027	0.487	1.027	0.578
	Natural Hydraulic Lime (NHL 3.5)	0.489	0.489	0.489	0.488							0.488	0.489	0.489
	Natural Hydraulic Lime (NHL 5)					0.487	0.487	0.487	0.488	0.487	2.053	0.487	2.053	0.879
	Jurra Kalk													
	Sand	0.072	0.072	0.072	0.068	0.075	0.075	0.075	0.072	0.075	0.198	0.068	0.198	0.093
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	1.050	1.050	1.050	1.044	1.049	1.049	1.049	1.048	1.049	3.278	1.044	3.278	1.420
	Total (Approx.) (a i + a ii)	6.945	6.945	6.945	7.124	7.320	7.222	7.320	13.440	7.320	15.704	6.945	15.704	9.078
	(b) Indenting + dowels + lime grout mix													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	6.945	6.945	6.945	7.124	7.320	7.222	7.320	13.440	7.320	15.704	6.945	15.704	9.078
	(ii) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	0.235	0.235	0.241
	(iii) Lime grout mix													
	Cement													
	Lime Putty	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.085	0.085	0.085	0.123
	Natural Hydraulic Lime (NHL 3.5)	0.136	0.136	0.136	0.136							0.136	0.136	0.136
	Natural Hydraulic Lime (NHL 5)					0.136	0.136	0.136	0.136	0.136	0.170	0.136	0.136	0.140
	Jurra Kalk													
	Sand	0.020	0.020	0.020	0.019	0.021	0.021	0.021	0.020	0.021	0.016	0.016	0.016	0.019
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.) (b ii & iii)	0.542	0.542	0.542	0.543	0.530	0.530	0.530	0.527	0.530	0.507	0.507	0.507	0.528
	Total (Approx.) (b i + b ii & iii)	7.487	7.487	7.487	7.667	7.850	7.752	7.850	13.967	7.850	16.211	7.487	7.487	8.882
	(c) Dowels + epoxy resin													
	(i) Indenting + lime mortar grout mix = total (Approx.) (a i + a ii)	6.945	6.945	6.945	7.124	7.320	7.222	7.320	13.440	7.320	15.704	6.945	15.704	9.078
	(ii) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	0.235	0.252	0.242
	(iii) Epoxy resin	0.025	0.025	0.025	0.023	0.023	0.023	0.023	0.024	0.023	0.023	0.023	0.025	0.024
	Total (Approx.) (c ii & iii)	0.275	0.275	0.275	0.275	0.260	0.260	0.260	0.259	0.260	0.259	0.259	0.275	0.266
	Total (Approx.) (c i + c ii & iii)	7.220	7.220	7.220	7.399	7.580	7.482	7.580	13.699	7.580	15.963	7.220	15.963	9.344
Repointing	**(a) Lime mortar**													
	Cement (General)													
	Lime Putty	0.178	0.624	0.178	0.178	0.177	0.177	0.177	0.178	0.177	0.305	0.177	0.624	0.263
	Natural Hydraulic Lime (NHL 3.5)	0.178	0.624	0.178	0.178							0.178	0.624	0.327
	Natural Hydraulic Lime (NHL 5)					0.177	0.177	0.177	0.178	0.177	0.610	0.177	0.610	0.285
	Jurra Kalk													
	Sand	0.026	0.012	0.026	0.025	0.027	0.027	0.027	0.026	0.027	0.059	0.012	0.059	0.029
	Brick Dust/Fire Clay/Fly Ash (Approx.)													
	Total (Approx.)	0.382	1.260	0.382	0.381	0.381	0.381	0.381	0.382	0.381	0.974	0.381	1.260	0.577
Pinning and consolidation	**(a) Dowels + lime grout mix**													
	(i) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	0.235	0.252	0.242
	(ii) Lime grout mix													
	Cement (General)													
	Lime Putty	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.068	0.068	0.076	0.075
	Natural Hydraulic Lime (NHL 3.5)	0.076	0.076	0.076	0.076							0.076	0.076	0.076
	Natural Hydraulic Lime (NHL 5)					0.076	0.076	0.076	0.076	0.076	0.136	0.076	0.136	0.091
	Jurra Kalk													
	Sand	0.011	0.011	0.011	0.011	0.012	0.012	0.012	0.011	0.012	0.008	0.008	0.012	0.011
	Crushed limestone/gravel/chippings (aggregates)	0.038	0.038	0.038	0.037	0.036	0.036	0.035	0.036	0.036	0.033	0.033	0.038	0.036
	Total (Approx.)	0.201	0.201	0.201	0.200	0.200	0.200	0.199	0.199	0.200	0.245	0.199	0.245	0.208
	Total (Approx.) (a i + a ii)	0.451	0.451	0.451	0.452	0.437	0.437	0.436	0.434	0.437	0.481	0.434	0.481	0.449
	(b) Dowels + epoxy resin													
	(i) Stainless steel dowels	0.250	0.250	0.250	0.252	0.237	0.237	0.237	0.235	0.237	0.236	0.235	0.252	0.242
	(ii) Epoxy resin	0.025	0.025	0.025	0.023	0.023	0.023	0.023	0.024	0.023	0.023	0.023	0.025	0.024
	Total (Approx.) (b i + b ii)	0.275	0.275	0.275	0.275	0.260	0.260	0.260	0.259	0.260	0.259	0.259	0.275	0.266
Plastic repair	**(a) Lime based mortar with aggregates**													
	Cement (General)													
	Lime Putty	0.565	0.565	0.565	0.564	0.564	0.564	0.564	0.691	0.689	0.518	0.518	0.691	0.588
	Natural Hydraulic Lime (NHL 3.5)	0.565	0.565	0.565	0.564							0.564	0.565	0.565
	Natural Hydraulic Lime (NHL 5)					0.564	0.564	0.564	0.691	0.689	1.036	0.564	1.036	0.714
	Jurra Kalk													
	Sand	0.139	0.139	0.139	0.131	0.144	0.144	0.144	0.102	0.106	0.100	0.100	0.144	0.128
	Crushed limestone/gravel/chippings (aggregates)	0.282	0.282	0.282	0.279	0.266	0.266	0.266	0.328	0.325	0.248	0.248	0.328	0.283
	Total (Approx.)	1.551	1.551	1.551	1.538	1.538	1.538	1.538	1.812	1.809	1.902	1.538	1.902	1.647
	(b) Lime based mortar (multi-layer plastic repair)													
	(i) Lime base mortar													
	Cement (General)													
	Lime Putty	0.889	0.889	0.889	0.887	0.886	0.886	0.887	1.085	1.083	0.814	0.814	1.085	0.925
	Natural Hydraulic Lime (NHL 3.5)	0.889	0.889	0.889	0.887				1.085		1.628	0.887	1.628	1.098
	Natural Hydraulic Lime (NHL 5)					0.886	0.886	0.887		1.083		0.886	1.083	0.952
	Jurra Kalk													
	Sand	0.219	0.219	0.219	0.205	0.227	0.227	0.205	0.159	0.166	0.157	0.157	0.227	0.199
	Crushed limestone/gravel/chippings (aggregates)	0.444	0.444	0.444	0.438	0.418	0.418	0.438	0.515	0.511	0.389	0.389	0.515	0.447
	Total (Approx.)	2.441	2.441	2.441	2.417	2.417	2.417	2.417	2.844	2.843	2.988	2.417	2.988	2.589
	(ii) Secondary fixing													
	[1] Stainless steel dowels	0.499	0.499	0.499	0.504	0.474	0.474	0.475	0.470	0.474	0.472			
	Total (Approx.)	0.499	0.499	0.499	0.504	0.474	0.474	0.475	0.470	0.474	0.472	0.470	0.504	0.485
	[2] Epoxy resin	0.049	0.049	0.049	0.045	0.046	0.046	0.046	0.048	0.046	0.046			
	Total (Approx.)	0.049	0.049	0.049	0.045	0.046	0.046	0.046	0.049	0.046	0.046	0.045	0.049	0.047
	[3] Non-ferrous tying wire	0.200	0.200	0.200	0.202	0.189	0.189	0.190	0.188	0.189	0.189			
	Total (Approx.)	0.200	0.200	0.200	0.202	0.189	0.189	0.190	0.188	0.189	0.189	0.188	0.202	0.194
	Total (Approx.) (b ii [1] + b ii [2] + b ii [3])	0.748	0.748	0.748	0.751	0.709	0.709	0.711	0.707	0.709	0.707	0.707	0.751	0.725
	Total (Approx.) (b i + b ii [1] + b ii [2] + b ii [3])	3.189	3.189	3.189	3.168	3.126	3.126	3.128	3.551	3.552	3.695	3.126	3.695	3.311

Source: Author, 2012.

Appendix J: Total Embodied Carbon Expenditure for Repairing 1 m^2 Stone Masonry Wall (kgCO$_2$e/kg/m^2)

Table J.1: Total embodied carbon expenditure carbon per 1 m^2 stone masonry wall repaired (kgCO$_2$e/kg/m^2)

		Stone Masonry Wall Repair Techniques/Total Embodied Carbon Expenditure Per m^2 Wall Repaired [kgCO$_2$e/kg/m^2]																				
		Replacement									**Repointing**			**Pinning and consolidation**						**Plastic Repair**		
	Collaborative Partners/Property	**(a) Indenting + Lime Mortar Grout Mix**			**(b) Indenting+ Dowels + Lime Grout Mix**			**(c) Dowels + Epoxy Resin**			**Lime Mortar**			**(a) Dowels + Lime Grout Mix**			**(b) Dowels + Epoxy Resin**			**(a) Lime Based Mortar + Aggregates**		
No. (code)	**Historic Scotland**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**	cradle-to-gate	gate-to-site	**Total**
HS1	Doune Castle	22.767	9.086	**31.853**	51.694	9.513	**61.207**	68.539	9.370	**77.909**	2.285	0.543	**2.828**	28.809	0.417	**29.226**	45.772	0.284	**46.056**	4.744	1.306	**6.050**
HS2	Melrose Abbey	24.747	6.681	**31.428**	53.928	7.075	**61.003**	70.519	6.935	**77.454**	3.199	0.679	**3.878**	28.978	0.351	**29.329**	45.772	0.254	**46.026**	7.491	1.503	**8.994**
HS3	Glasgow Cathedral	22.883	8.459	**31.342**	51.902	8.904	**60.806**	68.655	8.727	**77.382**	2.613	0.695	**3.308**	28.885	0.411	**29.296**	45.772	0.268	**46.040**	6.022	1.609	**7.631**
HS4	Old Palace/Palace of James V, Stirling Castle	22.767	9.273	**32.040**	51.694	9.709	**61.403**	68.539	9.545	**78.084**	2.285	0.600	**2.885**	28.809	0.415	**29.224**	45.772	0.272	**46.044**	4.744	1.336	**6.080**
HS5	King's Old Building/Douglas Block, Stirling Castle	22.767	9.273	**32.040**	51.694	9.709	**61.403**	68.539	9.545	**78.084**	2.285	0.600	**2.885**	28.809	0.415	**29.224**	45.772	0.272	**46.044**	4.744	1.336	**6.080**
HS6	Great Hall/Old Parliament House, Stirling Castle	22.767	9.273	**32.040**	51.694	9.709	**61.403**	68.539	9.545	**78.084**	2.285	0.600	**2.885**	28.809	0.415	**29.224**	45.772	0.272	**46.044**	4.744	1.336	**6.080**
HS7	Craignethan Castle	21.719	10.535	**32.254**	50.704	10.965	**61.669**	67.491	10.793	**78.284**	2.490	0.710	**3.200**	28.885	0.398	**29.283**	45.772	0.258	**46.030**	4.951	1.383	**6.334**
HS8	Jedburgh Abbey	25.348	18.397	**43.745**	54.315	18.683	**72.998**	71.120	18.640	**89.760**	2.428	0.351	**2.779**	28.847	0.274	**29.121**	45.772	0.243	**46.015**	5.898	0.903	**6.801**
HS9	Linlithgow Palace	24.351	15.701	**40.052**	53.235	16.083	**69.318**	70.123	15.983	**86.106**	2.133	0.397	**2.530**	28.869	0.391	**29.260**	45.772	0.282	**46.054**	5.898	1.164	**7.062**
	National Trust for Scotland (NTS)																					
NTS1	Newhailes Estate, Stable Block	27.777	9.921	**37.698**	57.192	10.492	**67.684**	73.549	10.183	**83.732**	4.036	1.212	**5.248**	29.237	0.518	**29.755**	45.772	0.262	**46.034**	5.569	1.702	**7.271**
NTS2	Newhailes Estate, Mainhouse	18.244	7.059	**25.303**	47.659	7.630	**55.289**	64.016	7.321	**71.337**	1.467	0.441	**1.908**	29.237	0.518	**29.755**	45.772	0.262	**46.034**	5.569	1.702	**7.271**
NTS3	Culross Palace	27.777	12.231	**40.008**	57.192	12.842	**70.034**	73.549	12.512	**86.061**	4.036	1.211	**5.247**	29.237	0.560	**29.797**	45.772	0.281	**46.053**	5.569	1.741	**7.310**
NTS4	Falkland Palace	27.777	12.118	**39.895**	57.192	12.740	**69.932**	73.549	12.423	**85.972**	4.036	1.220	**5.256**	29.237	0.573	**29.810**	45.772	0.305	**46.077**	5.569	1.794	**7.363**
NTS5	House of The Binns	27.777	12.168	**39.945**	57.192	12.761	**69.953**	73.549	12.435	**85.984**	4.036	1.221	**5.257**	29.237	0.543	**29.780**	45.772	0.267	**46.039**	3.595	1.220	**4.815**
NTS6	Threave House,Threave Estate, Castle Douglas	20.507	6.881	**27.388**	49.813	7.345	**57.158**	66.279	7.166	**73.445**	1.988	0.490	**2.478**	28.912	0.360	**29.272**	45.772	0.285	**46.057**	5.677	1.340	**7.017**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	26.473	8.338	**34.811**	55.779	8.801	**64.580**	72.245	8.623	**80.868**	3.647	0.895	**4.542**	28.912	0.359	**29.271**	45.772	0.285	**46.057**	5.677	1.329	**7.006**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	26.473	8.345	**34.818**	55.779	8.808	**64.587**	72.245	8.630	**80.875**	3.647	0.898	**4.545**	28.912	0.359	**29.271**	45.772	0.285	**46.057**	5.677	1.335	**7.012**
NTS9	Harmony House/St. Cuthbert House, Melrose	16.589	5.339	**21.928**	45.543	5.757	**51.300**	62.361	5.588	**67.949**	0.867	0.280	**1.147**	29.214	0.454	**29.668**	45.772	0.249	**46.021**	6.923	1.974	**8.897**
NTS10	Hamilton House, East Lothian	26.473	8.838	**35.311**	55.779	9.283	**65.062**	72.245	9.099	**81.344**	3.647	0.763	**4.410**	28.912	0.375	**29.287**	45.772	0.261	**46.033**	4.511	1.109	**5.620**
	The City of Edinburgh Council (CEC)																					
CEC1	15 Hillside Crescent & 30-32 Hillside Street	17.130	6.945	**24.075**	46.385	7.487	**53.872**	62.902	7.220	**70.122**	1.260	0.382	**1.642**	28.950	0.451	**29.401**	45.772	0.275	**46.047**	4.951	1.551	**6.502**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	17.130	6.945	**24.075**	46.385	7.487	**53.872**	62.902	7.220	**70.122**	1.260	0.382	**1.642**	28.950	0.451	**29.401**	45.772	0.275	**46.047**	4.951	1.551	**6.502**
CEC3	21-31 Hillside Street	17.130	6.945	**24.075**	46.385	7.487	**53.872**	62.902	7.220	**70.122**	1.260	0.382	**1.642**	28.950	0.451	**29.401**	45.772	0.275	**46.047**	4.951	1.551	**6.502**
CEC4	22-30 Shandwick Place, Edinburgh	17.559	7.124	**24.683**	46.814	7.667	**54.481**	63.331	7.399	**70.730**	1.260	0.381	**1.641**	28.950	0.452	**29.402**	45.772	0.275	**46.047**	4.951	1.538	**6.489**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	17.674	7.320	**24.994**	46.929	7.850	**54.779**	63.446	7.580	**71.026**	1.260	0.381	**1.641**	28.950	0.437	**29.387**	45.772	0.260	**46.032**	4.951	1.538	**6.489**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	17.559	7.222	**24.781**	46.814	7.752	**54.566**	63.331	7.482	**70.813**	1.260	0.381	**1.641**	28.950	0.437	**29.387**	45.772	0.260	**46.032**	4.951	1.538	**6.489**
CEC6	36-42 Forbes Road, Edinburgh	17.674	7.320	**24.994**	46.929	7.850	**54.779**	63.446	7.580	**71.026**	1.260	0.381	**1.641**	28.950	0.436	**29.386**	45.772	0.260	**46.032**	4.951	1.538	**6.489**
CEC7	4-11 Elm Row, Edinburgh	17.610	13.440	**31.050**	46.865	13.967	**60.832**	63.382	13.699	**77.081**	1.260	0.382	**1.642**	28.950	0.434	**29.384**	45.772	0.259	**46.031**	6.022	1.812	**7.834**
CEC8	148-164 Bruntsfield Place, Edinburgh	17.674	7.320	**24.994**	46.929	7.850	**54.779**	63.446	7.580	**71.026**	1.260	0.381	**1.641**	28.950	0.437	**29.387**	45.772	0.260	**46.032**	6.022	1.809	**7.831**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	25.399	15.704	**41.103**	54.595	16.211	**70.806**	71.171	15.963	**87.134**	3.253	0.974	**4.227**	29.124	0.481	**29.605**	45.772	0.259	**46.031**	6.362	1.902	**8.264**
	Minimum			**21.928**			**51.300**			**67.949**			**1.147**			**29.121**			**46.015**			**4.815**
	Maximum			**43.745**			**72.998**			**89.760**			**5.257**			**29.810**			**46.077**			**8.994**
	Average			**31.561**			**61.217**			**77.601**			**2.988**			**29.417**			**46.041**			**6.900**

No. (code)	Collaborative Partners/Property	**(b) Lime Based Mortar (multi-layer plastic repair)**		
		cradle-to-gate	gate-to-site	**Total**
HS1	Doune Castle	110.112	2.840	**112.952**
HS2	Melrose Abbey	114.429	3.031	**117.460**
HS3	Glasgow Cathedral	112.119	3.264	**115.383**
HS4	Old Palace/Palace of James V, Stirling Castle	110.112	2.858	**112.970**
HS5	King's Old Building/Douglas Block, Stirling Castle	110.112	2.858	**112.970**
HS6	Great Hall/Old Parliament House, Stirling Castle	110.112	2.858	**112.970**
HS7	Craignethan Castle	110.440	2.877	**113.317**
HS8	Jedburgh Abbey	111.924	2.055	**113.979**
HS9	Linlithgow Palace	111.924	2.610	**114.534**
	National Trust for Scotland (NTS)			
NTS1	Newhailes Estate, Stable Block	111.410	3.387	**114.797**
NTS2	Newhailes Estate, Mainhouse	111.410	3.387	**114.797**
NTS3	Culross Palace	111.410	3.516	**114.926**
NTS4	Falkland Palace	111.410	3.653	**115.063**
NTS5	House of The Binns	108.309	2.658	**110.967**
NTS6	Threave House,Threave Estate, Castle Douglas	111.577	2.844	**114.421**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	111.577	2.826	**114.403**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	111.577	2.834	**114.411**
NTS9	Harmony House/St. Cuthbert House, Melrose	113.540	3.760	**117.300**
NTS10	Hamilton House, East Lothian	109.747	2.453	**112.200**
	The City of Edinburgh Council (CEC)			
CEC1	15 Hillside Crescent & 30-32 Hillside Street	110.440	3.189	**113.629**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	110.440	3.189	**113.629**
CEC3	21-31 Hillside Street	110.440	3.189	**113.629**
CEC4	22-30 Shandwick Place, Edinburgh	110.440	3.168	**113.608**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	110.440	3.126	**113.566**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	110.440	3.126	**113.566**
CEC6	36-42 Forbes Road, Edinburgh	110.440	3.128	**113.568**
CEC7	4-11 Elm Row, Edinburgh	112.119	3.551	**115.670**
CEC8	148-164 Bruntsfield Place, Edinburgh	112.119	3.552	**115.671**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	112.653	3.695	**116.348**
	Minimum			**110.967**
	Maximum			**117.460**
	Average			**114.230**

Source: Author, 2012.

Appendix K: Total Embodied Carbon Expenditure ($kgCO_2e/kg$) for Stone Masonry Wall Repair Within 'Cradle-to-Gate'

Table K.1: Total embodied carbon expenditure ($kgCO_2e/kg$) for stone masonry wall repair within 'cradle-to-gate' and 2001-2010 maintenance periods

		Repair Techniques/Embodied Carbon Expenditure Within 'Cradle-to-Gate' Boundaries and 2001-2010 Maintenance Periods													
		(1) Natural Stone Replacement				**(2) Repointing**		**(3) Pinning and consolidation**			**(4) Plastic repair**				
No. (code)	**Property**	(a) Indenting using lime grout mix	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin	**Total $kgCO_2e/kg$ [Total 1]**	*Using lime mortar	**Total $kgCO_2e/kg$ [Total 2]**	(a) Using stainless steel dowels and lime grout mix	(b) Using stainless steel dowels and epoxy resin	**Total $kgCO_2e/kg$ [Total 3]**	(a) Using lime based mortar and aggregates	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair	**Total $kgCO_2e/kg$ [Total 4]**	**Cumulative embodied carbon expenditure ($kgCO_2e/kg$) [Total 1 + 2 + 3 + 4]**	
	Historic Scotland														
HS1	Doune Castle	22.767	129.235	102.809	**254.811**	594.100	**594.100**	4407.777	457.720	**4865.497**	407.984	1871.904	**2279.888**	**7994.296**	
HS2	Melrose Abbey	123.735	53.928	141.038	**318.701**	6909.840	**6909.840**	15068.560	5117.309	**20185.869**	2247.300	6865.740	**9113.040**	**36527.450**	
HS3	Glasgow Cathedral	457.660	207.608	274.620	**939.888**	125.424	**125.424**	10918.530	3204.040	**14122.570**	90.330	672.714	**763.044**	**15950.926**	
HS4	Old Palace/Palace of James V, Stirling Castle	478.107	310.164	42.494	**830.765**	1035.105	**1035.105**	2592.810	366.176	**2958.986**	170.784	2973.024	**3143.808**	**7968.664**	
HS5	King's Old Building/Douglas Block, Stirling Castle	45.534	51.694	7.539	**104.767**	98.255	**98.255**	1152.360	503.492	**1655.852**	123.344	440.448	**563.792**	**2422.666**	
HS6	Great Hall/Old Parliament House, Stirling Castle	364.272	413.552	52.775	**830.599**	1407.560	**1407.560**	1728.540	503.492	**2232.032**	735.320	6496.608	**7231.928**	**11702.119**	
HS7	Craignethan Castle	434.380	304.224	253.091	**991.695**	1871.733	**1871.733**	5054.876	343.290	**5398.166**	782.258	331.320	**1113.578**	**9375.172**	
HS8	Jedburgh Abbey	139.414	65.178	51.206	**255.798**	418.587	**418.587**	1566.392	514.935	**2081.327**	486.585	2126.556	**2613.141**	**5368.853**	
HS9	Linlithgow Palace	219.159	319.410	175.308	**713.877**	10601.010	**10601.010**	577.380	915.440	**1492.820**	353.880	3357.720	**3711.600**	**16519.307**	
	National Trust for Scotland (NTS)														
NTS1	Newhailes Estate, Stable Block	138.885	171.576	147.098	**457.559**	2065.624	**2065.624**	2923.700	947.480	**3871.180**	676.634	584.903	**1261.537**	**7655.900**	
NTS2	Newhailes Estate, Mainhouse	91.220	95.318	51.213	**237.751**	594.135	**594.135**	1754.220	1693.564	**3447.784**	376.464	4902.040	**5278.504**	**9558.174**	
NTS3	Culross Palace	416.655	285.960	294.931	**997.546**	3354.925	**3354.925**	1169.480	367.091	**1536.571**	267.423	2674.954	**2942.377**	**8831.419**	
NTS4	Falkland Palace	1388.850	1715.760	561.914	**3666.524**	4735.682	**4735.682**	6139.770	4705.819	**10845.589**	556.900	3570.691	**4127.591**	**23375.386**	
NTS5	House of The Binns	1111.080	2287.680	703.864	**4102.624**	5036.403	**5036.403**	2923.700	4577.200	**7500.900**	359.500	7442.994	**7802.494**	**24442.421**	
NTS6	Threave House,Threave Estate, Castle Douglas	1025.350	1494.390	187.570	**2707.310**	1145.545	**1145.545**	1445.600	1811.198	**3256.798**	340.620	4463.080	**4803.700**	**11913.353**	
NTS7	Gate Lodge, Threave Estate, Castle Douglas	105.892	167.337	154.604	**427.833**	145.880	**145.880**	433.680	270.513	**704.193**	113.540	397.214	**510.754**	**1788.660**	
NTS8	Kilton Mains, Threave Estate, Castle Douglas	529.460	836.685	182.057	**1548.202**	729.400	**729.400**	1156.480	962.585	**2119.065**	397.390	1771.843	**2169.233**	**6565.900**	
NTS9	Harmony House/St. Cuthbert House, Melrose	49.767	91.086	37.417	**178.270**	26.010	**26.010**	204.498	42.110	**246.608**	83.076	681.240	**764.316**	**1215.204**	
NTS10	Hamilton House, East Lothian	264.730	223.116	182.780	**670.626**	162.547	**162.547**	289.120	298.891	**588.011**	180.440	501.544	**681.984**	**2103.168**	
	The City of Edinburgh Council (CEC)														
CEC1	15 Hillside Crescent & 30-32 Hillside Street	232.968	222.648	113.224	**568.840**	34.650	**34.650**	289.500	194.531	**484.031**	23.697	231.924	**255.621**	**1343.142**	
CEC2	15, 16, 16A, 17-19 Hillside Crescent	102.780	148.432	138.384	**389.596**	19.278	**19.278**	463.200	91.544	**554.744**	24.755	33.132	**57.887**	**1021.505**	
CEC3	21-31 Hillside Street	119.910	324.695	50.322	**494.927**	142.254	**142.254**	289.500	320.404	**609.904**	99.020	331.320	**430.340**	**1677.425**	
CEC4	22-30 Shandwick Place, Edinburgh	1888.471	399.323	1165.291	**3453.085**	513.236	**513.236**	4689.033	327.728	**5016.761**	84.167	1656.600	**1740.767**	**10723.849**	
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	199.364	170.353	130.698	**500.415**	170.100	**170.100**	2316.000	1968.196	**4284.196**	0.000	159.034	**159.034**	**5113.745**	
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	46.883	0.000	0.000	**46.883**	267.422	**267.422**	320.187	320.404	**640.591**	2633.932	0.000	**2633.932**	**3588.828**	
CEC6	36-42 Forbes Road, Edinburgh	300.458	516.219	164.325	**981.002**	63.000	**63.000**	144.750	91.544	**236.294**	49.510	552.200	**601.710**	**1882.006**	
CEC7	4-11 Elm Row, Edinburgh	786.991	505.205	171.131	**1463.327**	76.003	**76.003**	2616.212	577.643	**3193.855**	60.220	20.181	**80.401**	**4813.586**	
CEC8	148-164 Bruntsfield Place, Edinburgh	627.427	342.582	4.441	**974.450**	270.724	**270.724**	9.843	6.408	**16.251**	128.269	700.743	**829.012**	**2090.437**	
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	436.609	117.379	118.856	**672.844**	1922.523	**1922.523**	1182.143	119.923	**1302.066**	108.154	1802.448	**1910.602**	**5808.035**	
	Minimum	22.767	0.000	0.000	**46.883**	19.278	**19.278**	9.843	6.408	**16.251**	0.000	0.000	**57.887**	**1021.505**	
	Maximum	1888.471	2287.680	1165.291	**4102.624**	10601.010	**10601.010**	15068.560	5117.309	**20185.869**	2633.932	7442.994	**9113.040**	**36527.450**	
	Average	453.549	459.949	220.203	**1094.517**	1779.266	**1779.266**	2867.943	1185.303	**4053.246**	470.820	2098.617	**2540.211**	**9254.534**	

Source: Author, 2012.

Appendix L: Total Embodied Carbon Expenditure ($kgCO_2e/kg$) for Stone Masonry Wall Repair Within 'Gate-to-Site'

Table L.1: Total embodied carbon expenditure ($kgCO_2e/kg$) for stone masonry wall repair within 'gate-to-site' and 2001-2010 maintenance periods

		Repair techniques/Embodied Carbon Expenditure Within 'Gate-to-Site Boundaries and 2001-2010 Maintenance Periods												
		(1) Natural Stone Replacement				**(2) Repointing**		**(3) Pinning and consolidation**			**(4) Plastic repair**			
No. (code)	**Property**	(a) Indenting using lime grout mix	(b) Indenting using lime grout mix and secondary fixing of stainless steel dowels and lime grout mix	(c) Indenting using lime grout mix and secondary fixing of stainless steel dowels and epoxy resin	**Total $kgCO_2e/kg$ [Total 1]**	*Using lime mortar	**Total $kgCO_2e/kg$ [Total 2]**	(a) Using stainless steel dowels and lime grout mix	(b) Using stainless steel dowels and epoxy resin	**Total $kgCO_2e/kg$ [Total 3]**	(a) Using lime based mortar and aggregates	(b) Using lime based mortar with aggregates + stainless steel dowels + epoxy resin + non-ferrous wire) for multi-layer plastic repair	**Total $kgCO_2e/kg$ [Total 4]**	**Overall total embodied carbon expended ($kgCO_2e/kg$) [Total 1 + 2 + 3 + 4]**
	Historic Scotland													
HS1	Doune Castle	9.086	23.783	14.055	**46.924**	141.180	**141.180**	63.801	2.840	**66.641**	112.316	48.280	**160.596**	**416.061**
HS2	Melrose Abbey	33.405	7.075	13.870	**54.350**	1466.640	**1466.640**	182.520	28.397	**210.917**	450.900	181.860	**632.760**	**2344.027**
HS3	Glasgow Cathedral	169.180	35.616	34.908	**239.704**	33.360	**33.360**	155.358	18.760	**174.118**	24.135	19.584	**43.719**	**490.901**
HS4	Old Palace/Palace of James V, Stirling Castle	194.733	58.254	5.918	**258.905**	271.800	**271.800**	37.350	2.176	**39.526**	48.096	77.166	**125.262**	**695.493**
HS5	King's Old Building/Douglas Block, Stirling Castle	18.546	9.709	1.050	**29.305**	25.800	**25.800**	16.600	2.992	**19.592**	34.736	11.432	**46.168**	**120.865**
HS6	Great Hall/Old Parliament House, Stirling Castle	148.368	77.672	7.350	**233.390**	369.600	**369.600**	24.900	2.992	**27.892**	207.080	168.622	**375.702**	**1006.584**
HS7	Craignethan Castle	210.700	65.790	40.474	**316.964**	533.707	**533.707**	69.650	1.935	**71.585**	218.514	8.631	**227.145**	**1149.401**
HS8	Jedburgh Abbey	101.184	22.420	13.421	**137.025**	60.513	**60.513**	14.878	2.734	**17.612**	74.498	39.045	**113.543**	**328.693**
HS9	Linlithgow Palace	141.309	96.498	39.958	**277.765**	1973.090	**1973.090**	7.820	5.640	**13.460**	69.840	78.300	**148.140**	**2412.455**
	National Trust for Scotland (NTS)													
NTS1	Newhailes Estate, Stable Block	49.605	31.476	20.366	**101.447**	620.302	**620.302**	51.800	5.423	**57.223**	206.793	883.427	**1090.220**	**1869.192**
NTS2	Newhailes Estate, Mainhouse	35.295	15.260	5.857	**56.412**	178.605	**178.605**	31.080	9.694	**40.774**	115.055	149.028	**264.083**	**539.874**
NTS3	Culross Palace	183.465	64.210	50.173	**297.848**	1006.644	**1006.644**	22.400	2.254	**24.654**	83.603	84.419	**168.022**	**1497.168**
NTS4	Falkland Palace	605.900	382.200	94.912	**1083.012**	1431.499	**1431.499**	120.330	31.357	**151.687**	179.400	117.079	**296.479**	**2962.677**
NTS5	House of The Binns	486.720	510.440	119.003	**1116.163**	1523.649	**1523.649**	54.300	26.700	**81.000**	122.000	182.658	**304.658**	**2538.750**
NTS6	Threave House,Threave Estate, Castle Douglas	344.050	220.350	20.280	**584.680**	282.353	**282.353**	18.000	11.277	**29.277**	80.400	113.760	**194.160**	**1090.470**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	33.352	26.403	18.453	**78.208**	35.800	**35.800**	5.385	1.684	**7.069**	26.580	10.061	**36.641**	**157.718**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	166.900	132.120	21.748	**320.768**	179.600	**179.600**	14.360	5.994	**20.354**	93.450	45.004	**138.454**	**659.176**
NTS9	Harmony House/St. Cuthbert House, Melrose	16.017	11.514	3.353	**30.884**	8.400	**8.400**	3.178	0.229	**3.407**	23.688	22.560	**46.248**	**88.939**
NTS10	Hamilton House, East Lothian	88.380	37.132	23.020	**148.532**	34.007	**34.007**	3.750	1.704	**5.454**	44.360	11.210	**55.570**	**243.563**
	The City of Edinburgh Council (CEC)													
CEC1	15 Hillside Crescent & 30-32 Hillside Street	94.452	35.934	12.996	**143.382**	10.505	**10.505**	4.510	1.917	**6.427**	7.290	6.697	**13.987**	**174.301**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	41.670	23.958	15.884	**81.512**	5.845	**5.845**	7.216	0.550	**7.766**	7.755	0.957	**8.712**	**103.835**
CEC3	21-31 Hillside Street	48.615	52.409	5.776	**106.800**	43.128	**43.128**	4.510	1.925	**6.435**	31.020	9.567	**40.587**	**196.950**
CEC4	22-30 Shandwick Place, Edinburgh	766.186	65.400	136.141	**967.727**	155.193	**155.193**	73.210	1.970	**75.180**	26.146	47.520	**73.666**	**1271.766**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	83.047	28.496	15.615	**127.158**	51.435	**51.435**	34.960	11.180	**46.140**	0.000	4.501	**4.501**	**229.234**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	19.283	0.000	0.000	**19.283**	60.289	**60.289**	4.833	1.820	**6.653**	818.216	0.000	**818.216**	**904.441**
CEC6	36-42 Forbes Road, Edinburgh	124.440	86.350	19.632	**230.422**	19.050	**19.050**	2.180	0.520	**2.700**	15.380	15.640	**31.020**	**283.192**
CEC7	4-11 Elm Row, Edinburgh	600.633	139.670	36.987	**777.290**	23.042	**23.042**	39.221	3.269	**42.490**	18.120	0.639	**18.759**	**861.581**
CEC8	148-164 Bruntsfield Place, Edinburgh	259.860	57.305	0.531	**317.696**	81.862	**81.862**	0.148	0.036	**0.184**	38.532	22.200	**60.732**	**460.474**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	269.952	34.854	26.658	**331.464**	575.634	**575.634**	19.524	0.678	**20.202**	32.334	59.120	**91.454**	**1018.754**
	Minimum	9.086	0.000	0.000	**19.283**	5.845	**5.845**	0.148	0.036	**0.184**	0.000	0.000	**4.501**	**88.939**
	Maximum	766.186	510.440	136.141	**1116.163**	1973.090	**1973.090**	182.520	31.357	**210.917**	818.216	883.427	**1090.220**	**2962.677**
	Average	197.407	92.346	30.791	**311.305**	425.209	**425.209**	40.982	7.098	**47.985**	129.950	106.529	**216.901**	**940.908**

Source: Author, 2012.

Appendix M: Cumulative Embodied Carbon Expenditure for Stone Masonry Wall Repair Within ‘Cradle-to-Site’

Table M.1: Cumulative embodied carbon expenditure for stone masonry wall repair within ‘cradle-to-site’ and 2001-2010 maintenance periods

		CumulativeEmbodied Carbon Expenditure (kgCO$_2$e/kg) Within 'Cradle-to-Site' Boundaries and 2001-2010 Maintenance Periods								
		Replacement			**Repointing**	**Pinning and Consolidation**		**Plastic Repair**		
	Collaborative Partners/Property	(a) Indenting + Lime Mortar Grout Mix	(b) Indenting+ Dowels + Lime Grout Mix	(c) Dowels + Epoxy Resin	Lime Mortar	(a) Dowels + Lime Grout Mix	(b) Dowels + Epoxy Resin	(a) Lime Base Mortar + Aggregates	(b) Lime Base Mortar (multi-layer plastic repair)	**Cumulative (kgCO$_2$e/kg)**
No. (code)	**Historic Scotland**									
HS1	Doune Castle	31.853	153.018	116.864	735.280	4471.578	460.560	520.300	1920.184	**8409.637**
HS2	Melrose Abbey	157.140	61.003	154.908	8376.480	15251.080	5145.706	2698.200	7047.600	**38892.117**
HS3	Glasgow Cathedral	626.840	243.224	309.528	158.784	11073.888	3222.800	114.465	692.298	**16441.827**
HS4	Old Palace/Palace of James V, Stirling Castle	672.840	368.418	48.412	1306.905	2630.160	368.352	218.880	3050.190	**8664.157**
HS5	King's Old Building/Douglas Block, Stirling Castle	64.080	61.403	8.589	124.055	1168.960	506.484	158.080	451.880	**2543.531**
HS6	Great Hall/Old Parliament House, Stirling Castle	512.640	491.224	60.125	1777.160	1753.440	506.484	942.400	6665.230	**12708.703**
HS7	Craignethan Castle	645.080	370.014	293.565	2405.440	5124.526	345.225	1000.772	339.951	**10524.573**
HS8	Jedburgh Abbey	240.598	87.598	64.627	479.100	1581.270	517.669	561.083	2165.601	**5697.546**
HS9	Linlithgow Palace	360.468	415.908	215.266	12574.100	585.200	921.080	423.720	3436.020	**18931.762**
	National Trust for Scotland (NTS)									
NTS1	Newhailes Estate, Stable Block	188.490	203.052	167.464	2685.926	2975.500	952.903	883.427	1468.330	**9525.092**
NTS2	Newhailes Estate, Mainhouse	126.515	110.578	57.070	772.740	1785.300	1703.258	491.519	5051.068	**10098.048**
NTS3	Culross Palace	600.120	350.170	345.104	4361.569	1191.880	369.345	351.026	2759.373	**10328.587**
NTS4	Falkland Palace	1994.750	2097.960	656.826	6167.181	6260.100	4737.176	736.300	3687.770	**26338.063**
NTS5	House of The Binns	1597.800	2798.120	822.867	6560.052	2978.000	4603.900	481.500	7625.652	**27467.891**
NTS6	Threave House,Threave Estate, Castle Douglas	1369.400	1714.740	207.850	1427.898	1463.600	1822.475	421.020	4576.840	**13003.823**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	139.244	193.740	173.057	181.680	439.065	272.197	140.120	407.275	**1946.378**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	696.360	968.805	203.805	909.000	1170.840	968.579	490.840	1816.847	**7225.076**
NTS9	Harmony House/St. Cuthbert House, Melrose	65.784	102.600	40.770	34.410	207.676	42.339	106.764	703.800	**1304.143**
NTS10	Hamilton House, East Lothian	353.110	260.248	205.800	196.554	292.870	300.595	224.800	512.754	**2346.731**
	The City of Edinburgh Council (CEC)									
CEC1	15 Hillside Crescent & 30-32 Hillside Street	327.420	258.582	126.220	45.155	294.010	196.448	30.987	238.621	**1517.443**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	144.450	172.390	154.268	25.123	470.416	92.094	32.510	34.089	**1125.340**
CEC3	21-31 Hillside Street	168.525	377.104	56.098	185.382	294.010	322.329	130.040	340.887	**1874.375**
CEC4	22-30 Shandwick Place, Edinburgh	2654.657	464.723	1301.432	668.429	4762.243	329.698	110.313	1704.120	**11995.615**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	282.411	198.849	146.313	221.535	2350.960	1979.376	0.000	163.535	**5342.979**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	66.166	0.000	0.000	327.711	325.020	322.224	3452.148	0.000	**4493.269**
CEC6	36-42 Forbes Road, Edinburgh	424.898	602.569	183.957	82.050	146.930	92.064	64.890	567.840	**2165.198**
CEC7	4-11 Elm Row, Edinburgh	1387.624	644.875	208.118	99.045	2655.433	580.912	78.340	20.820	**5675.167**
CEC8	148-164 Bruntsfield Place, Edinburgh	887.287	399.887	4.972	352.586	9.991	6.444	166.801	722.943	**2550.911**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	706.561	152.233	145.514	2498.157	1201.667	120.601	140.488	1861.568	**6826.789**
	Minimum	**31.853**	**0.000**	**0.000**	**25.123**	**9.991**	**6.444**	**0.000**	**0.000**	1125.340
	Maximum	**2654.657**	**2798.120**	**1301.432**	**12574.100**	**15251.080**	**5145.706**	**3452.148**	**7625.652**	38892.117
	Average	**650.956**	**552.295**	**250.994**	**2204.475**	**2908.925**	**1192.305**	**600.770**	**2182.540**	10192.975

Source: Author, 2012.

Appendix N: Normalised Embodied Carbon Expenditure [(Total kgCO_2e/kg/(Total m^2)] for Stone Masonry Wall Repair Within ‘Cradle-to-Site’

Table N.1: Normalised embodied carbon expenditure [(Total kgco_2e/kg)/(Total m^2)] for stone masonry wall repair within ‘cradle-to-site’ and 2001-2010 maintenance periods

		Normalised Embodied Carbon Expenditure [(Total kgCO_2e/kg)/(Total m^2)] Within 'Cradle-to-Site' Boundaries and 2001-2010 Maintenance Periods										
		Replacement			Repointing	Pinning and Consolidation		Plastic Repair				
	Collaborative Partners/Property	(a) Indenting + Lime Mortar Grout Mix	(b) Indenting + Dowels + Lime Grout Mix	(c) Dowels + Epoxy Resin	Lime Mortar	(a) Dowels + Lime Grout Mix	(b) Dowels + Epoxy Resin	(a) Lime Based Mortar + Aggregates	(b) Lime Based Mortar (multi-layer plastic repair)	**Normalised [(Total kgCO_2e/kg)/(Total m^2)]**		
No. (code)	**Historic Scotland**									**Minimum**	**Maximum**	**Average**
HS1	Doune Castle	31.853	61.207	77.909	2.828	29.226	46.056	6.050	112.952	**2.828**	**112.952**	**48.386**
HS2	Melrose Abbey	31.428	61.003	77.454	3.878	29.329	46.026	8.994	117.460	**3.878**	**117.460**	**49.691**
HS3	Glasgow Cathedral	31.342	60.806	77.382	3.308	29.296	46.040	7.631	115.383	**3.308**	**115.383**	**48.988**
HS4	Old Palace/Palace of James V, Stirling Castle	32.040	61.403	78.084	2.885	29.224	46.044	6.080	112.970	**2.885**	**112.970**	**48.458**
HS5	King's Old Building/Douglas Block, Stirling Castle	32.040	61.403	78.082	2.885	29.224	46.044	6.080	112.970	**2.885**	**112.970**	**48.458**
HS6	Great Hall/Old Parliament House, Stirling Castle	32.040	61.403	78.084	2.885	29.224	46.044	6.080	112.970	**2.885**	**112.970**	**48.459**
HS7	Craignethan Castle	32.254	61.669	78.284	3.200	29.283	46.030	6.334	113.317	**3.200**	**113.317**	**48.689**
HS8	Jedburgh Abbey	43.745	72.998	89.760	2.779	29.121	46.015	6.801	113.979	**2.779**	**113.979**	**52.196**
HS9	Linlithgow Palace	40.052	69.318	86.106	2.530	29.260	46.054	7.062	114.534	**2.530**	**114.534**	**51.198**
	National Trust for Scotland (NTS)											
NTS1	Newhailes Estate, Stable Block	37.698	67.684	83.732	5.248	29.755	46.034	7.271	279.682	**5.248**	**279.682**	**84.203**
NTS2	Newhailes Estate, Mainhouse	25.303	55.289	71.338	1.908	29.755	46.034	7.271	114.797	**1.908**	**114.797**	**46.840**
NTS3	Culross Palace	40.008	70.034	86.061	5.247	29.797	46.053	7.310	114.926	**5.247**	**114.926**	**51.961**
NTS4	Falkland Palace	39.895	69.932	85.972	5.256	29.810	46.077	7.363	115.063	**5.256**	**115.063**	**51.969**
NTS5	House of The Binns	39.945	69.953	85.984	5.257	29.780	46.039	4.815	110.967	**4.815**	**110.967**	**50.852**
NTS6	Threave House,Threave Estate, Castle Douglas	27.388	57.158	73.445	2.478	29.272	46.057	7.017	114.421	**2.478**	**114.421**	**47.414**
NTS7	Gate Lodge, Threave Estate, Castle Douglas	34.811	64.580	80.868	4.542	29.271	46.057	7.006	114.403	**4.542**	**114.403**	**50.048**
NTS8	Kilton Mains, Threave Estate, Castle Douglas	34.818	64.587	80.875	4.545	29.271	46.057	7.012	114.411	**4.545**	**114.411**	**50.053**
NTS9	Harmony House/St. Cuthbert House, Melrose	21.928	51.300	67.950	1.147	29.668	46.021	8.897	117.300	**1.147**	**117.300**	**46.266**
NTS10	Hamilton House, East Lothian	35.311	65.062	81.344	4.410	29.287	46.033	5.620	112.200	**4.410**	**112.200**	**49.588**
	The City of Edinburgh Council (CEC)											
CEC1	15 Hillside Crescent & 30-32 Hillside Street	24.075	53.871	70.122	1.642	29.401	46.223	6.593	113.629	**1.642**	**113.629**	**46.083**
CEC2	15, 16, 16A, 17-19 Hillside Crescent	24.075	53.872	70.122	1.642	29.401	46.047	6.502	113.630	**1.642**	**113.630**	**46.056**
CEC3	21-31 Hillside Street	24.075	53.872	70.123	1.642	29.401	46.047	6.502	113.629	**1.642**	**113.629**	**46.056**
CEC4	22-30 Shandwick Place, Edinburgh	24.683	54.481	70.730	1.641	29.402	46.047	6.489	113.608	**1.641**	**113.608**	**46.233**
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	25.036	54.779	71.026	1.641	29.387	46.032	0.000	113.566	**0.000**	**113.566**	**45.503**
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	24.781	0.000	0.000	1.543	29.387	46.032	6.489	0.000	**0.000**	**46.032**	**15.426**
CEC6	36-42 Forbes Road, Edinburgh	24.994	54.779	71.026	1.641	29.386	46.032	6.489	113.568	**1.641**	**113.568**	**46.312**
CEC7	4-11 Elm Row, Edinburgh	31.050	59.821	77.081	1.642	29.384	46.031	7.834	115.667	**1.642**	**115.667**	**48.582**
CEC8	148-164 Bruntsfield Place, Edinburgh	24.994	10.523	71.029	1.641	29.385	46.029	7.831	115.671	**1.641**	**115.671**	**42.441**
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	41.103	70.806	87.134	4.227	29.605	46.031	8.264	116.348	**4.227**	**116.348**	**52.409**
	Overall Minimum	**21.928**	**0.000**	**0.000**	**1.147**	**29.121**	**46.015**	**0.000**	**0.000**			
	Overall Maximum	**43.745**	**72.998**	**89.760**	**5.257**	**29.810**	**46.223**	**8.994**	**279.682**			
	Overall Average	**31.563**	**56.342**	**73.125**	**2.985**	**29.417**	**46.052**	**6.538**	**117.539**			

Source: Author, 2012.

Appendix O: Percentage of Embodied Carbon Expenditure Within ‘Cradle-to-Site’ Boundaries and 2001-2010 Maintenance Periods

Table O.1: Percentage of embodied carbon expenditure within ‘cradle-to-site’ boundaries and 2001-2010 maintenance periods

		Percentage (%) of Embodied Carbon Expenditure Within 'Cradle-to-Site' Boundaries and 2001-2010 Maintenance Periods															
		Replacement						**Repointing**		**Pinning and Consolidation**				**Plastic Repair**			
	Collaborative Partners/Property	(a) Indenting + Lime Mortar Grout Mix		(b) Indenting+ Dowels + Lime Grout Mix		(c) Dowels + Epoxy Resin		Lime Mortar		(a) Dowels + Lime Grout Mix		(b) Dowels + Epoxy Resin		(a) Lime Based Mortar + Aggregates		(b) Lime Based Mortar (multi-layer plastic repair)	
No. (code)	**Historic Scotland**	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site	cradle-to-gate	gate-to-site
HS1	Doune Castle	71.48%	28.52%	84.46%	15.54%	87.97%	12.03%	80.80%	19.20%	98.57%	1.43%	99.38%	0.62%	78.41%	21.59%	97.49%	2.51%
HS2	Melrose Abbey	78.74%	21.26%	88.40%	11.60%	91.05%	8.95%	82.49%	17.51%	98.80%	1.20%	99.45%	0.55%	83.29%	16.71%	97.42%	2.58%
HS3	Glasgow Cathedral	73.01%	26.99%	85.36%	14.64%	88.72%	11.28%	78.99%	21.01%	98.60%	1.40%	99.42%	0.58%	78.91%	20.09%	97.17%	2.83%
HS4	Old Palace/Palace of James V, Stirling Castle	71.06%	28.94%	84.19%	15.81%	87.78%	12.22%	79.20%	20.80%	98.58%	1.42%	99.41%	0.59%	78.03%	21.97%	97.47%	2.53%
HS5	King's Old Building/Douglas Block, Stirling Castle	71.06%	28.94%	84.19%	15.81%	87.78%	12.22%	79.20%	20.80%	98.58%	1.42%	99.41%	0.59%	78.03%	21.97%	97.47%	2.53%
HS6	Great Hall/Old Parliament House, Stirling Castle	71.06%	28.94%	84.19%	15.81%	87.78%	12.22%	79.20%	20.80%	98.58%	1.42%	99.41%	0.59%	78.03%	21.97%	97.47%	2.53%
HS7	Craignethan Castle	67.34%	32.66%	82.22%	17.78%	86.21%	13.79%	77.81%	22.19%	98.64%	1.36%	99.44%	0.56%	78.17%	21.83%	97.46%	2.54%
HS8	Jedburgh Abbey	57.94%	42.06%	74.41%	25.59%	79.23%	20.77%	87.37%	12.63%	99.06%	0.94%	99.47%	0.53%	86.72%	13.28%	98.20%	1.80%
HS9	Linlithgow Palace	60.80%	39.20%	76.80%	23.20%	81.44%	18.56%	84.31%	15.69%	98.66%	1.34%	99.39%	0.61%	83.52%	16.48%	97.72%	2.28%
	Minimum (%)	**57.94%**	**21.26%**	**74.41%**	**11.60%**	**79.23%**	**8.95%**	**77.81%**	**12.63%**	**98.57%**	**0.94%**	**99.38%**	**0.53%**	**78.03%**	**13.28%**	**97.17%**	**1.80%**
	Maximum (%)	**78.74%**	**42.06%**	**88.40%**	**25.59%**	**91.05%**	**20.77%**	**87.37%**	**22.19%**	**99.06%**	**1.43%**	**99.47%**	**0.62%**	**86.72%**	**21.97%**	**98.20%**	**2.83%**
	Average (%)	**69.02%**	**30.98%**	**82.46%**	**17.54%**	**86.20%**	**13.80%**	**81.32%**	**18.68%**	**98.70%**	**1.30%**	**99.42%**	**0.58%**	**80.71%**	**19.19%**	**97.57%**	**2.43%**
	National Trust for Scotland (NTS)																
NTS1	Newhailes Estate, Stable Block	73.68%	26.32%	84.50%	15.50%	87.84%	12.16%	76.91%	23.09%	98.26%	1.74%	99.43%	0.57%	76.59%	23.41%	39.83%	60.17%
NTS2	Newhailes Estate, Mainhouse	72.10%	27.90%	86.20%	13.80%	89.74%	10.26%	76.89%	23.11%	98.26%	1.74%	99.43%	0.57%	76.59%	23.41%	97.05%	2.95%
NTS3	Culross Palace	69.43%	30.57%	81.66%	18.34%	85.46%	14.54%	76.92%	23.08%	98.12%	1.88%	99.39%	0.61%	76.18%	23.82%	96.94%	3.06%
NTS4	Falkland Palace	69.63%	30.37%	81.78%	18.22%	85.55%	14.45%	76.79%	23.21%	98.08%	1.92%	99.34%	0.66%	75.63%	24.37%	96.83%	3.17%
NTS5	House of The Binns	69.54%	30.46%	81.76%	18.24%	85.54%	14.46%	76.77%	23.23%	98.18%	1.82%	99.42%	0.58%	74.66%	25.34%	97.60%	2.40%
NTS6	Threave House,Threave Estate, Castle Douglas	74.88%	25.12%	87.15%	12.85%	90.24%	9.76%	80.23%	19.77%	98.77%	1.23%	99.38%	0.62%	80.90%	19.10%	97.51%	2.49%
NTS7	Gate Lodge, Threave Estate, Castle Douglas	76.05%	23.95%	86.37%	13.63%	89.34%	10.66%	80.30%	19.70%	98.77%	1.23%	99.38%	0.62%	81.03%	18.97%	97.53%	2.47%
NTS8	Kilton Mains, Threave Estate, Castle Douglas	76.03%	23.97%	86.36%	13.64%	89.32%	10.67%	80.24%	19.76%	98.77%	1.23%	99.38%	0.62%	80.96%	19.04%	97.52%	2.48%
NTS9	Harmony House/St. Cuthbert House, Melrose	75.65%	24.35%	88.78%	11.22%	91.78%	8.22%	75.59%	24.41%	98.47%	1.53%	99.46%	0.54%	77.81%	22.19%	96.79%	3.21%
NTS10	Hamilton House, East Lothian	74.97%	25.03%	85.73%	14.27%	88.81%	11.19%	82.70%	17.30%	98.72%	1.28%	99.43%	0.57%	80.27%	19.73%	97.81%	2.19%
	Minimum (%)	**69.43%**	**23.95%**	**81.66%**	**11.22%**	**85.46%**	**8.22%**	**75.59%**	**17.30%**	**98.08%**	**1.23%**	**99.34%**	**0.54%**	**74.66%**	**18.97%**	**39.83%**	**2.19%**
	Maximum (%)	**76.05%**	**30.57%**	**88.78%**	**18.34%**	**91.78%**	**14.54%**	**82.70%**	**24.41%**	**98.77%**	**1.92%**	**99.46%**	**0.66%**	**81.03%**	**25.34%**	**97.81%**	**60.17%**
	Average (%)	**73.12%**	**26.88%**	**85.06%**	**14.94%**	**88.41%**	**11.59%**	**78.47%**	**21.53%**	**98.44%**	**1.56%**	**99.40%**	**0.60%**	**78.03%**	**21.97%**	**87.75%**	**12.25%**
	The City of Edinburgh Council (CEC)																
CEC1	15 Hillside Crescent & 30-32 Hillside Street	71.15%	28.25%	86.10%	13.90%	89.70%	10.30%	76.74%	23.26%	98.47%	1.53%	99.02%	0.98%	76.47%	23.53%	97.19%	2.81%
CEC2	15, 16, 16A, 17-19 Hillside Crescent	71.15%	28.85%	86.10%	13.90%	89.70%	10.30%	76.73%	23.27%	98.47%	1.53%	99.40%	0.60%	76.15%	23.85%	97.19%	2.81%
CEC3	21-31 Hillside Street	71.15%	28.85%	86.10%	13.90%	89.70%	10.30%	76.74%	23.26%	98.47%	1.53%	99.40%	0.60%	76.15%	23.85%	97.19%	2.81%
CEC4	22-30 Shandwick Place, Edinburgh	71.14%	28.86%	85.93%	14.07%	89.54%	10.46%	76.78%	23.22%	98.46%	1.54%	99.40%	0.60%	76.30%	23.70%	97.21%	2.79%
CEC5	131-141 Bruntsfield Place, Edinburgh (Stone Type A)	70.59%	29.41%	85.67%	14.33%	89.33%	10.67%	76.78%	23.22%	98.51%	1.49%	99.44%	0.56%	0.00%	0.00%	97.25%	2.75%
	131-141 Bruntsfield Place, Edinburgh (Stone Type B)	70.86%	29.14%	0.00%	0.00%	0.00%	0.00%	81.60%	18.40%	98.51%	1.49%	99.44%	0.56%	76.30%	23.70%	0.00%	0.00%
CEC6	36-42 Forbes Road, Edinburgh	70.71%	29.29%	85.67%	14.33%	89.33%	10.67%	76.78%	23.22%	98.52%	1.48%	99.44%	0.56%	76.30%	23.70%	97.25%	2.75%
CEC7	4-11 Elm Row, Edinburgh	56.72%	43.28%	78.34%	21.66%	82.23%	17.77%	76.74%	23.26%	98.52%	1.48%	99.44%	0.56%	76.87%	23.13%	96.93%	3.07%
CEC8	148-164 Bruntsfield Place, Edinburgh	70.71%	29.29%	85.67%	14.33%	89.32%	10.68%	76.78%	23.22%	98.52%	1.48%	99.44%	0.56%	76.90%	23.10%	96.93%	3.07%
CEC9	20-24A Frederick Street, 71-81 Rose Street & 52 Rose Street Lane, Edinburgh	61.79%	38.21%	77.10%	22.90%	81.68%	18.32%	76.96%	23.04%	98.38%	1.62%	99.44%	0.56%	76.98%	23.02%	96.82%	3.18%
	Minimum (%)	**56.72%**	**28.25%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**76.73%**	**18.40%**	**98.38%**	**1.48%**	**99.02%**	**0.56%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
	Maximum (%)	**71.15%**	**43.28%**	**86.10%**	**22.90%**	**89.70%**	**18.32%**	**81.60%**	**23.27%**	**98.52%**	**1.62%**	**99.44%**	**0.98%**	**76.98%**	**23.85%**	**97.25%**	**3.18%**
	Average (%)	**67.82%**	**32.08%**	**70.23%**	**13.85%**	**73.35%**	**10.65%**	**77.58%**	**22.42%**	**98.48%**	**1.52%**	**99.36%**	**0.64%**	**63.78%**	**19.62%**	**80.93%**	**2.44%**
	Percentage (%) across all properties																
	Minimum (%)	**56.72%**	**21.26%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**75.59%**	**12.63%**	**98.08%**	**0.94%**	**99.02%**	**0.53%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
	Maximum (%)	**78.74%**	**43.28%**	**88.78%**	**25.59%**	**91.78%**	**20.77%**	**87.37%**	**24.41%**	**99.06%**	**1.92%**	**99.47%**	**0.98%**	**86.72%**	**25.34%**	**98.20%**	**60.17%**
	Average (%)	**69.90%**	**30.07%**	**77.43%**	**15.26%**	**80.73%**	**11.89%**	**79.19%**	**20.81%**	**98.54%**	**1.46%**	**99.39%**	**0.61%**	**72.47%**	**19.91%**	**86.55%**	**7.01%**

Source: Author, 2012.

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