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GREEN MAINTENANCE FOR HERITAGE BUILDINGS: AN EMERGING CONCEPT OF EMBODIED CARBON APPRAISAL

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Abstract: *It is well accepted that maintenance is essential for long-term performance of any building. Importantly, it contributes to simultaneous retention of cultural value in historic fabric of heritage buildings. Progressively, the efficiency of maintenance interventions for heritage buildings can be assessed in terms of cost, building conservation philosophy and, increasingly, conformity to environmental sustainability. Commonly, low carbon consideration in heritage buildings is considered difficult to achieve due to their limited retrofitting capability. On the other hand, maintenance is one mechanism by which allows carbon savings, initiated through necessary repair strategies. This paper proposed Green Maintenance model for evaluating the efficacy of maintenance interventions for heritage buildings, based on embodied carbon appraisal. It utilised repair material life cycle data within cradle-to-site boundary of life cycle assessment (LCA), in the form of generated Environmental Maintenance Impact (EMI). Moreover, formulaic expressions of the model used to calculate the relative merits of selected maintenance intervention over a given time frame. Emergently, the model represents a framework for selection of maintenance interventions in relation to cost, philosophy and embodied carbon expenditure i.e. CO_2 emissions. Significantly, this integrated multi-criteria approach of maintenance decision-making enables carbon emissions to be accounted for an adoption of sustainable repair approach for heritage buildings.*

Keywords: *Green Maintenance, Heritage Buildings, Embodied Carbon Appraisal, Life Cycle Assessment (LCA), Environmental Maintenance Impact (EMI), Sustainable Repair*

Introduction

Heritage buildings were commonly defined as something which passed down from one generation to another (Fielden, 1979; 1994 and 2003; Prentice, 1993), which may comprise of buildings (UNESCO, 1972), either individual or group which are commonly associated with heritage event (Burra Charter, 2013) and inherited with cultural heritage significances and of outstanding universal values (The Commissioner of Law Revision, Malaysia, 2005). Heritage buildings were also commonly preserved to safeguard architectural values (Feilden, 1994 and 2003) and cultural resources through protection of financial, economic and societal capital invested in their historic fabric. Importantly, conservation also prolongs their life and function; involving maintenance, repair and restoration (see example of restored heritage laterite stones structures in Figure 1 and Figure 2).

Figure 1: Restored Gate of the A Famosa, Malacca, Malaysia
(Adopted from Hasbollah, 2014)

Figure 2: The Phanom Rung Temple, Buriram Province, Thailand
(Adopted from Ruangsup, 2013)

Commonly, the definition of heritage buildings is vary and contextual within regional and construction era. The definition is normally parallel with the significance of their structure, as this universally invokes statutory protection either through a listing system, associative or intrinsic value (Historic Scotland, SHEP document, 2009; 2011). English Heritage in Historic England 1990 Planning (Listed Buildings and Conservation Areas) Act 1990 defined heritage buildings as structures of special architectural and historical importance, which may inherited national importance that containing evidential values. On the other hand, Historic Scotland valued heritage buildings as local greatest assets, buildings with special architectural or historic interest which are recognised by Listed Buildings and Conservation Areas (Scotland) Act 1997 (Historic Scotland, 2011). Meanwhile, The National Trust for Scotland (NTS) appreciated heritage buildings as structures with special character and locality, comprises of any size and type and frequently originates within important historic and natural settings (NTS, 2005; 2012).

Significantly, heritage buildings not only reflect importance of previous functions as well as past activities, but also explaining the records of their historic fabric. It is well understood that their historic fabric is also commonly rooted in particular forms and means of tangibles and intangible expression. In 2013, ICOMOS Australia through Burra Charter (revised version) in Article 1, defined that historic fabric of heritage buildings may include components, contents, spaces and views. These also mean aesthetic, historic, scientific, social or spiritual values for the past, present or future generations (Burra Charter, 2013). Additionally, these can be laid on the perspective of cultural significance values, which are embodied in the building itself. Therefore, in order to safeguard these values of heritage buildings, it is crucial to optimise their long term performance.

In general, the long-term performance of any building is essentially underpinned by maintenance. Maintenance and repair are crucial to the survival and in-service use of any building (Dann and Cantell, 2007); in the form of simultaneous retention of cultural values in the historic fabric, to "stave off decay by daily care" (SPAB, 2008) and prolonging the life of building's components (Bell, 1997; Maintain our Heritage, 2004). Moreover, maintenance reduces the need for many, often unnecessary costly repairs in the longer term (UWE, 2003). Unfortunately however, the importance of maintenance in terms of reducing embodied carbon expenditure expended during repair of heritage buildings has been ignored by academia and industry alike. Generally, the approach to maintenance evaluation is not always straightforward. Historic Scotland (2008) indicated that *"there can be difficulties in identifying a generic hierarchy of maintenance interventions within historic buildings"* (Historic Scotland, 2008). Commonly, in regards to an evaluation of such repair, difficult decisions need to be taken into account to manage the relevant parameters. These include decisions on budgetary and cost restraints as well as philosophical frameworks of building conservation: reduced intervention; like for like material replacement; and, respect for traditional craft skills (Bell, 1997). However, consideration and evaluation of building maintenance in the context of environmental sustainability conformity, through repair efficiency and embodied carbon expenditure remains unclear.

Maintenance of heritage buildings is crucial in ensuring financial, environmental and social capital invested in the protection of their historic fabric is not wasted. Traditionally, maintenance has been recognised as a cost commitment associated with a building (Wise, 1984). But, any maintenance intervention also has a carbon commitment and there is an increasing international focus on reducing carbon in the built environment (Stern, 2006). However, this largely centres on new build works. Conversely, upgrading and maintenance of heritage buildings receives little attention in the context of low carbon consideration. Low carbon repair in heritage buildings is considered difficult to achieve due to their limited retrofitting capability. As previously highlighted, it is well accepted that maintenance is essentially a way of prolonging the lifespan of heritage buildings. Also, maintenance is one mechanism by which enables carbon savings, initiated through necessary strategies. Therefore, contribution of maintenance to the lifetime carbon emissions, expended from heritage buildings repair, in a way that cumulatively is significant. Moreover, associating maintenance with a life cycle carbon approach of heritage buildings repair will leads to the concept of 'green' maintenance, which can be seen as maintenance with minimal environmental impact. This can be demonstrated with maintenance regimes (example of over a period of 100 years), showing on how this concept can model the associated carbon commitment and facilitate options appraisal for heritage buildings. Significantly, this paper proposed Green Maintenance model for evaluating the efficacy of maintenance interventions for heritage buildings, based on embodied carbon appraisal that signify integration of cost, philosophy and environmental impact.

Literature Review

This section is comprised of a review of the relevant literature on the maintenance of heritage buildings from the perspectives of integration of cost, philosophy and environmental impact. The review also highlighted an association of maintenance interventions with embodied carbon expenditure. It also provides an insight into embodied carbon expenditure and its appraisal in heritage buildings repair.

Maintenance of Heritage Buildings: An integration of Cost, Philosophy and Environmental Impact

It is well recognised that protection of historic fabric of heritage buildings through maintenance is not only undertaken from a cultural perspective but also from an economic point of view. Remarkably, the scale of the importance of maintenance is reflected in the fact that 50% of Europe's national wealth is enclosed within their existing built environments (which include heritage buildings) (Balaras et al., 2005). Moreover, a combination of premature deterioration and lack of regular maintenance can extensively devalue these existing assets. In the context of United Kingdom's Gross Domestic Product (GDP), maintenance accounts for nearly half of the total expenditure on construction nationally (Balaras et al, 2005). Additionally, the UK's built environment contains 450,000 listed and 10.6 million pre-1944 buildings (Maintain Our Heritage, 2004). In 1995, the financial value of repair works to the existing built environment of UK was calculated at £30 billion (in 1995 prices). Comparatively, this figure increased to £36 billion in 2002 (at 2002 prices) [DTI, 2002; Arup, 2003]. For example, 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). Moreover, 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.

Comparatively, Malaysian Heritage Buildings Inventory by the National Museum indicated an approximately of 20787 pre-war buildings located in 162 Malaysian cities and town locally (Kayan, 2003). Of the total number of these buildings, the highest numbers of 1763 units of pre-war buildings are located within the Federal Territory of Kuala Lumpur and Putrajaya Planning Area (Kayan, 2003). Meanwhile, it was recorded that about 113 heritage buildings and structures that had been gazetted under jurisdiction of National Heritage Act 2005 (Act 645) are located within 15 states in Malaysia (Kayan, 2006). Undoubtedly, heritage buildings are important in portraying the historical past but given their age, their structures will not be standing for too long unless proper maintenance works to stave off decay are carried out. Proper maintenance strategies might lead to growth of repair market for heritage buildings.

Progressively, there is an expanding market for heritage buildings repair, i.e. economic cost is incurred for maintenance, both in the national and international context. Looking ahead, however, recognition of the contribution of maintenance should be expanded, not only to cover the protection of the historic fabric of heritage buildings and economic costs of existing built environment, but also to address the perspective embodied carbon appraisal of environmental impact. In addition to the cost perspective, this kind of investment not only provides significant advantage to the maintenance of historic fabric, but also can reduce the embodied carbon expenditure expended in maintenance intervention for heritage buildings.

Maintenance Intervention Association with Embodied Carbon Expenditure

Hammond and Jones (2008a) stated 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). It is inevitable that the resources in existing building construction are already becoming depleted. Kayan et al., (2017a and 2017b) suggest that 10% of CO_2 emissions from usage traditional material sector. The National Trust for Scotland (NTS) also echoed that, *'the greenest building is the one that is already built'* (NTS, 2005; 2012). Significantly, this statement is substantiated by the premise that an existing structure of heritage buildings negates the necessity for the expenditure of further resources in their maintenance and repair. Reducing embodied carbon expenditure for these existing structures of heritage buildings is therefore essential for their sustained utility efficiency, in the form of low carbon materials. It is well recognised that existing buildings (including heritage buildings) bear *"a cost associated with their environmental impact"* (Historic Scotland, 2008). Commonly, overall 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 via retrofitting capability (EU, 2010). On the other hand, 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). Importantly, the realisation of this is vital for achieving the overall reduction in carbon emissions, through heritage building life span. For instance, 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). It must be emphasised that, a substantial proportion of these embodied carbon expenditure (CO_2 emissions) have been attributed to the operations as well as the maintenance and repair of existing buildings i.e. including heritage buildings.

Embodied Carbon Expenditure in Heritage Buildings Repair

It is well known that maintenance has been traditionally accepted as a cost commitment that is associated with a building (Wise, 1984). But, any maintenance intervention also entails a carbon obligation, and there is an increasing international focus on reducing carbon in the built environment (Stern, 2006). Theoretically, maintenance contributes to the lifetime carbon emissions in a way that may be cumulatively significant. In practice however, this focus largely centres only on new build and upgrading works on existing buildings, and not on maintenance and repair. Nowadays, an evaluation of carbon emissions from repair to structures and historic fabric of heritage buildings has attracted considerably less attention. It is quite interesting to note that legislation to control carbon emissions, particularly in buildings has been established in many countries. Regrettably, there is no specific guideline that targets reduced carbon emissions as a consequence of heritage buildings repair. Moreover, earlier studies that have attempted to evaluate embodied carbon expenditure for heritage building maintenance through embodied carbon appraisal for repairs have been limited in scope.

Basically, 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. It is very often that repair is undertaken to attain a simple objective i.e. to retain existing buildings in a serviceable condition. Theoretically, it is well understood that 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, particularly its efficiency in the context of environmental impact. It is well accepted that maintenance has a complex relationship with carbon emissions as these are linked to subtle changes to the historic building fabric of heritage buildings that can occur as a result of repair. But, very little of previous work has focused on the embodied carbon expenditure as a consequence of repair processes, and more specifically the repair of historic fabric of heritage buildings. Undeniably, the ability of maintenance to reduce embodied carbon expenditure expended from repairs is largely disregarded by relevant organisations and industry alike.

On the other hand, 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). Nowadays, 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). Commonly, 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). Likewise, 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 (SBSA, 2009). There has been no prevalent development of a unifying model using LCA to date however, specifically evaluating the efficacy of repair during the maintenance phase in terms of the embodied carbon expenditure.

Preferably, 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. But, this measurement has been consistently shown to have a high degree of inaccuracy and variability. This is mainly 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). It must be noted that the specification includes all of the embodied carbon expended prior to the product or materials reaching the point of use (i.e. building site). In addition, certain aspects of the degradation of heritage buildings may relate to higher embodied carbon expenditure (such as the results of aging and the decay processes that occur with building structures, elements and components. This include gaps in the historic fabric lead to higher air volume changes and associated heat loss; dampness that may require dehumidification; saturated building materials as a function of defective detailing and rainwater also leads to reduced thermal performance through the altered conductivity of the repair materials. All of these degradation processes are associated with heritage buildings structures, elements and components relate to potentially higher embodied carbon expenditure. In this paper, an evaluation of the selected repair techniques for repairs in heritage buildings were undertaken using repair material life cycle data within cradle-to-site boundary of LCA, in the form of EMI. Based on formulaic expression of Green Maintenance model, relative merits of any selected maintenance over a given time frame were determine to identify the most efficient repair, twinned with embodied carbon appraisal i.e. measuring and controlling the embodied carbon expenditure.

Embodied Carbon Appraisal of Repair for Heritage Buildings

Unlike the case with new construction materials, the guidelines and regulations for usage of traditional repair materials of heritage buildings to achieve embodied carbon reduction are unclear. Also, their relative roles in helping to attain this aim remain vague. Nowadays, there has been a broad range of embodied carbon coefficient values for repair materials, as generated by previous LCA guidelines, commonly for new builds and materials for upgrading works. Unfortunately, there is no specific data value for traditional materials used in repair of structures, elements and components of heritage buildings. Presently, there is also no well-established data describing the environmental impact of traditional materials of these buildings as opposed to modern materials. For example, 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 addition, 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). Meanwhile, Bastion Middleburg, Melaka, Malaysia had consistently facing difficulties in finding the locally available of original laterite stones for repair due to closure of local quarries (Kayan et al., 2017a and 2017b). Significantly, the decline and closure of stone quarries 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. Remarkably, these changes have had a significant impact, particularly on carbon emissions, as existing buildings, such as historic masonry buildings need to be regularly maintained. Also, such buildings are to be repaired in accordance with best conservation practice (Forster 2010a and 2010b).

In general, total carbon expenditure within the maintenance and repair process is very much determined by procurement and availability of repair materials. Ideally, the selection of repair materials for heritage buildings is based on like for like principles. Fundamentally, the applicability of this philosophy is the main tenet underpins suitability and defensibility of the repair. These philosophical parameters could be extended to more specifically encapsulate sustainability. Each repair technique of heritage buildings has a different longevity and associated embodied carbon expenditure. Significantly, 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. Then, the selection process for maintenance and repairs is clearly a function of characteristics of philosophical defensibility, cost, durability and environmental impact. In addition, repair techniques applied to any structures, elements or components of heritage buildings can be selected to cater for preferences in one or more of the aforementioned requirements. In this paper, the efficiency of repair techniques for heritage buildings has been focused on the environmental impact factor. It must be noted however, maintenance that attempts to achieve embodied carbon reduction in heritage buildings, cannot be made solely, or rely upon, a single repair technique. Therefore, a unified concept and methodology that has the ability to evaluate the efficiency of a single, or a combination repair techniques in different repair scenarios in terms of environmental impact has been developed in this paper, through and emerging Green Maintenance model.

Green Maintenance Model: Concept and Methodology

Philosophically, the main tenets associated with building conservation include: least intervention; like for like material replacement; honesty and distinguishability; integrity; reversibility; respect for historic patina; and respect for traditional craft skills (Bell, 1997). Emphasise on these philosophies is commonly laid on the success of maintenance intervention. Therefore, the success of maintenance intervention for heritage buildings is not only evaluated on the quality of the repair, but also conformity to aforementioned principles. In addition, interventions that fit within the philosophical context are generally high quality, have better compatibility with the fabric, highly defensible and have greater longevity than insensitive, often inappropriate repairs. On the other hand, costs associated with maintaining a building can be contributed to retaining or increasing its value in economic context. Adding to the complexity of prioritisation within the philosophical and economic context, a third and emerging factor in the evaluation of maintenance is environmental sustainability. Figure 3 represents the traditionally accepted conceptual model of sustainability with environmental, societal and economic factors, overlaid with the three factors that influence maintenance for buildings, namely; environment, cost and philosophy. Ideally, those interventions that intersect with all three contexts would potentially be considered as being the most sustainable concept and methodology for maintenance i.e. Green Maintenance.

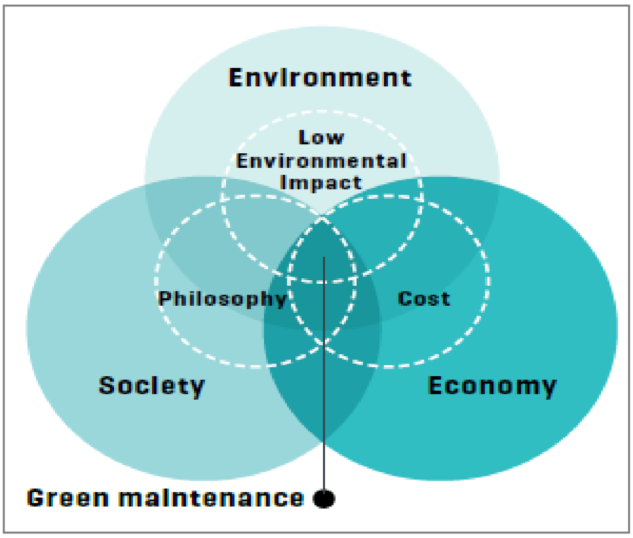

Figure 3: Green Maintenance Conceptual Model
Source: Forster, et al., 2011 and 2013; Kayan, 2013.

As previously discussed, there is clearly a relationship between the number, type as well as longevity of repair, with embodied energy and CO_2 expenditure expended in repairs. Most likely, a durable repair requiring fewer repeat interventions and this will incur less CO_2 expenditure over the lifespan of the building than a less durable alternative. For example, although replacing natural stone is a significantly more durable than plastic repair, the energy associated is a great deal higher. Figure 4 demonstrates 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. In practice, 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. It must be also noted that maintenance intervention is assumed to be taking place 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. For example, in the case of 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. In contrast, 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.

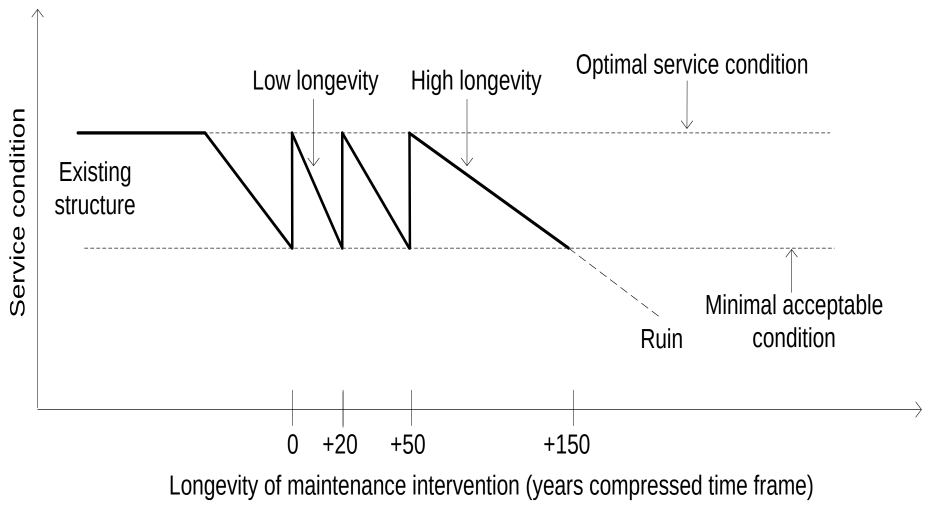

Figure 4: Impact of Maintenance Interventions on the Service Condition over the Whole Life of Buildings
Source: Adopted from Forster, et al., 2011.

It is clear that, for the Green Maintenance concept and methodology to be of rationale use, the embodied carbon expenditure of the repairs must be evaluated using comparable, reproducible methods. For instance, process analysis assessment methods of Life Cycle Assessment (process analysis (P-LCA) can be 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 (Kayan, 2013). Based on this concept and methodology, the influences of maintenance intervention (n), total wall repaired area (m^2) and longevity of repair on embodied carbon expenditure can be quantified based on Environmental Maintenance Impact (EMI). In the case of heritage buildings, the frequency of their maintenance interventions obviously affects their embodied carbon expenditure. However, the time between interventions is influenced by many variables; longevity of repair, resourcing and geographical location, technological development, mode of transportation, degree of exposure, building detailing, quality of initial work and specification. Consideration upon these variables is essential in establishing association of Green Maintenance and sustainable repair approach for heritage buildings.

Green Maintenance and Sustainable Repair Approach
The Burra Charter of International Council on Monuments and Sites (ICOMOS) suggests that maintenance should be the first priority and must "be distinguished from repair because repair involves restoration or reconstruction" (ICOMOS, 1999). This important difference has been discussed by Worthing et al. (2002), who suggest that repair work is effective at "prolonging the life of the element and the building the fabric (Worthing et al., 2002). Meanwhile, Figure 5 intersects the embodied carbon expenditure (CO_2 emission) for each maintenance intervention on the service condition graph. Each maintenance intervention (repairs) is characterised by its longevity and embodied carbon expenditure. In the context of sustainable repair approach, the Green Maintenance concept and methodology distinguishes between 'brown' and 'green'

maintenance: namely, those repairs of high and low carbon impact respectively. Figure 5 also demonstrates that the cumulative effect of 'brown' maintenance increases the total embodied carbon expended far more quickly than 'green' maintenance. In contrast, the former is synonymous with less efficient repairs, which have lower longevity and higher embodied carbon (more CO_2 emission).

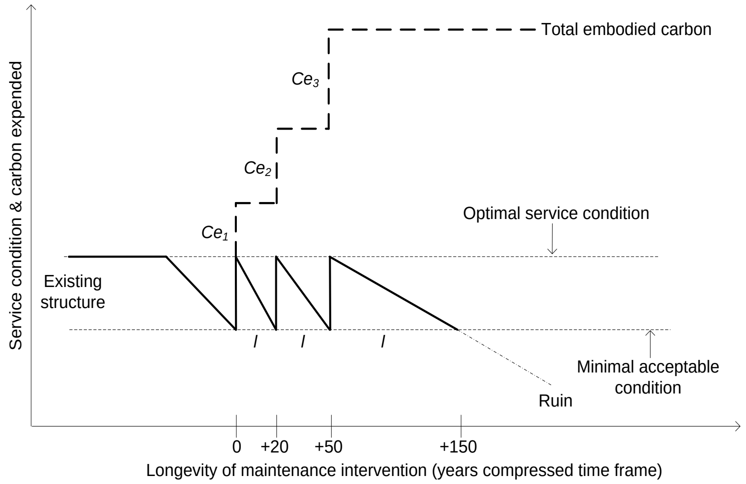

Figure 5: Relationship between Longevity of Repair and Embodied Carbon Expenditure
Source: Forster, et al., 2011 and 2013; Kayan, 2013.

In practice, the higher the embodied carbon expenditure (more CO_2 emissions) is due to more frequent maintenance intervention. In the case of historic buildings repair, however, various mechanisms may exist to attain total CO_2 emissions reduction. These include of locally sourced repair materials usage, engagement of regional companies to undertake repair work and selection low embodied carbon materials. Normally, in order to attain low embodied carbon expenditure for repair materials, preference is given to repair techniques with higher longevity. Theoretically, the higher the longevity of repair, the less number of maintenance intervention to be undertaken (lower embodied carbon expenditure and less CO_2 emissions). In the case of historic masonry buildings, natural stone replacement is more 'greener' in terms of embodied carbon expenditure as opposed to plastic repair (lower longevity, high embodied carbon expenditure and more CO_2 emissions). It must be emphasised however that the complexity of repair longevity, using either single or combined repair techniques in different repair scenarios within the selected boundary of LCA and the maintenance period, requires an appropriate approach for determining 'brown' and 'green' maintenance in historic buildings.

Previously, Energy Modelling in Traditional Scottish Houses (EMITSH) in 2008 and LCA report of Technology Assessment for Radically Improving the Built Asset Base (TARBASE) in 2009 show that historic buildings have capability to attained optimum performance (EMITSH, 2008; Historic Scotland, 2008; TARBASE, 2009). For example, EMITSH successfully identified a generic hierarchy of interventions for all traditional dwellings in Scotland by developing general rules-of-thumb for an informed selection of technologies and measures to reduce the carbon dioxide emissions. Additionally, EMITSH has adopted the measures with high probability of user-acceptance, such as improving of lighting and appliance which carried out first, followed by basic insulation such as roof insulation. Consequently, technology-replacing measures, such as more advanced appliance options (e.g. improving refrigeration) and boiler upgrades were the other adopted measures. On the other hand, TARBASE had effectively delivered technological solutions which will allow a radical, visible, step change input to policies and programmes designed to reduce the carbon footprint of the

UK building stock (Carbon Vision target of a 50% reduction in carbon emissions by 2030 on the UK's existing built assets), since at least 75% of the building stock that will be present in 2030 is already in existence. Within UK's existing buildings, TARBASE primary aims is to assess the potential of present and future technologies available for carbon intensity reduction under three headings namely- (i) building fabric and installed heating, ventilating, and air conditioning (HVAC), (ii) energy production and storage, and (iii) end-use equipment. However, both of the works are conversely attempted to make historic buildings more energy efficient using retrofitting approach and not by means of adopting sustainable repair approach in reducing CO_2 emissions.

Relatively, if we can evaluate the efficacy of repair in terms of its embodied carbon expenditure (CO_2 emissions) based on Green Maintenance concept and methodology, it could then be tailored to suit the EMI aspects rather than the longevity of repair alone. It must be emphasise that, to fully appreciate the EMI of the repair, the boundary of LCA and maintenance profile period must be set appropriately. Figure 6 shows how EMI of repair builds up. For example, in the context of historic masonry buildings, this is the cumulative effect of maintenance interventions over the stone masonry walls' life, denoted by n1, n2 and n3. Noted that each intervention (repair) has embodied carbon expenditure (ce) and a longevity of repair (*l*).

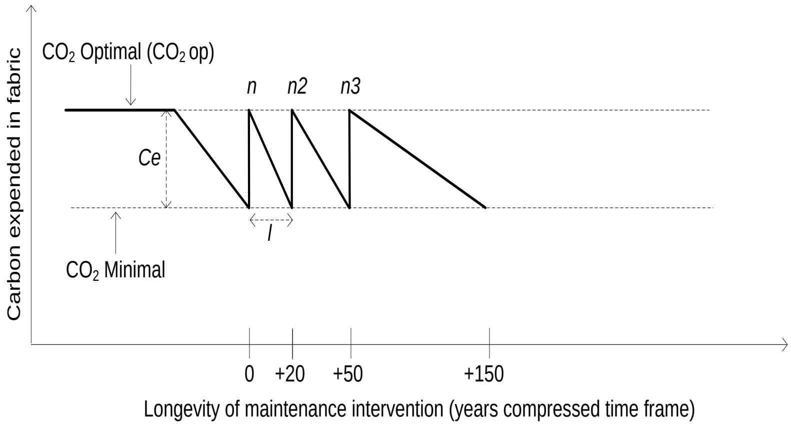

Figure 6: Determination of Theoretical 'Environmental Maintenance Impact' (EMI) Of Maintenance Interventions

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

The total embodied carbon expended by maintenance interventions through repair is illustrated by the following 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 *i*th maintenance intervention [evaluated by within 'cradle-to-site' tools of LCA] [$tCO_2e/t/m^2$]

Based on the 'Green Maintenance' concept and methodology and respective functional units, the efficiency of single or combined repair techniques undertaken in different repair scenarios can be tested based on their EMI.

Functional Units and Cumulative Embodied Carbon Expenditure for Repair

Initially, embodied carbon expenditure to repair heritage building's structures, elements or components (based on unit) for respective repair technique (functional units of $tCO_2e/t/units$) were determined based on maintenance intervention (n) and total repaired area/quantities or unit, within the 'cradle-to-site' of LCA on yearly basis, for the selected maintenance period. Cumulatively, the embodied carbon expended for each repair technique was then calculated by multiplying the total area/quantities or unit of structures, elements or components repaired with their respective generated functional units. Overall total of embodied carbon expenditure for all undertaken repair techniques for structures, elements or components within 'cradle-to-site' could be calculated using Equation No. (2):

$$Total\ approximate\ of\ embodied\ carbon\ expenditure\ (per\ units\ repaired)$$
$$= \sum ECEcradle-to-site\ (unit)_{n} = ECEcradle-to-gate\ (unit)_{n} + ECEgate-to-site\ (unit)_{n}$$

Equation No. (2)

where;
ECEcradle-to-gate (unit)$_n$ = embodied carbon expenditure value on every units repaired structures/elements/components using relevant repair techniques within 'cradle-to-gate' boundary
ECEgate-to-site (unit)$_n$ = embodied carbon expenditure value for transporting repair materials used in repairing one unit of structures, elements or components using relevant repair techniques within 'gate-to-site' boundary

The Green Maintenance results were then tested on its total EMI, by evaluating the influences of longevity of repair within the selected maintenance period. The testing is to ascertain Green Maintenance practicality and compatibility, either for single or a combination of repair techniques in different repair scenarios.

Total Environmental Maintenance Impact (EMI)
Green Maintenance model results were generated by evaluating the influences of longevity of repair within the selected maintenance period (in this case is within a hundred years period). This could be expressed as in Equation No. (3):

$$Total\ \ of\ Environmental\ Maintenance\ Impact\ (EMI)\ (100\ years)$$
$$= \sum_{ti=1}^{n} EMI(100yrs)cradle-to-site_{tn} = EMIcradle-to-site_{\,t1} + EMIcradle-to-site_{\,t2} \ldots EMIcradle-to-site_{\,tn}$$

Equation No. (3)

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
EMI$_{(100yrs)}$*cradle-to-site*$_{tn}$ = total embodied carbon expenditure for quarrying/mining, processing and manufacturing and transporting of repair materials used in repair, using either single or a combination of repair techniques in different repair scenarios in one hundred years

of maintenance profile periods within the 'cradle-to-site' boundary [generated from Equation No. (2).

Testing of Green Maintenance Model Based on Embodied Carbon Appraisal for Repair

In this paper, four common repair techniques for laterite stones were used for testing of Green Maintenance such as stone replacement, plastic repair, pinning and consolidation and repointing. These repair techniques could be viewed in terms of relative levels of intrusion to the original fabric. In this case, repair techniques are assessed based upon how destructive they are in terms of contribution of damage to original historic fabric of buildings. It must be noted that the number of repair options (scenarios) may beneficial relating to technical and philosophical aspect of masonry conservation; least intervention, like for like material replacement, honesty and distinguishability and etc. Normally, repeated repointing on deteriorated mortar joints would have limited effect on adjacent laterite structure. However, the removal of deteriorated laterite stone and replacement with a new stone block unit logically requires removal of greater quantities (e.g. in mass kg of materials) of original fabric. It must be emphasised that certain combinations of laterite stones repair are more common than others. In practice, stone replacement would be practically done only once, while plastic repair is commonly followed by natural stone replacement within selected maintenance period. In contrast, it would be highly unusual to replace the stone and then undertake plastic repair within the same period. In this paper, it is identified that 4 repair techniques in 4 scenarios in 100 years of arbitrary maintenance period (Figure 7).

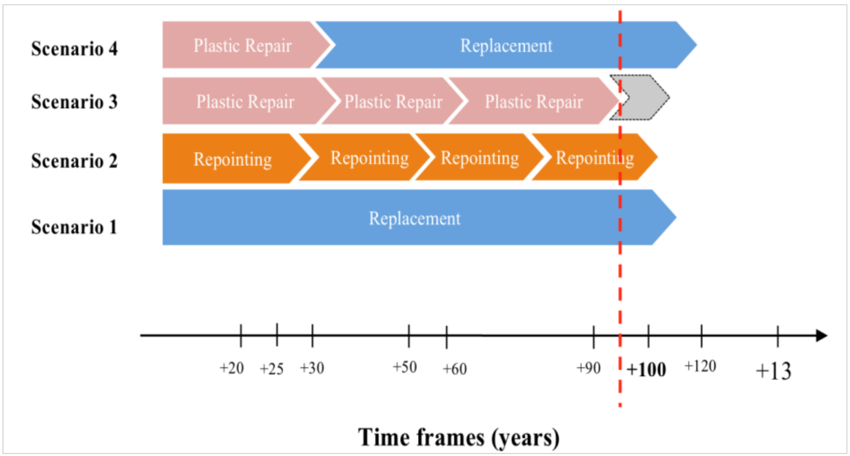

Figure 7: Repair Techniques and Scenarios for Stone Masonry Wall

Source: Adopted from Forster, et al., 2011, Kayan, 2013, Kayan 2017, Kayan et al 2017a; 2017b, Mahmud et al., 2017a; Mahmud et al., 2017b.

Testing of Green Maintenance model can be undertaken by comparing embodied carbon expended in repair with either a single or combination of repair techniques for laterite stones, based on EMI, within selected maintenance arbitrary period. For this purpose, several inputs are required in calculation; material data derived from Crishna et al., (2011) and Hammond and Jones (2011) for Embodied Carbon Coefficient (ECC). It must be noted that different values from foreign material and ECC data were always influenced by national difference in fuel mixes and electricity generation. On the other hand, open access of ICE database would increase the quality of this paper. Ideally, selection of ECC values in ICE is made meticulously based on average number of CO_2 emissions. The suggested ECC value for salvaged material is 0. Relatively, for bigger scale of project, the material needs another secondary process (e.g. manufacturing of brick dust). Transportation data (gate-to-site) derived from DEFRA (2008) in Kayan et al., (2017a and 2017b) based on 1.32 x 10^{-4} $kgCO_2$ emission factor based on Heavy Good Vehicle (HGV) in UK for 2005. CO_2 emission factor will be multiplied by weight of good the distance (shortest and most direct distance travelled from resourcing location) to building site. Figure 8 establishes embodied carbon expenditure undertaken on 1 m^2 of laterite stone structures ($tco_2e/t/m^2$).

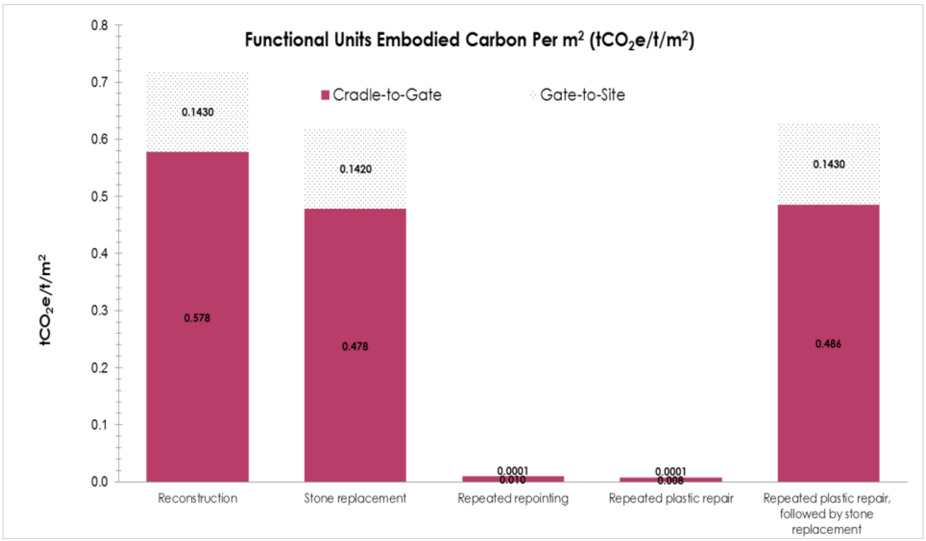

Figure 8: Embodied Carbon per M^2 ($Tco_2e/T/M^2$) for Bastion Middelburg Repair

Source: Kayan, 2017.

Figure 9 represents the total EMI expended in five different repair techniques and scenarios for laterite stones of Bastion Middelburg. Total EMI generated is based on total wall surface area of the bastion (2,666.67m^2), multiply with value of Functional Units of Embodied Carbon Per m^2 ($tCO_2e/t/m^2$). Initially, within 100 years period, the results show that reconstruction has the highest value of EMI of 1,926.32 tCO_2e/t. Comparatively, EMI for stone replacement was slightly lower, 1,655.7 tCO_2e/t. On the other hand, EMI for repeated repointing, repeated plastic repairs and repeated plastic repair, followed by stone replacement is 425. 9 tCO_2e/t, 256.2 tCO_2e/t and 1,239.0 tCO_2e/t respectively. In this paper, it must be noted that generated EMI is mainly influenced by longevity o repair and life expectancy of materials used in laterite stones repair (BCIS, 2006 and BRE, 2016). It must be also emphasised that, average life expectancy of 100 years of laterite stones repair does not take account of a well-maintained laterite stones structures and buildings. In some cases, there are many examples of laterite stones still functioning satisfactorily in heritage buildings that are several hundred years old (Kayan et al., 2017a and 2017b).

Figure 9 also summarises the EMI [generated from Equation No. (3)], evaluated in terms of embodied carbon expenditure, over the 100-year maintenance period for different repair techniques and scenarios at the same sample properties (in this case Bastion Middleburg, Melaka Malaysia). The results also suited as an evident that stone replacement has the highest embodied carbon expenditure of all the interventions. The results show that there are high functional units ($tCO_2e/t/m^2$) in making repairs using the natural stone replacement technique. When this is placed in context of a 100-year maintenance period however, it has the lowest EMI due to the short life expectancy of the other interventions. In addition, within a 100-year maintenance profile period, 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 other word, natural stone replacement is the most 'greenest' and the least destructive repair technique as it contributes to the lowest embodied carbon expenditure (tCO_2e/t) with the least number of maintenance intervention (n) in 100 years period.

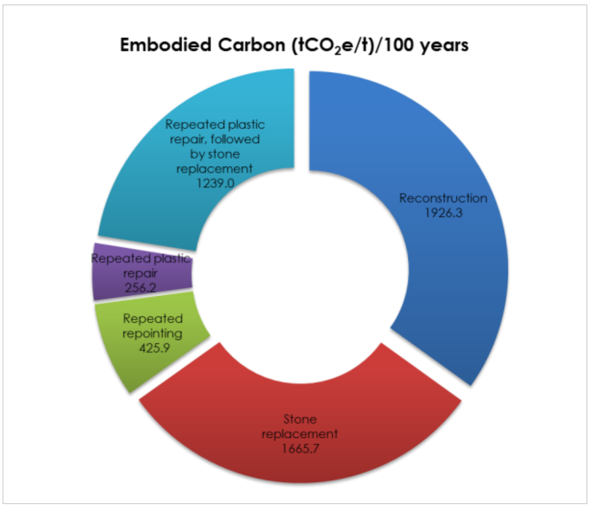

Figure 9: Total EMI for Laterite Stones Repair of Bastion Middelburg within 100 Years Period
Source: Kayan, 2017.

It can be established that the higher the longevity of repair (the fewer interventions undertaken) using the selected repair techniques and scenarios, the less carbon expended on repairs (less CO_2 emissions). This is parallel with sustainable repair approach of Green Maintenance concept and methodology. Significantly, the results also revealed that repeated repointing contributed to nearly 86% and 75% lower total EMI (theoretically this repair technique contributes to lesser amount of CO_2 emissions) compared to reconstruction and stone replacement respectively. Despite the lower EMI for repeated repointing techniques, the whole surface of the bastion is essentially required overall surface (in m^2) repointing works within the same period. Therefore, EMI for repointing could be higher than reconstruction and stone replacement within the same time frame. Notably, the stone replacement is commonly undertaken on small surface areas (lesser are in m^2 based on quantity block of stone), implicates consistently low EMI as compared to the reconstruction and repeated repointing. The results also show that transportation accounts to maximum of 50% of total EMI. This is mainly influenced by CO_2 emission factor of used mode of transportation and distance travelled for repair materials during delivery process from resourcing location to building site.

Discussion

The results from this paper demonstrate that there is a relationship between the number of maintenance intervention (n) and the embodied carbon expenditure (CO_2 emission) expended from heritage buildings repair. Generally, a durable repair undertaken upon a building requires a lower number of repeat interventions. Thus, 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 heritage buildings. In the context of repair materials however, it must be emphasised that problems can arise because the evaluation of the longevity of a repair is often inaccurate (Ashworth, 1996 and Douglas, 1994). Additionally, databases of information associated with the longevity of building components are prone to inaccuracy and inconsistency. This is mainly due to discrepancies in Estimated Service Life (ESL). Despite this problem, a comparison of the efficiency of repair techniques for heritage buildings repair in terms of embodied carbon expenditure can be attained using approximate relative values of service life (lifespan) of building components and repair materials.

Significantly, the Green Maintenance model in this paper is 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. Also, this paper effectively associates embodied carbon appraisal for repair to heritage buildings with LCA that leads to Green Maintenance concept and methodology. Importantly, unifying concept of Green Maintenance model can be seen as a tool for promoting good maintenance interventions in terms of embodied carbon expenditure, with minimal environmental impact. In this paper, emphasis of the model is lays on any current carbon assessment. In broader context, it is hoped that this model will be adopted by those entrusted with the repair and maintenance of traditional materials of heritage buildings, and embodied carbon appraisal will become a key performance indicator in the intervention strategies.

Such an appraisal of embodied carbon expenditure based on Green Maintenance model can be undertaken in reference to repair efficacy, longevity, ability to conform to building conservation philosophy and, finally, sustainability. The model shows that the frequency of maintenance interventions (n), such as repair to structures, elements and components of heritage buildings clearly affects the level of CO_2 emissions. Significantly, the complexity of prioritisation within the context of philosophical, economic and sustainability has led to the establishment of the model. In practice, the best or the 'greenest' techniques are associated with low CO_2 emissions, high longevity and philosophical adherence. In effect, the model had determined "how green" the repairs are in terms of embodied carbon expenditure. This is mainly to understand the potential for reducing embodied carbon expenditure (reduction of CO_2 emissions repair) based on 'cradle-to-site' of LCA.

Conclusion

Progressively, Green Maintenance concept and methodology will be positively welcomed as our society moves towards a low carbon economy and materials. Moreover, the level of awareness in our society upon the importance of selection and prioritises low embodied carbon materials is also increasing steadily. While low carbon trading in building industry becomes more prevalent, Green Maintenance model is also important as it can be converted into a supplementary financial cost in maintenance decision making process. This paper shows that EMI of the model has ability to provide guidance for the flexible selection of maintenance options that minimise embodied carbon expenditure i.e. mitigation and reduction of CO_2 emission. Encouragingly, this promotes sustainable solutions for the repair of existing built environment, including heritage buildings. On the other hand, the model also complements the growth in 'green procurement' that is now being accepted as an important niche in existing building maintenance and repair market. It must be emphasised that emerging concept of embodied carbon appraisal for repair based on Green Maintenance would benefit from agreed cross party definitions for all organisations responsible for the maintenance of heritage buildings, particularly in achieving sustainable repair.

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