

## GREEN MAINTENANCE FOR HERITAGE BUILDINGS: LATERITE STONE REPAIR APPRAISAL

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**Abstract:** Maintenance is widely accepted as important mechanism for survival of heritage buildings. Progressively, their maintenance had shift towards sustainability, encompassing economic, societal and environmental domain. Meanwhile, the efficiency of maintenance and repair for heritage buildings is no exception and also conforms to these broad domains. Moreover, previous works and study on their repair appraisal within environmental domain garnered little attention. Emergently, low carbon consideration for heritage buildings became increasingly important in achieving a sustainable repair and this was supported by 'Green Maintenance' concept and methodology. Primarily, the aim of this paper is to gives insight on how 'Green Maintenance' has capability to evaluate low carbon repair for laterite stone structure, based on selected case studies of Bastion Middleburg and St Paul's Church of the UNESCO World Heritage Site of Melaka, Malaysia. Notably, it is discovered that laterite stone repair appraisal results based on the model shows that cumulative embodied carbon expenditure expended from repair can be represented in the form of Environmental Maintenance Impact (EMI) of 'Green Maintenance' model. Significantly, the EMI of the model also shows its ability to relay the 'true' CO<sub>2</sub> emissions for laterite stone repair, within selected maintenance time frame. Additionally, calculation procedures through formulaic expression of the model enabled evaluation of EMI for repair within 'cradle-to-site' boundary of Life Cycle Assessment (LCA). Most importantly, Green Maintenance model shows its ability as a tool for maintenance decision-making, which enables determination of sustainable repair approach for heritage buildings.

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

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### Introduction

Maintenance of heritage buildings is crucial in ensuring that the 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 (Wise, 1984), and it is generally underpinned the long-term performance associated with any building (Kayan, et al, 2018b). 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. Moreover, low carbon consideration in heritage buildings is considered difficult to achieve, mainly due to their limited retrofitting capability. It is well accepted that maintenance is essentially a way of prolonging the lifespan of heritage buildings. Also, it 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.

Associating repair with a life cycle carbon approach of heritage buildings repair will leads to the concept of ‘green’ maintenance concept and methodology, which can be seen as maintenance with minimal environmental impact. This can be demonstrated with maintenance regimes 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 aims to proposed Green Maintenance model for evaluating the efficacy of maintenance interventions for heritage buildings, based on embodied carbon appraisal that signifies integration of cost, philosophy and environment. The model utilise repair material life cycle data within cradle-to-site boundary of life cycle assessment (LCA) scope, in the form of generated Environmental Maintenance Impact (EMI). This paper is also attempts to gives insight on how ‘Green Maintenance’ has capability to evaluate low carbon repair for laterite stone structure of heritage buildings, based on selected case studies of Bastion Middleburg and St Paul’s Church of the UNESCO World Heritage Site of Melaka, Malaysia.

### ***What are Heritage Buildings?***

Heritage buildings were defined as something which passed down from one generation to another (Feilden, 1979; 1994 and 2003; Prentice, 1993). Also, they inherited (UNESCO, 1972) outstanding universal value (The Commissioner of Law Revision, Malaysia, 2005). Therefore, their conservation is significant; protecting cultural resources by retaining financial, economic and societal capital invested in their historic fabric. It is well known that these also prolong their life and function; involving maintenance, repair and restoration. Commonly, heritage buildings were conserved to safeguard its inherited cultural significance and architectural values (Feilden, 1994 and 2003). Burra Charter (2013) had classified heritage buildings as either individual or group of monuments or structures. Notably, they are commonly associated with important historic event, as well as inherited important significances and values which essentially to be protected using ‘Green Maintenance’ approach.

### ***‘Green Maintenance’ for Heritage Buildings***

It is well accepted that ‘green’ maintenance of heritage buildings is crucial for ensuring that the financial, economic and societal capital invested in the fabric is retained. In the context of Malaysia, the ‘green’ concept in building sector was coined and gained serious attention after the economic crisis in 1997 (Azam et al., 2017). Nowadays, with regard to heritage buildings maintenance and repair sector, this had shifted towards sustainability, under the ‘Green Maintenance’ concept and methodology. Significantly, ‘Green Maintenance’ has the potential to refocus the traditional view of the repair of building, towards sustainability (Forster et al., 2011; Kayan, 2013; Kayan, 2015) and therefore, go some way to satisfy legally binding sustainability targets. Bell (1997) and British Standards Institution (1998) claimed that this has

been embedded in the principal building conservation legislative frameworks and charters (Bell, 1997; British Standards Institution, 2008). It is quite clear that a main tenet of these frameworks is sustainability. It laid on main tenets of cost analysis that beneficial for maintenance investment. On the other hand, this is widely debated over philosophy of undertaking maintenance which promotes least intervention, like for like material, honesty, integrity etc. (Bell, 1997). This led to the question on how maintenance's philosophical vs. cost-guided may beneficial to reduce the environmental impact to ensure the survival and protection of historic fabric of heritage buildings.

Practically, protection of historic fabric heritage buildings through maintenance is not only undertaken from a cultural perspective, but also from an economic viewpoint. For instance, the fact that 50% of Europe's national wealth is encapsulated within its existing built environment (Balaras et al., 2005; Forster and Kayan, 2009; Forster et al., 2013, Kayan, et al., 2018a and 2018b). Theoretically, premature deterioration associated with lack of regular maintenance can extensively devalue these existing assets. Looking ahead, however, recognition of the contribution of maintenance should be expanded. In this context, it is 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. Meaningfully, a substantial proportion of carbon emissions have been attributed to the operations as well as the maintenance and repair of existing buildings i.e. including heritage buildings.

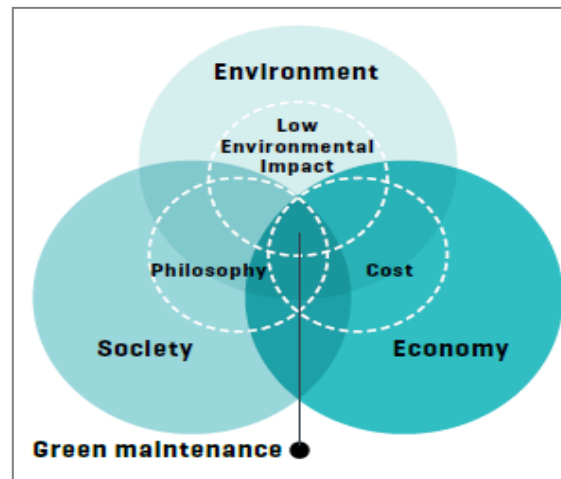
Nowadays, the cost implications of repairs must be considered within the context of the associated carbon expenditure. Moreover, these measures are increasing in prevalence and form a part of carbon reduction strategies. It must be noted that this work practically applies a mathematical modelling method developed by Forster et al., (2011), and reflects the growing importance of the meaningful determination of the carbon cost associated with repair interventions. Chronologically, Forster et al's (2011) effort into Green Maintenance was developed from mid stage doctoral research undertaken by Kayan (2013). Subsequently, this was further developed and the work was published in 2013. Notably, this current paper is a logical and meaningful continuation of Kayan's (2013) doctoral research and practically applies the established theory, notably on the development of 'Green Maintenance' concept and methodology.

Emergently, 'Green Maintenance' concept and methodology support sustainability agenda that call for protection of the cultural significance which embodied in historic fabric of heritage buildings, while impartially sustaining the other capital such as economy and environmental inclusively. Under the umbrella of this concept and methodology, philosophical factor, cost and low environmental impact factor were interlaid into evaluation. Intervention (repair technique) that comply and integrate with all the three factors in will be considered as being greenest. It is well accepted that maintenance of heritage buildings have significant contribution of environmental impact in terms of energy and embodied carbon. In this context, embodied carbon is emitted in the form of CO<sub>2</sub> emissions, released through the process of materials extraction, manufacturing, transportation. Notably, 10% of CO<sub>2</sub> emissions in building sector are contributed by the usage of traditional material (Mahmud et al, 2017a; 2017b). Out of this percentage, 70% and 15% are associated with their manufacturing and transportation respectively (Kayan et al, 2018a).

Relatively, traditional material sector is commonly the biggest contributor to maintenance and repair market of heritage buildings. Meanwhile, longevity of repair and their respective impact upon Total Environmental Maintenance Impact (EMI) became an important factor in selecting

the sustainable repair techniques. In this paper, quantification of EMI in the forms of CO<sub>2</sub> emission using Life Cycle Assessment (LCA) will be tested and analytically compared using case studies of laterite stone buildings located in UNESCO World Heritage Sites of Melaka, Malaysia. Progressively, as carbon abatement became a priority for each country in the world, therefore, Green Maintenance concept and methodology in quantification of CO<sub>2</sub> emissions, particularly for heritage buildings repair will be positively welcomed.

Figure 1 denotes the traditionally accepted conceptual model of sustainability which signifies an integration of environmental, societal and economic factors. When this conceptual model is overlaid with three factors that influence maintenance for historic buildings, namely; environment, cost and philosophy, it will resulting to the most sustainable intervention. Relatively, this model designates that any evaluation of maintenance intervention should be based on conservation philosophy, cost and low environmental impact factors (Kayan, et al, 2018a). Preferably, those maintenance interventions that integrated with all three factors would potentially be considered as being the most sustainable i.e. ‘Green Maintenance’.

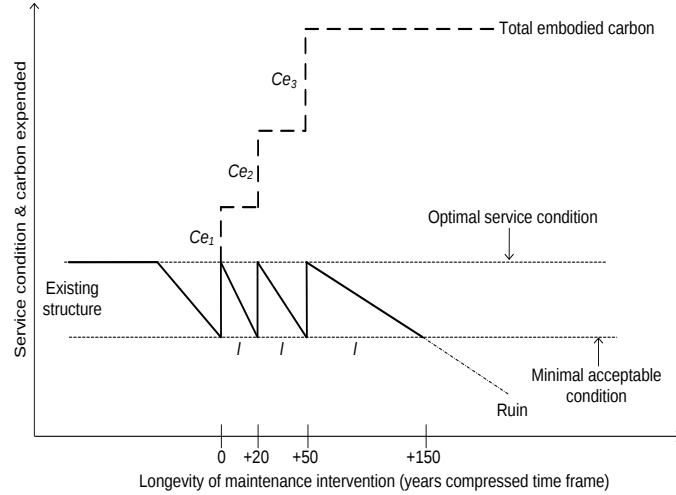


**Figure 1: ‘Green Maintenance’ conceptual model.**  
Source: Forster, et al., 2011 and 2013; Kayan, 2013.

Conceptually, Green Maintenance set the priorities of low carbon material usage, using either single or a combination of repair techniques, over different repair scenarios. These were evaluated within selected time frame of maintenance period to identify the best repair options in terms of all aforementioned factors. At the same time this also attains to determine on how to reduce CO<sub>2</sub> emissions, based on Life Cycle Inventory data compilation as well as LCA calculations. Based on the LCA, the measurement of CO<sub>2</sub> would include the extraction of raw materials to the end of the product’s lifetime (cradle-to-grave) of LCA boundaries. However, it must be noted that, in acquiring accurate result of LCA, the measurement of the work of this paper is limited to cradle-to-site analysis (raw material extraction and processing, transportation, manufacturing, transportation to the building site). In this paper, Green Maintenance sets out an insight on the association of maintenance and repair with CO<sub>2</sub> emissions, particularly in selecting the low carbon repair for heritage buildings.

Meanwhile, proposition of relationship between each intervention and CO<sub>2</sub> emissions, characterised by its longevity (*l*) and embodied carbon expenditure (*C<sub>e</sub>*) on the service graph condition (Figure 2). In this representation, the downward sloping signifies the decline condition of the buildings over the life cycle of repair. During repair, each intervention is important to keep the buildings at the optimal service condition. Along the repair process

however, CO<sub>2</sub> were emitted via embodied carbon expenditure. Theoretically, the more frequent the maintenance intervention, the greater embodied carbon expended for repair (Forster et al., 2011). In the context of sustainable repair approach perspectives, the Green Maintenance concept and methodology distinguishes between ‘brown’ and ‘green’ maintenance: namely, those repairs of high and low carbon impact respectively. Cumulatively, effect of ‘brown’ maintenance increases the total embodied carbon expended far more quickly than ‘green’ maintenance. Conversely, the former is synonymous with less efficient repairs, which have lower longevity and higher embodied carbon (more CO<sub>2</sub> emission).



**Figure 2: Relationship between longevity of repair and embodied carbon expenditure.**

Source: Forster, et al., 2011 and 2013; Kayan, 2013.

Importantly, Green Maintenance gives the preference to the repair technique with high longevity. Those repair techniques with high longevity are subsequently require lesser number of repeating interventions and may incur lower embodied carbon expenditure over the life span of the building. In practice however, there will be a single or combination of repair techniques are needed for repair within certain maintenance arbitrary period. Thus, attain practicality of Green Maintenance model, consideration on numbers of intervention, embodied carbon expenditure (in the form of CO<sub>2</sub> emission) expended from repair is paramount important. It must be emphasised that, every intervention is also influenced by other variables including material durability, degree of exposure, building detailing, quality of repair and specification. Comparatively, non-durable materials may not consume much energy during production. But, they may require frequent replacement and resulting in higher EMI.

In Green Maintenance model, generated Total EMI (Equation 1) is the multiplication of area repaired (in this case is wall surface) with material used in tonnage (t) with their respective Embodied Carbon Coefficient (ECC), plus with multiplication of material used (t) with CO<sub>2</sub> emission factor and resourcing location (km) for respective frequency of repair (n) within hundred-year arbitrary period (Mahmud et al., 2017b).

$$\sum EMI_{\text{cradle-to-site}} = \text{Area repaired} \times \{ [\text{Material used (t)} \times ECC] + [\text{Material (t)} \times \text{Emission factor} \times \text{Resourcing location (km)}] \} \times \text{Frequency of repair (n)/100year}$$

Equation No. (1)

Practically, if we can evaluate the efficacy of laterite stone repair in terms of its embodied carbon expenditure (CO<sub>2</sub> emissions), apparently, Green Maintenance model could then be tailored to suit the EMI (Kayan, 2013 and 2015, Kayan et al., 2018a). It must be noted that the scope of LCA in this paper was defined by taking into account the EMI as the parameter in comparing embodied carbon expenditure (CO<sub>2</sub> emissions) from laterite stone repair of the selected case studies.

### **Case Studies: Epistemological of Research**

Laterite stone repair appraisal in this paper was undertaken by adoption of multiple case studies research approach. Notably, UNESCO World Heritage Site of Melaka was adopted as the focus area of laterite stone structure selection for this research. This is mainly because of the high amount of heritage properties of laterite stone structures at this heritage site area (Kayan et al., 2017a; 2017b). In addition, the heritage properties of this area inherited mixture of East and West cultural significance such as buildings with Dutch and Portuguese architectural influences (Majid and Manan, 2017). Moreover, epistemological of this research is grounded on multiple case studies approach, in which typically associated with the use of multiple sources of evidence and a strong context (Knight and Ruddock, 2008). In this research, document of historical maintenance data and records of laterite stone repair is clearly a pivotal consideration in determining case studies approach. These records were primarily composed of repair type, date of executing the works, cost, and specification information etc.

It must be emphasised that identification of the suitable a case studies for this research was primarily assessed on the intactness of historic maintenance data and records of the selected case studies, i.e. laterite stone structures repair. These data are relating to the longevity of repairs and measurement of quantities of laterite stones repair materials used during maintenance phase. It must be noted that, the main requirements for the effective utilisation of Green Maintenance model for this research were details of specification and sourcing of the materials. Additionally, the longevity and duration between repeat interventions and the extent of the works undertaken were considered for calculation procedures of the model. Subsequently, embodied carbon expenditure of laterite stone of in this paper can be evaluated and comparatively tested using EMI of Green Maintenance model for respective selected case studies.

### ***Bastion Middelburg, Melaka, Malaysia***

Bastion Middelburg (Figure 3) was originally constructed in 1641 by the Portuguese as part of defence system (as Melaka Fort), together with other eight (8) bastions (SEAARCH, 2008). Located at UNESCO World Heritage Site of Melaka Malaysia, Bastion Middleburgh is considered heritage buildings in Malaysian architecture.



**Figure 3: Bastion Middelburgh, Melaka, Malaysia**

Source: Authors, 2018.

Historically, the bastion constructed mainly using rich of iron and alumina materials of laterite stones (JWN, 2008) (Figure 4). Archaeological evidences also show that, the Portuguese had built the bastion using locally sourced laterite stones from nearby quarries of St. Paul Hill, St. John Hill, Pulau Jawa, Pulau Upeh (Figure 5) and other several islands around Straits of Melaka (JWN, 2010). To date however, not only due to shortage of supply of laterite stones, there is also no active stones quarry in this area, mainly because of their closure (Ibrahim, 2007). Therefore, over the years, Bastion Middelburg repair is constantly facing difficulties, particularly in finding the locally available of original laterite stones; make them rare in terms of materials used. Based on relevant and currently available records, reconstruction works of the Bastion Middelburg, using laterite stones, cemented with concrete and mortars (Figure 6) only has been officially started in November 2007, and has taken about one year to complete (JWN, 2008).



**Figure 4: Bastion Middelburgh, Melaka, Malaysia-laterite stones**

Source: Authors, 2018.



**Figure 5: Pulau Upeh, Melaka, Malaysia**  
Source: Authors, 2018.



**Figure 6: Bastion Middleburg, Melaka-laterite blocks, cemented with concrete and mortars**  
Source: Authors, 2018.

### ***St Paul' Church, Melaka, Malaysia***

Originally, St. Paul's Church was built as a chapel on the hill by prominent Portuguese navigator Duarte Coelho in 1521. Over the years, it was continuously enlarged and expanded by the Jesuits. Historically, it has endured series of adaptive changes; from college, to hospital and partially military function through the era of Portuguese, Dutch and British. Nowadays, the ruined structure of the buildings was famously known as Our Lady of the Annunciation. Culturally, the chapel was erected as the mark of thanksgiving, as a part of culture of Christian community. Then, it was later was christened as Nossa Senhora da Graca, signified the meaning of 'Our Lady of Grace' after Coelho's battle with the Chinese, during Portuguese return to Melaka on 21<sup>st</sup> of October 1521. Subsequently, this led to the hill of Melaka, in which being always referred as 'The Hill of Our Lady'. In 1545, larger church was built at the base of the hill-Nossa Senhora da Annonciada or "Our Lady of the Annunciation" to mark the arrival of St. Francis Xavier, as we know St. Paul's Church building today.

A glimpse on the plan of the ruined church as it exists today, it evidently illuminates the different time-line of construction, particularly using laterite stones as its main materials. For instance, the thicker laterite stone walls of the chancel and scarcity are revealing of the additional strength needed to support an upper floor and high tower of the church. This wall

was hundred feet tall to its pyramidal roof. It was reinforced at ground level central pillar. Uniquely, the Portuguese used originally local laterite blocks. It is common that laterite stones were cemented by concrete and mortar, which was suitable for building solid, massive laterites walls (Figure 7) which could withstand attacks from enemies i.e. as a fortress as well as its distinctive nave and interior of laterite stones (Figure 8).



**Figure 7: St. Paul's Church, Melaka-solid and massive side laterite walls**  
Source: Authors, 2018.



**Figure 8: St Paul Church, Melaka-distinctive nave and interior of laterite stones**  
Source: Authors, 2018.

On the other hand, the basic construction tools available at the time in fact led the Portuguese to denote to laterites as 'iron stone'; such was their difficulty in cutting and dressing it. Due to necessity, couple with Melaka's seaside location (see seaward wall of laterite stone materials in Figure 9 and Figure 10), had caused the Portuguese to repair the church with easier to shape coral rock as a filler between the laterite, over the years. Based on historic and previous maintenance records, the laterite was carried from Pulau Upeh as well as from Cape Rachado

(Khoo, 1998). Remarkably, the traces of abandoned laterite stones quarry at Pulau Upeh remained to this day (Figure 11). Significantly, after the Dutch 1606 siege, the church's tower is long painted white. Remarkably, the function of the tower (Figure 12) is not only to aid navigation of ships, but also function as a much military turret as a civilian belfry (tower). Astonishingly, according to one of the earliest post-war Dutch maps, produced in 1656, the building at one time has been converted into a hospital. However, over the centuries, this building has also been adapted re-use as partially military function, which signifies usage of strong materials such as laterite stones as the main materials for its construction.



**Figure 9: St. Paul's Church, Melaka-seaward wall of laterite stone materials**

Source: Authors, 2018.



**Figure 10: St. Paul's Church, Melaka-detail of side door frame on seaward side wall using laterite stones**

Source: Authors, 2018.



**Figure 11: The traces of abandoned laterite stone quarry at Pulau Upeh**  
Source: Authors, 2018.



**Figure 12: St. Paul's Church, Melaka-view of church towards side of former tower using laterite stones**  
Source: Authors, 2018.

During British occupation in Melaka, they continued to use the building as military base. After that, the church was then left as a more neglected ruin until a series of renovation led by the Malacca Historical Society in 1930s. Additionally, the Society also had reported the story of the church in the English language and responsible for much of what is left of St. Paul's today. Notably, the Society also responsible in removing a wall that physically connected the Dutch lighthouse to the church's front façade. This will involve physical excavations of its sacristy and chancel to reveal the original building in 1930s. Also, the society was also plays their roles in photographing and moving all the extant tombstones and their respective ornate (Figure 13) from the floor of the church to its laterite stone walls, where in-situ damaged occur at a much slower rate.



**Figure 13: St. Paul's Church, Melaka-ornate of Dutch tombstone relocated beside laterite stone walls**  
Source: Authors, 2018.

Significantly, laterite stone of both case studies show its capability to stand as strong building material. Notably, it also able to stands nobly through conflicts (noted that both building survived from different colonial era), as well with the test of time under tropical hot climate which influenced its longevity of the repair. Theoretically, faster rate of deterioration of repair materials contribute to more frequent repair (Kayan 2013, Kayan 2015 and McGibbon et al., (2018). It also denotes larger deteriorated area and higher total area repaired. Table 1 summarised the profile of laterite stones used for Bastion Middelburg and exposed external wall of St Paul's Church. Historic maintenance data and records show that, originally, laterite stones of both case studies are locally sourced from Ilha das Pedros (Pulau Upeh, Melaka, Malaysia) and Cape Rachado (Port Dickson, Negeri Sembilan, Malaysia near Linggi Fort). Evidently, proofs of these can be seen on laterite cutting over the island, surrounding area and salvaged material from other buildings surrounding the location of both building which are built either by Portuguese and Dutch (Khoo, 1998).

Nowadays however, there are no active stone quarries within the area due to their closure. Physically, laterite stones of both case studies are ferruginous deposits of vesicular structure. Naturally, it is soft until it can be cut using a spade, to be made into regular block when in freshly state. Then, after it has been cut, it rapidly harden and highly resistant to weathering. Once it is exposed to the air and sun, crystallisation processes were following due to its high iron content of sesquioxides. Despite requirement of sustainable repair as specified in the Conservation Management Plan for Melaka (CMP) UNESCO World Heritage Site, which signify appropriate treatment that closely related to their repair materials, methodologies, techniques and workmanship, little research has been done for laterite stone of both case studies. Moreover, there is lack of previous research on material particularly on laterite stone appraisal in terms of environmental impact for heritage structures.

**Table 1: Construction material of Bastion Middelburg and St Paul's Church**

|                                           | (A) Bastion Middelburg<br> | (B) St Paul's Church<br>                                           |
|-------------------------------------------|-------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Type of Stone</b>                      | Laterite Stone                                                                                              | Laterite Stone (L) and Dutch Brick (D)                                                                                                               |
| <b>Total Wall Surface (m<sup>2</sup>)</b> | 2,666.67 m <sup>2</sup>                                                                                     | 603.52m <sup>2</sup> (L) and 12m <sup>2</sup> (D)                                                                                                    |
| <b>No of Stone Blocks used</b>            | 16,000 unit                                                                                                 | 2,736 unit                                                                                                                                           |
| <b>Size of Stone (mm/block)</b>           | 558mm x 355mm x 228mm                                                                                       | 600mm x 300mm x 250mm (L) and 215mm x 125mm x 40mm (D)                                                                                               |
| <b>Mass of Stone (t/block)</b>            | ±0.1 t/block                                                                                                | ±0.1 t/block (L) ±0.002 t/block (D)                                                                                                                  |
| <b>Mortar Profile (Proportion)</b>        | 1:1:3 of limestones, sand and white cement                                                                  | 1:3 of limestones, sand for early mortar<br>1:1:2 of limestones, brick dust and sand for later mortar<br>1:1:3 of limestones, sand and white cement. |

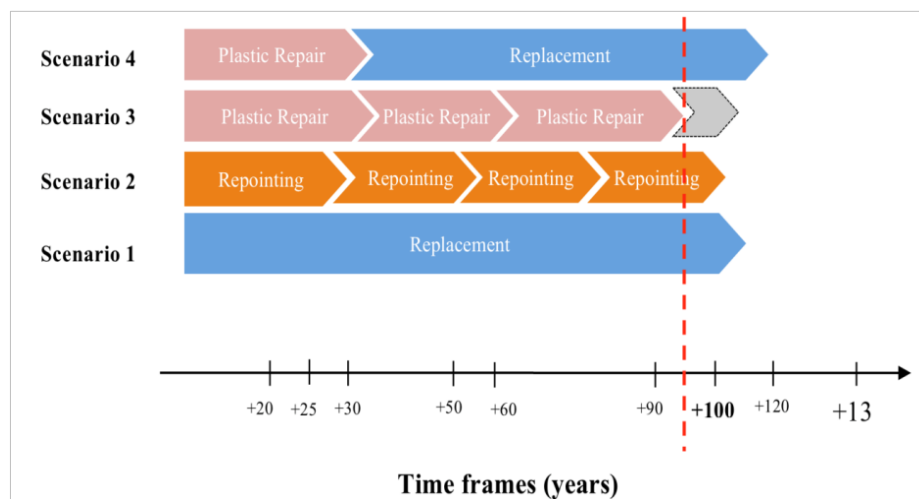
Source: Mahmud et al., 2017b.

It must be emphasised that, a great deal of lime required in construction of both case studies. It is found that only one type of mortar was specified and used for Bastion Middelburg repair. In contrast, there is no exact proportion recorded in maintenance document for St Paul's Church. It is identified that three different mixtures of proportion for mortars seen to cross cutting each other, used for laterite stone repair of both case studies based on Table 1. In practice, the appointed contractor for repair should undertake analysis on lime mortar profiles prior to the repair works on both case studies. This requirement is mainly to determine the mixtures of proportion for lime mortar material. At first, several samples of the existing pointing from different spot of wall surface were selected. Then, these samples were taken to lab to be analysed; to determine compositions, mixture, proportion and respective resourcing location.

It is must be noted that the nature and issues of maintenance and repair of two different buildings are different in nature. For example, the latest reconstruction works of the Bastion Middelburg only has been officially started in November 2007 and completed in 2008 (JWN, 2008). In addition, Bastion Middelburg repair was also consistently facing difficulties in finding the locally available of original laterite stones in large scale with proper guidelines. Comparatively, for St Paul's Church, several interventions (works) had been undertaken between the years of 2003 to 2012 (Mahmud 2017a and 2017b). These interventions had been undertaken as partially to fulfil the requirements set out by guideline and documentation process established by Jabatan Warisan Negara Malaysia (JWN). It must be noted however, previous repair works undertaken on both case studies are consistently ignored sustainable repair approach, as demonstrated and designated by Green Maintenance model. Considering this chronological series of maintenance and repair of both case studies, Green Maintenance model might provide a practical way for decision maker (e.g. conservationist and authorities) to select the most sustainable repair technique. Clearly, laterite stone appraisal based on the model might assist maintenance decision making process. Significantly, this appraisal might useful in helping the decision maker to attain informed maintenance decision by utilising CO<sub>2</sub> emissions expended from repair. This can be justified and further explained in testing of the Green Maintenance model.

### Testing of the Green Maintenance Based on Laterite Stone Repair Appraisal

In this paper, four common repair techniques and scenarios for laterite stone were used for testing of Green Maintenance, compared in 100 years of arbitrary maintenance period (Figure 14). They are stone replacement, plastic repair, pinning and consolidation and repointing respectively. These repair techniques could be viewed in terms of relative levels of intrusion to the original fabric of heritage buildings, longevity of repair and embodied carbon expenditure. It must be noted that the number of repair options (scenarios) may be beneficial relating to technical and philosophical aspect of conservation for heritage buildings. Normally, repeated repointing on loose and deteriorated mortar joints would have limited effect on adjacent laterite structure. Comparatively, the removal of deteriorated or damaged laterite stone and replacement with a new stone block unit is logically requires however, removal of greater quantities 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 the same time frame. Conversely, it would be highly uncommon to replace the stone and then undertake plastic repair within the same maintenance period.



**Figure 14: Repair techniques and scenarios for stone masonry wall**

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

Testing of Green Maintenance concept and methodology in this paper is done on the basis of comparing embodied carbon expended for repair. Embodied carbon expenditure either a single or combination of repair techniques for laterite stones within selected maintenance arbitrary period, were calculated based on EMI. For this purpose, several inputs are required in calculation; material data was derived from Crishna et al., (2011), while for Embodied Carbon Coefficient (ECC) were derived from Hammond and Jones (2011). It must be noted that different values from foreign inputs for both material and CEC data were always influenced by national difference in fuel mixes and electricity generation. On the other hand, open access of Inventory of Carbon and Energy (ICE) database would increase the quality of this paper. Ideally, selection of ECC values in ICE is meticulously made based on average number of CO<sub>2</sub> emissions. For the purpose of this paper, the recommended ECC value for salvaged material is zero as there is no embodied energy involved for their production. Relatively, for bigger scale of conservation project for heritage buildings, some of the repair materials need another secondary process of manufacturing (e.g. brick dust). Transportation data (gate-to-site) derived from DEFRA (2008) in Kayan et al., (2017a; 2017b) were based on  $1.32 \times 10^{-4}$  kgCO<sub>2</sub> emission factor based on Heavy Good Vehicle (HGV) in UK for 2005. CO<sub>2</sub> emission factor will be

multiplied by mass kg of materials transported to building site and weight of distance for delivery (shortest and most direct distance travelled from resourcing location in km) to building site (Table 2).

**Table 2: Inputs for calculation for laterite stone appraisal**

| Material              | ECC   | Bastion Middelburg (A)                  |               |                 | St Paul's Church (B)                          |                      |                 |
|-----------------------|-------|-----------------------------------------|---------------|-----------------|-----------------------------------------------|----------------------|-----------------|
|                       |       | Resourcing Location                     | Distance (km) | Remarks         | Resourcing Location                           | Distance (km)        | Remarks         |
| <b>Laterite Stone</b> | 0.781 | Prachinburi, Thailand                   | 1,797 km      | Imported        | Salvaged Material (surrounding building site) | *Considered as 0. km | Locally sourced |
| <b>Brick</b>          | 0.060 | Not used                                | Not used      | Locally sourced | Tajia Industries, Melaka, Malaysia            | 15.5 km              | Locally sourced |
| <b>Sand</b>           | 0.005 | Bukit Senggeh, Melaka, Malaysia         | 37.7 km       | Locally sourced | Bukit Senggeh, Melaka, Malaysia               | 37.7 km              | Locally sourced |
| <b>Brick Dust</b>     | 0.22  | Not used                                | Not used      | Locally sourced | Alai Kandang, Melaka, Malaysia                | 8.7 km               | Locally sourced |
| <b>Limestone</b>      | 0.017 | Kuari ISB, Alor Gajah, Melaka, Malaysia | 46.1 km       | Locally sourced | Kuari ISB, Alor Gajah, Melaka, Malaysia       | 46.1 km              | Locally sourced |
| <b>White Cement</b>   | 0.469 | Klebang Besar, Melaka, Malaysia         | 7.6 km        | Locally sourced | Klebang Besar, Melaka, Malaysia               | 7.6 km               | Locally sourced |

Source: Adopted from Mahmud et al., (2017a; 2017b)

## Results and Discussion

Table 3 shows embodied carbon expenditure associated with alternative repair techniques and scenarios undertaken on normalized  $1\text{m}^2$  and overall surface Bastion Middelburg ( $2,666.67\text{m}^2$ ) and St Paul's Church ( $616.52\text{m}^2$ ). Functional unit of  $\text{kgCO}_2\text{e/t/m}^2$  is used with respective EMI for each repair techniques and scenarios, attributed within 100 years of arbitrary period. Notably, stone replacement possibly lasts about 100 years before requires next replacement (1 time of intervention (n) of its EMI attributed in 100 years period). Comparatively, repeated repointing and repeated plastic repair only lasts up to 25 years and 30 years respectively (4.0 and 3.33 times within the same period) (Kayan, 2013). In scenario 4, plastic repair and the decayed natural stone is assumed to be removed after 30y (1 time intervention of single plastic repair) and new stone to be built in. As with scenario 1 of the stone replacement will last beyond the 100 years period, therefore only 0.7 of its EMI is attributed. It must be noted that, comparative generated EMI in Table 3 were also calculated for each repairs techniques and scenarios within 'cradle-to-site' boundary of LCA as formulated based on Equation No. (1).

Also, it is evidently showed that stone replacement has highest embodied carbon either in per  $1\text{m}^2$  ( $0.621$  and  $0.421 \text{ kgCO}_2\text{e/t/m}^2$ ) and overall surface ( $1665.7$  and  $245.22 \text{ kgCO}_2\text{e/t/m}^2$ ) for both Bastion Middelburg (A) and St Paul's Church (B) respectively. The results also revealed that repeated repointing contributes to the second highest amount of  $\text{CO}_2$  emissions, but it has low initial embodied carbon expenditure. It is mainly due to its low longevity of repair as

indicated in Scenario 2. Considering the nature of this type of repair and the quality of workmanship, it is essential to repoint all overall surface of the wall within the same period. In addition, in every repointing works, it will subsequently contribute to greater amount of CO<sub>2</sub> emissions as this technique requires more maintenance interventions. Conversely, repeated plastic repair had low embodied carbon emissions for both case studies.

In practice however, the usage of plastic repair technique needs further intervention. This is mainly due to its low longevity, which resulting further of CO<sub>2</sub> emissions within the same period (see Scenario 4). In addition, the usage of cement based in mortar is technically incompatible and will also limit the longevity. Subsequently, this will lead to frequent intervention and high CO<sub>2</sub> emissions. Thus, stone replacement is an ideal technique to be utilised due to its high longevity as well as having ability to deal with large area of deterioration. However, there are significant differences found in the amounts of CO<sub>2</sub> emissions for both structures.

|                              | Functional unit/Frequency of Intervention | Scenario 1: Stone Replacement |                    | Scenario 2: Repeated Repointing |                    | Scenario 3: Repeated Plastic Repair |                    | Scenario 4: Plastic Repair, then Stone Replacement |                    |
|------------------------------|-------------------------------------------|-------------------------------|--------------------|---------------------------------|--------------------|-------------------------------------|--------------------|----------------------------------------------------|--------------------|
|                              |                                           | A                             | B                  | A                               | B                  | A                                   | B                  | A                                                  | B                  |
| Stone Replacement            | CO <sub>2</sub> e.m <sup>2</sup>          | 0.621                         | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.621                                              | L=0.405<br>B=0.015 |
|                              | Intervention (n)                          | -                             | 1                  | -                               | -                  |                                     |                    | 0.7                                                | 0.7                |
|                              | Average EMI                               | -                             | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.435                                              | L=0.284<br>B=0.010 |
| Repointing                   | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  | 0.010                           | L=0.064<br>B=0.006 |                                     |                    |                                                    |                    |
|                              | Intervention (n)                          | -                             | -                  | 4                               | 4                  |                                     |                    |                                                    |                    |
|                              | Average EMI                               | -                             | -                  | 0.040                           | L=0.252<br>B=0.024 |                                     |                    |                                                    |                    |
| Plastic Repair               | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  |                                 |                    | 0.008                               | L=0.009<br>B=0.001 | 0.008                                              | L=0.009<br>B=0.001 |
|                              | Intervention (n)                          |                               |                    |                                 |                    | 3.33                                | 3.33               | 1                                                  | 1                  |
|                              | Average EMI                               |                               |                    |                                 |                    | 0.026                               | L=0.029<br>B=0.003 | 0.008                                              | L=0.009<br>B=0.001 |
| TOTAL EMI (1m <sup>2</sup> ) |                                           | 0.621                         | 0.421              |                                 |                    | 0.026                               | 0.032              | 0.443                                              | 0.304              |
| TOTAL EMI (OVERALL)          |                                           | 1665.7                        | 245.22             | 425.9                           | 152.402            | 256.2                               | 17.53              | 1239.0                                             | 177                |
|                              | Functional unit/Frequency of Intervention | Scenario 1: Stone Replacement |                    | Scenario 2: Repeated Repointing |                    | Scenario 3: Repeated Plastic Repair |                    | Scenario 4: Plastic Repair, then Stone Replacement |                    |
|                              |                                           | A                             | B                  | A                               | B                  | A                                   | B                  | A                                                  | B                  |
| Stone Replacement            | CO <sub>2</sub> e.m <sup>2</sup>          | 0.621                         | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.621                                              | L=0.405<br>B=0.015 |
|                              | Intervention (n)                          | -                             | 1                  | -                               | -                  |                                     |                    | 0.7                                                | 0.7                |
|                              | Average EMI                               | -                             | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.435                                              | L=0.284<br>B=0.010 |
| Repointing                   | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  | 0.010                           | L=0.064<br>B=0.006 |                                     |                    |                                                    |                    |
|                              | Intervention (n)                          | -                             | -                  | 4                               | 4                  |                                     |                    |                                                    |                    |
|                              | Average EMI                               | -                             | -                  | 0.040                           | L=0.252<br>B=0.024 |                                     |                    |                                                    |                    |
| Plastic Repair               | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  |                                 |                    | 0.008                               | L=0.009<br>B=0.001 | 0.008                                              | L=0.009<br>B=0.001 |
|                              | Intervention (n)                          |                               |                    |                                 |                    | 3.33                                | 3.33               | 1                                                  | 1                  |
|                              | Average EMI                               |                               |                    |                                 |                    | 0.026                               | L=0.029<br>B=0.003 | 0.008                                              | L=0.009<br>B=0.001 |
| TOTAL EMI (1m <sup>2</sup> ) |                                           | 0.621                         | 0.421              |                                 |                    | 0.026                               | 0.032              | 0.443                                              | 0.304              |
| TOTAL EMI (OVERALL)          |                                           | 1665.7                        | 245.22             | 425.9                           | 152.402            | 256.2                               | 17.53              | 1239.0                                             | 177                |
|                              | Functional unit/Frequency of Intervention | Scenario 1: Stone Replacement |                    | Scenario 2: Repeated Repointing |                    | Scenario 3: Repeated Plastic Repair |                    | Scenario 4: Plastic Repair, then Stone Replacement |                    |
|                              |                                           | A                             | B                  | A                               | B                  | A                                   | B                  | A                                                  | B                  |
| Stone Replacement            | CO <sub>2</sub> e.m <sup>2</sup>          | 0.621                         | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.621                                              | L=0.405<br>B=0.015 |
|                              | Intervention (n)                          | -                             | 1                  | -                               | -                  |                                     |                    | 0.7                                                | 0.7                |
|                              | Average EMI                               | -                             | L=0.406<br>B=0.015 | -                               | -                  |                                     |                    | 0.435                                              | L=0.284<br>B=0.010 |
| Repointing                   | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  | 0.010                           | L=0.064<br>B=0.006 |                                     |                    |                                                    |                    |
|                              | Intervention (n)                          | -                             | -                  | 4                               | 4                  |                                     |                    |                                                    |                    |
|                              | Average EMI                               | -                             | -                  | 0.040                           | L=0.252<br>B=0.024 |                                     |                    |                                                    |                    |
| Plastic Repair               | CO <sub>2</sub> e.m <sup>2</sup>          | -                             | -                  |                                 |                    | 0.008                               | L=0.009<br>B=0.001 | 0.008                                              | L=0.009<br>B=0.001 |
|                              | Intervention (n)                          |                               |                    |                                 |                    | 3.33                                | 3.33               | 1                                                  | 1                  |
|                              | Average EMI                               |                               |                    |                                 |                    | 0.026                               | L=0.029<br>B=0.003 | 0.008                                              | L=0.009<br>B=0.001 |
| TOTAL EMI (1m <sup>2</sup> ) |                                           | 0.621                         | 0.421              |                                 |                    | 0.026                               | 0.032              | 0.443                                              | 0.304              |
| TOTAL EMI (OVERALL)          |                                           | 1665.7                        | 245.22             | 425.9                           | 152.402            | 256.2                               | 17.53              | 1239.0                                             | 177                |

Source: Adopted from Mahmud et al., (2017a; 2017b)

**Table 3: EMI (1m<sup>2</sup> and overall surface) over scenarios within 100y arbitrary maintenance period**

In the context of total EMI of 1m<sup>2</sup> as well as within selected maintenance arbitrary period (in this case 100 year period), it is recognised that the differences of the results value is mainly due the different resourcing locations between imported stone and salvaged material (as previously shown in Table 2 and Table 3 respectively). In the case of Bastion Middelburg, its imported laterite stones used for repair are procured and transported from Prachinburi, Thailand, which become the main impetus of high CO<sub>2</sub> emissions. Comparatively, due to material scarcity for St Paul's Church, brick has been used to replace the deteriorate laterite, lead to the philosophical debate e.g. like for like material is relatively not adopted.

It is widely known that the usage of salvaged material is emphasised to reduce the CO<sub>2</sub> emissions from transportation phase. It must be emphasised however, sound salvaged materials need to be carefully cleaned down and well sorted to suitable dimension and arranged in stacks corresponding to the various lengths. More importantly, they also can be obtained from various sources such as abandoned old buildings, salvage contractors and use-material dealers. This subsequently demands meticulous view from experts on the 'trade-off' situation between the cost of loss in historic fabric and CO<sub>2</sub> emissions. Heritage buildings are known for its uniqueness and therefore, their uniqueness should be retained through its fabric. Usage of incompatible material is unacceptable, even though it can be defensibly good in terms of CO<sub>2</sub> emissions. Historically, laterite stones of both case studies are found to be locally sourced and are abundant throughout the South region in West Malaysia (Mahmud et al., 2017a; 2017b). Considering this, significant efforts can be done in re-opening the old quarry to reduce CO<sub>2</sub> emissions through usage of locally sourced laterite stones rather than using incompatible material with unknown durability.

## **Conclusion**

It has been shown by this research that the usage of LCA is proven as environmental management tool to assist the reduction of CO<sub>2</sub> emissions expended from repair. Significantly, Green Maintenance model adoption for laterite stone appraisal in terms of environmental impact is proven to be a good approach in selecting the most sustainable repair for heritage buildings. In addition, the model also able to provides a sustainable solution, by giving priority towards repair options that have low CO<sub>2</sub> emissions. The results show that EMI of the model relay the 'true' CO<sub>2</sub> emissions for laterite stone repair, within selected maintenance time frame. This paper demonstrated that this can be achieved through the quantification 'true' CO<sub>2</sub> emissions from heritage buildings repair. Additionally, calculation procedures through formulaic expression of the model enable evaluation of EMI within 'cradle-to-site' boundary of LCA, based on selected case studies of heritage buildings. Notably, the model also gives preference to repair options that has high longevity, which consequently contributed to lower maintenance interventions and less intrusion to historic fabric. Most importantly, Green Maintenance model shows its capability as a tool for achieving informed maintenance decision, which enables adoption of sustainable repair approach for heritage buildings.

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