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Green Maintenance for Heritage Buildings: Low Carbon Laterite Stones Repair Appraisal

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Sustainability commonly denotes an integration of economic, environmental and societal domains. Low carbon repair of buildings also conforms to these broad domains. Environmental consideration in low carbon repair appraisal for heritage buildings has become increasingly important and this paper supports this expanding area. This paper gives an insight on how ‘Green Maintenance’ concept and methodology practically determine and ultimately substantiate appraisal on low carbon repair for laterite stones of selected multiple case studies of heritage buildings located at Historical City of Melaka, Malaysia. This paper also provides highlights of comparative study and analysis of these case study buildings on their common techniques and materials for laterite stones repair. This has been achieved through quantification of embodied carbon expenditure expended in laterite stones repair within ‘cradle-to-site’ boundary of Life Cycle Assessment (LCA) using formulaic expression and calculation procedure of ‘Green Maintenance’ model. The calculation procedures of the model were adopted to enable evaluation of CO_2 emissions in terms of embodied carbon expenditure expended from laterite stones repair for selected case studies during maintenance phase. It is found that stone replacement technique is considered as the most sustainable repair technique, mainly due to its high longevity of repair, in terms of generated Environmental Maintenance Impact (EMI) of Green Maintenance modelling. More importantly, EMI of the model relays the true value of CO_2 emissions contextualised within the longevity of repair and minimal intervention that allow low carbon repair appraisal approach.

1. Introduction: ‘Green Maintenance’ Concept

Discourse of heritage buildings conservation particularly in maintenance and repair had shift to an innovative level towards sustainability agenda. It may revolve around the cost analysis to ensure meaningful benefit over the investment or broad philosophical debate in conducting maintenance project such as least intervention, like for like material, honesty, integrity etc. (Bell, 1997). In greater analysis, the question is how philosophical vs. cost-guided maintenance may be beneficial to lessen the environmental impact of ensuring the survival of heritage buildings. As a solution, the ‘Green Maintenance’ concept and methodology support sustainability agenda that calls for protection of the cultural significance embodied in the fabric of heritage buildings while preserving other capitals such as economy and the environment. The concept takes philosophical factor, cost factor, and low environmental impact factor into evaluation. The intervention (repair technique) undertaken that comply with the three factors in Figure 1 will be considered as being the most sustainable. As one of the ways to promote low environmental impact, it is found that maintenance of heritage buildings has significant contribution of environmental impact in terms of energy and embodied carbon. Embodied carbon is CO_2 emissions released through the process of extraction, manufacturing, and transportation of materials that consume a fair amount of energy in terms of electricity and fuels in maintenance and repair. The fact is that 10 % of CO_2 emissions are contributed from the material sector. The maintenance and repair of heritage heavily depends on the material sector. The longevity of repair and the impact represented in Total Environmental Maintenance Impact (EMI) became an important variable in selecting the repair techniques in ‘Green

Maintenance' concept and methodology. The practicality in measurement of CO_2 using Life Cycle Assessment (LCA) will be tested in the case study of laterite stone buildings in historical city of Melaka, Malaysia.

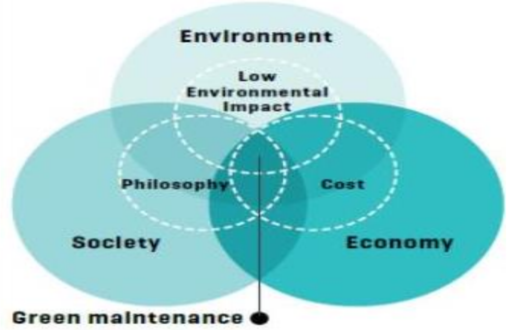

Figure 1: 'Green Maintenance' concept (Kayan, 2013)

2. 'Green Maintenance' Methodology

'Green Maintenance' put the priorities on low carbon material and repair techniques (either single or combination) selection during maintenance period based on the measurement of CO_2 emissions. The measurement of CO_2 emissions would cover the extraction of raw materials to the end of the product's lifetime (cradle-to-grave) of LCA boundaries, but in acquiring accurate result, the measurement is limited to cradle-to-site analysis (raw material extraction and processing, transportation, manufacturing, and transportation to the building site). 'Green Maintenance' sets out an insight on the relationship between maintenance and repair, and CO_2 emissions in selecting the low carbon repair for heritage buildings. Figure 2 shows the proposition of relationship between each intervention and CO_2 emissions characterised by its longevity (l) and embodied carbon expenditure (Ce) on the service graph condition. The downward sloping signifies the declining condition of the buildings over the life cycle of repair. Each intervention is important to keep the buildings at the optimal service condition, but it contributes to CO_2 emissions. Hypothetically, the more frequent the maintenance intervention, the greater the embodied carbon expended (Forster et al., 2011).

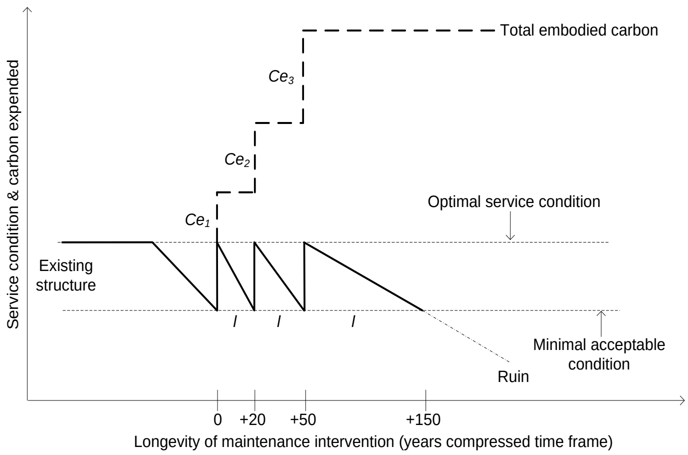

Figure 2: Relationship between longevity of repair and embodied carbon expenditure (Forster et al., 2011)

'Green Maintenance' gives higher preference to the repair technique that has high longevity which subsequently incurred lesser number of repeating interventions and may incur lesser embodied carbon expenditure over the life span of the building. There will be a single or combination of repair techniques in a certain maintenance period in practical. High consideration on numbers, type of repair, and the embodied energy and CO_2 expended in repairs are therefore paramount important in this evaluation. Every intervention is also influenced by other variables including material durability, degree of exposure, building detailing, quality of repair, and specification. The generated Total EMI (Eq(1)) is the product of area repaired (in this case is wall surface), material used in tonnage (t), and their respective Embodied Carbon Coefficient (ECC) added to the product of material used (t), CO_2 emission factor, and resourcing location (km) for respective frequency of repair (n) within hundred-year arbitrary period.

$\sum$ EMI cradle to site = Area repaired x {[Material used (t) x ECC] + Material (t) x Emission factor x Resource location (km)]} x Frequency of repair (n) / 100 y (1)

3. Case Studies: Bastion Middelburg and St Paul's Church

Embodied carbon expenditure of laterite stone of selected heritage buildings in this research can be evaluated and comparatively tested using EMI by adopting multiple case studies research approach. The epistemological underpinning for this research is grounded in case studies typically associated with the use of multiple sources of evidence and a strong context (Knight and Ruddock, 2008). Document of historical maintenance data and records of laterite stones repair is clearly a pivotal consideration in determining case studies approach. The selected case studies were located at the Historic City of Melaka, broadly known for its fort constructed with laterite stone. Several notable buildings designated within the Melaka Fort are the Bastion Middelburg and St Paul's Church. Bastion Middelburg was constructed in 1641 as part of a defence system, a large structure with another eight (8) bastions. Within the fort was entirely taken up by buildings and one of the remarkable buildings is St Paul's Church. St Paul's Church was built in mid-1560 by Duerte Coleho, enlarged by Jesuits. It has historically endured adaptive changes from being a college, a hospital, and a partial military function through the era of Portuguese, Dutch and British. Both case studies significantly show the capability of laterite stone to stand as a strong building material, being able to stand nobly through conflicts and with the test of time under tropical hot climate.

Table 1 summarised the construction profile of laterite stones for Bastion Middelburg and St Paul's Church generated by various resources and direct measurement. It is believed that the laterite stones were locally sourced from Ilha das Pedros (Pulau Upeh, Melaka, Malaysia) as can be seen on the laterite cutting over the island (Khoo, 1998). Presently, there are no active stone quarries within the area due to their closure. Physically, laterite stones for St Paul's Church are ferruginous deposits of vesicular structure, soft until it can be cut using a spade to be made into regular blocks when it is in freshly state. After it has been cut and exposed to the air and sun, it rapidly hardens due to the crystallisation of components of iron content sesquioxides (three atoms of oxygen with two atoms (or radicals) of clay soils). This makes it highly resistant to weathering. Beyond its uniqueness, little research has been done for this material particularly on maintenance and repair. Their maintenance and repair demanded attention in the Conservation Management Plan for Melaka (CMP) UNESCO World Heritage Site regarding the appropriate treatment that is closely related to materials, methodologies, techniques and workmanship.

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

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

A great deal of lime was required in construction of both case studies. Only 1 type of mortar was specified for Bastion Middelburg. Meanwhile, there is no exact proportion recorded in the maintenance document for St Paul's Church. By using various literatures to fit the purpose of this paper, it is identified that 3 generations of mortars cross cut each other based on Table 1. Emphasised that the appointed contractor should undertake analysis on lime mortar profiles. This is mainly to determine the proportion, started with selecting several samples of the existing pointing from different spots of the wall surface. These samples were taken to the lab to be analysed to determine compositions, mixture, proportion and respective resourcing location. It must be emphasised that the nature of maintenance and repair of two different buildings are differ where reconstruction works of the Bastion Middelburg only has been officially started in November 2007 and completed in 2008 (JWN, 2008). The project of Bastion Middelburg repair was consistently facing difficulties in finding locally available original laterite stones in large scale with proper guidelines. For St Paul's Church on the other hand, several interventions in between 2003 to 2012 had been done partially with guideline and better documentation due to the establishment of Jabatan Warisan Negara in 2008. It may set the bar for maintenance of 'newly' reconstructed of Bastion Middelburg. 'Green Maintenance' concept and methodology in this paper introduces the practical way for decision makers (conservationist and authorities) to select the most sustainable repair technique with a basis of CO_2 emissions in their analysis by using two different case studies with different variables e.g. nature, type of project, design, location.

3.1 Testing 'Green Maintenance' on Repair Technique Utilised

The number of repair options (scenarios) that may be beneficial to the technical and philosophical aspect of masonry conservation. For example, repeated repointing on deteriorated mortar joints would have limited effect on adjacent laterite structure. In contrast, the removal of deteriorated laterite stone and replacement with a new stone block unit logically requires removal of greater quantities of original fabric. It must be noted that certain combinations of laterite stones repair are more common than others. Stone replacement would be practically done only once, while plastic repair is commonly followed by natural stone replacement within selected arbitrary maintenance period. 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 3 repair techniques in 4 scenarios of repair in 100 y arbitrary maintenance period (Figure 3).

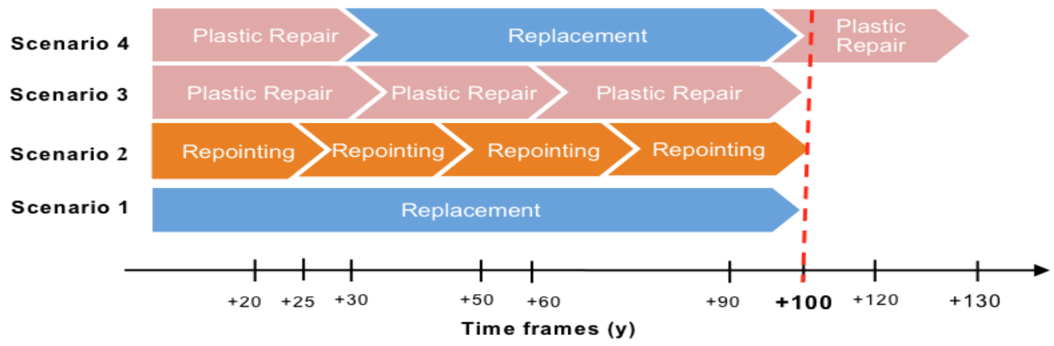

Figure 3: Repair scenario and time frames (Forster et al., 2011)

Testing of 'Green Maintenance' concept and methodology can be done by comparing embodied carbon expended, either a single or a combination of repair techniques for laterite stones, based on EMI (adapted from previous study) in selected maintenance arbitrary period. Several inputs are required in the calculation; Material data derived from ICE database by Hammond and Jones (2011) for Embodied Carbon Coefficient (ECC). Different values from foreign data were always influenced by national difference in fuel mixes and electricity generation. Open access of ICE database would increase the quality of this paper. 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. For a bigger scale project, the material needs a secondary process (e.g. manufacturing of brick dust). Transportation data (gate-to-site) derived from DEFRA (2008) in Kayan et al. (2017) based on 1.32×10^{-4} kg CO_2 emission factor based on Heavy Good Vehicle (HGV) in UK for 2005. CO_2 emission factor will be multiplied by weight of good and distance (shortest and most direct distance travelled from resourcing location) to the building site (see Table 2).

Table 2: Inputs for calculation

Material	ECC	Bastion Middelburg (A)	St Paul's Church (B)
Laterite Stone	0.781	Prachinburi, Thailand (1,797 km)	Salvaged Material
Brick	0.060	-	Tajia Industries, Melaka, Malaysia (15.5 km)
Sand	0.005	Bukit Senggeh, Melaka, Malaysia (37.7 km)	Bukit Senggeh, Melaka, Malaysia (37.7 km)
Brick Dust	0.22	-	Alai Kandang, Melaka, Malaysia (8.7 km)
Limestone	0.017	Kuari ISB, Alor Gajah, Melaka, Malaysia (46.1 km)	Kuari ISB, Alor Gajah, Melaka, Malaysia (46.1 km)
White Cement	0.469	Klebang Besar, Melaka, Malaysia (7.6 km)	Klebang Besar, Melaka, Malaysia (7.6 km)

4. Results and discussion

Table 3 shows embodied carbon expenditure associated with alternative repair techniques and scenarios undertaken on normalised 1 m^2 and overall surface Bastion Middelburg (2,666.67 m^2) and St Paul's Church (616.52 m^2) using functional unit of kg CO_2-eq/t/m^2 with their respective EMI attribution within 100 y arbitrary period.

Table 3: EMI (1 m^2 and overall surface) over scenarios within 100 y arbitrary maintenance period

	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_2-eq.m^2	0.621	L = 0.406 B = 0.015	-	-			0.621	L = 0.405 B = 0.015
	Intervention (n)	-	1	-	-			0.7	0.7
	Average EMI	-	L = 0.406 B = 0.015	-	-			0.435	L = 0.284 B = 0.010
Repointing	CO_2-eq.m^2	-	-	0.010	L = 0.064 B = 0.006				
	Intervention (n)	-	-	4	4				
	Average EMI	-	-	0.040	L = 0.252 B = 0.024				
Plastic repair	CO_2-eq.m^2	-	-			0.008	L = 0.009 B = 0.001	0.008	L = 0.009 B = 0.001
	Intervention (n)					3.33	3.33	1	1
	Average EMI					0.026	L = 0.029 B = 0.003	0.008	L = 0.009 B = 0.001
Total EMI (1 m^2)		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

Table 3 also reports embodied carbon expenditure of different repair techniques per 1 m^2 and overall surface for both case studies, categorised by different scenarios based on common practice in 100 y. Stone replacement possibly lasts about 100 y before it requires next replacement (1 time of intervention (n) of its EMI was attributed to the 100 y period). Repeated repointing and repeated plastic repair only lasts up to 25 y and 30 y 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 afters 30 y (1 time intervention of single plastic repair) and new stone is to be built in. As with scenario 1, the stone replacement will last beyond the 100 y period, therefore only 0.7 of its EMI is attributed. Comparative EMI in Table 3 were calculated for each repair techniques and scenarios within 'cradle-to-site' boundary of LCA as formulated Equation 1. It evidently shows that stone replacement has the highest embodied carbon both in per 1 m^2 (0.621 and 0.421 kg CO_2-eq/t/m^2) and overall surface (1665.7 and 245.22 kg CO_2-eq/t/m^2) for both Bastion Middelburg (A) and St Paul's Church (B). The results also revealed that repeated repointing contribute to the second highest amount of CO_2 emissions, but it has a low initial embodied carbon. This is mainly due to its low longevity of repair as denoted in Scenario 2. Considering this type of repair and the quality of workmanship, it is essential to repoint all overall surface of the wall within the same period that will subsequently contribute to greater amount of CO_2 emissions. Repeated plastic repair had low embodied carbon emissions for both case studies. In practice, the usage of plastic repair technique needs further intervention (e.g. stone replacement) due to its low longevity and lead to a further contribution of CO_2 emissions in 100 y (see Scenario 4). The usage of cement based in mortar is technically incompatible and will also limit the longevity which will later lead to frequent intervention and high CO_2 emissions. Stone replacement is an ideal technique to be utilised due to its high longevity and ability to deal with high area of deterioration. There are, however, significant differences found in the amounts of CO_2 emissions for both structures. By taking on total EMI of 1 m^2, it is recognised that the difference is mainly due the resourcing locations between imported stone and salvaged material (see Table 2). For Bastion Middelburg, imported laterite stones from Prachinburi, Thailand had become the main impetus of CO_2 emissions. Comparatively, due to material scarcity for St Paul's

Church, brick is alternatively used and has led to the philosophical debate e.g. like for like material. The usage of salvaged material is emphasised to reduce the CO_2 emissions from transportation phase. Sound salvaged should be carefully cleaned down, sorted to suitable dimensions and arranged in stacks corresponding to their various lengths. They perhaps 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_2 emissions The usage of incompatible of material though, is unacceptable in context of heritage building even though it can be defensibly good in terms of CO_2 emissions. Historically, laterite stones are found to be locally sourced and abundant throughout the South region in West Malaysia. Significant efforts must be done in re-opening the old quarry to reduce CO_2 emissions rather than using incompatible material with unknown durability.

5. Conclusions

The usage of LCA is proven as environmental management tool to assist the reduction of CO_2 emissions but it needs to be enhanced over time particularly for other exposed element in laterite structure such as foundation part, paint etc. This paper needs further data exploration and validation from multiple resources in a future study. In this paper, 'Green Maintenance' model is proven to be a good approach in selecting the most sustainable repair in maintenance through generated embodied carbon expenditure for laterite stone repair. 'Green Maintenance' gives a preference to a repair technique that has high longevity, which consequently offers less maintenance intervention and CO_2 emissions. The sustainable repair technique (stone replacement) suggested in the result needs further evaluation specifically on a compatible but imported material and incompatible but local sourced from short distance with variety scale of maintenance. It is noted that stone replacement is costly due to material requirement and skilled labour (workmanship) to conduct high quality of repair but the cost will decrease with improvement of physical condition. It clearly demonstrates that if maintenance works is planned properly through 'Green Maintenance' concept and methodology, the cost could be reduced in longer period of time and therefore its environmental impact as well. As low carbon trading in building industry becomes more prevalent, Green Maintenance' concept and methodology will be positively welcomed as our society moves towards a low carbon economy, materials, and 'green' procurement.

Acknowledgments

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