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GREEN MAINTENANCE FOR HERITAGE BUILDINGS: AN APPRAISAL APPROACH FOR ST PAUL'S CHURCH IN MELAKA, MALAYSIA

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ABSTRACT

Maintenance is an important conservation activity in ensuring the survival of heritage buildings for future generations. Knowledge and practices in this field have essentially shifted toward the sustainability framework, comprised of economic, societal, and environmental parameters. Regarding the environment, low carbon repair became the main item on the sustainability agenda for heritage buildings, and this case study supports this growing agenda by examining the "Green Maintenance" concept and methodology. The study aims to determine the applicability of Green Maintenance in assessing low carbon repair for laterite stone structures based on their embodied carbon expenditure, focusing on St Paul's Church within the Historical City of Melaka, Malaysia. In addition, this study highlights the nature of the maintenance and common techniques and materials used in laterite stone repairs. The results reveal that the most sustainable repair techniques are influenced by the longevity of the repair and the embodied carbon expenditure, represented by the Environmental Maintenance Impact (EMI) of Green Maintenance modeling. The EMI measures the amount of "true" CO_2 emissions in a sample of laterite-stone-repair techniques over the selected maintenance period, which can be calculated through the "cradle-to-site" boundary of the Life Cycle Assessment (LCA). The study also found that the quality of repair (workmanship), material durability, and selection of materials to deal with specific areas of deterioration are other variables to be considered when determining the most sustainable technique.

Keywords: Environmental Maintenance Impact (EMI); Green maintenance; Heritage building; Laterite stones; Life Cycle Assessment (LCA)

1. INTRODUCTION

At least half of the buildings that will be used worldwide in 2050 have already been built, and heritage buildings will soon constitute a significant portion of the global building stock (Levine et al., 2007). Kamal et al. (2008) reported that 39,000 of Malaysia's historical buildings were available in early 1992, and that number is expected to grow. In the UK, English Heritage (2010) announced that 1.5% of its historical buildings would be added into the existing building stock in a year, and 372,000 of them will be designated as heritage buildings. These trends therefore indicate that heritage buildings must be given priority in any development of technology, documents, policies, tools, and certification schemes toward shaping a more sustainable and better world.

The maintenance of heritage buildings is now largely accepted as a necessity for conservation

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(Sodangi et al., 2013). Recently, the discussion surrounding heritage-building conservation, particularly in maintenance and repair, has shifted toward sustainability. This shift has permeated the cost-analysis cycle, ensuring that there are meaningful gains on investment in maintenance projects, or sparked broad philosophical debates in conducting maintenance projects, such as the principle of least intervention, "like-for-like" materials, and honesty and integrity (Bell, 1997). Both analyses are important to ensure that high-quality interventions are undertaken in the maintenance of heritage buildings. The question raised is how philosophical vs. cost-guided approaches may be beneficial in reducing environmental impact (i.e., CO_2 emissions) while ensuring the survival of heritage buildings. In this paper, the "Green Maintenance" concept and methodology is proposed to support the sustainability agenda, call for the protection of the cultural significance embedded in heritage buildings, and simultaneously preserve economic and environmental capital (Kayan et al., 2016). Green Maintenance brings philosophical factors, cost, and environmental impact into the decision-making process; therefore, the repair techniques that best comply with these factors will be considered the most sustainable (see Figure 1).

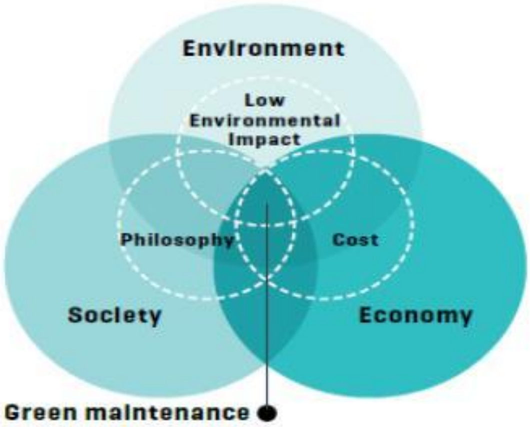

Figure 1 The green maintenance concept (Source: Forster et al., 2011)

The need for low environmental impact is primarily associated with the threat of global warming, exacerbated by the generation of CO_2 emissions and resource depletion and requiring the full attention of experts, governments, and citizens around the world. The Green Maintenance of heritage buildings offers a wide range of benefits related to the mitigation of embodied carbon expenditure in repair. "Embodied carbon" refers to hidden carbon incurred in the processes of raw material acquisition, material transportation, and the processing and manufacturing of buildings (Giesekam et al., 2016). Calculating embodied carbon is considered "ahead of the game" in combating today's environmental problems (De Wolf et al., 2017).

It is well known that the investment of energy in the construction of heritage buildings was made a long time ago. However, the maintenance of heritage buildings, aiming to double the buildings' lifespan, contributes to their high environmental impact through embodied carbon expenditure in repair. Materials related to maintenance account for more than 10% of total emissions, 70% of which is allocated to manufacturing and 15% to transportation (Rawlinson & Weight, 2007). Additionally, the construction industry consumes about 40% of the world's stone, gravel, and sand supply for maintenance, quarrying 50–300 million tons each year (Crishna et al., 2011). In the past, building materials were locally sourced, more economic, and easily quarried, such as laterite stone (Dimes & Ashurts, 1998). However, due to the scarcity of materials, local products are impossible to find, and materials must be outsourced from other countries if like-for-like repair strategies are preferred. Further, the weight of materials influences the mode of transportation and fuel consumption, which creates different amounts of

CO_2 emissions. The environmental impact caused by recurring embodied carbon (i.e., energy) expenditures in each maintenance project is subject to the longevity of the repair and the durability of materials (Dixit et al, 2010). The solution needed to change the way we think about this problem must engage every player in the reduction of CO_2 emissions in the built environment, which can be informed through the Green Maintenance concept and methodology.

Ideally, understanding the longevity of repair and the single impact over the arbitrary maintenance period will become important variables in selecting low-carbon repair techniques. In this paper, these variables are represented by the total Environmental Maintenance Impact (EMI), which is calculated using Kayan's (2013) simplified mathematical equation (see Equation 1). The carbon footprint of maintenance and repair from the resource extraction (cradle) to use phase (building site) of Life Cycle Assessment (LCA) will be tested through a case study of a laterite stone building (i.e., St Paul's Church) in the Historical City of Melaka, Malaysia. This paper applies a mathematical modeling method to quantify CO_2 emissions, which was developed by Forster et al. (2011) and adopted by Kayan (2013); thus, the present study represents a logical, practical continuation of the established theory. To attain a practical application of the Green Maintenance concept, the embodied carbon expenditure of repair must be evaluated using comparable and reproducible methods that can be adapted to different contexts (e.g., geographical settings, materials).

2. GREEN MAINTENANCE METHODOLOGY

By addressing the relationship between CO_2 emissions and maintenance and repair, the Green Maintenance methodology provides some insight into the selection of low-carbon repair techniques for heritage buildings. To understand the relationship between each intervention, they are characterized by their longevity (l) and embodied carbon expenditure (Ce), as shown on the service graph (see Figure 2; Kayan et al., 2017).

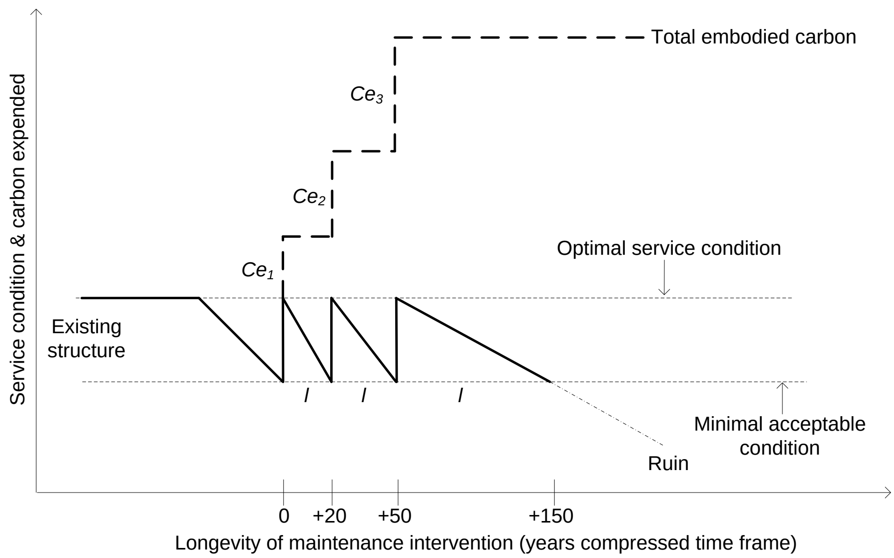

Figure 2 Relationship between longevity of repair and embodied carbon expenditure (Source: Kayan, 2013)

The downward slope signifies a declining condition over the life cycle of repair. Each intervention is important toward keeping the building at optimal service condition. Hypothetically, the more frequent the maintenance intervention, the greater the amount of embodied carbon expended (Forster et al., 2011). Thus, Green Maintenance places preference on repair techniques that have high longevity, which subsequently results in fewer interventions and decreased embodied carbon expenditure over the building's lifespan (Forster et al., 2013). Practically, however, there may be multiple repair techniques applied in a given maintenance period; hence, the number of interventions needed over the building's lifespan, the type of repair required, and the embodied carbon and CO_2 expenditures in repair are paramount to this evaluation (Kayan et al., 2017). Additionally, each intervention is influenced by other variables, including material durability, degree of exposure, building detailing, quality of repair, and specification. For example, a less durable material may not consume much energy during production but may require frequent replacement, thus resulting in higher total embodied carbon expenditure.

The total embodied carbon expenditure in maintenance and repair is calculated through a simplified equation, as follows:

$$\sum ce = A\ (comp)i * \sum[\, m_n * ECC](comp)i\,] + \sum[m_n\ * \ ef * distance\ (km)]\ (comp)i \qquad (1)$$

where $A\ (comp)i$ is the area of a particular component repaired, m_n is the mass (kg) per m^2, ECC is the embodied carbon coefficient stored in the database, $distance\ (km)$ is the distance of the repair material to the building site in kilometers, ef is the emissions factor stored in the database, $\sum cei_{tn}$ is the embodied carbon emissions of the maintenance intervention (repair technique).

To test the Green Maintenance model, the present study adopts a quantitative mixed-methods approach, whereas the case study was mainly used to collect data on maintenance (i.e., conservation reports and interviews). To quantify the CO_2 emissions from the repair of St. Paul's Church, several steps needed to be followed, as illustrated in Figure 3.

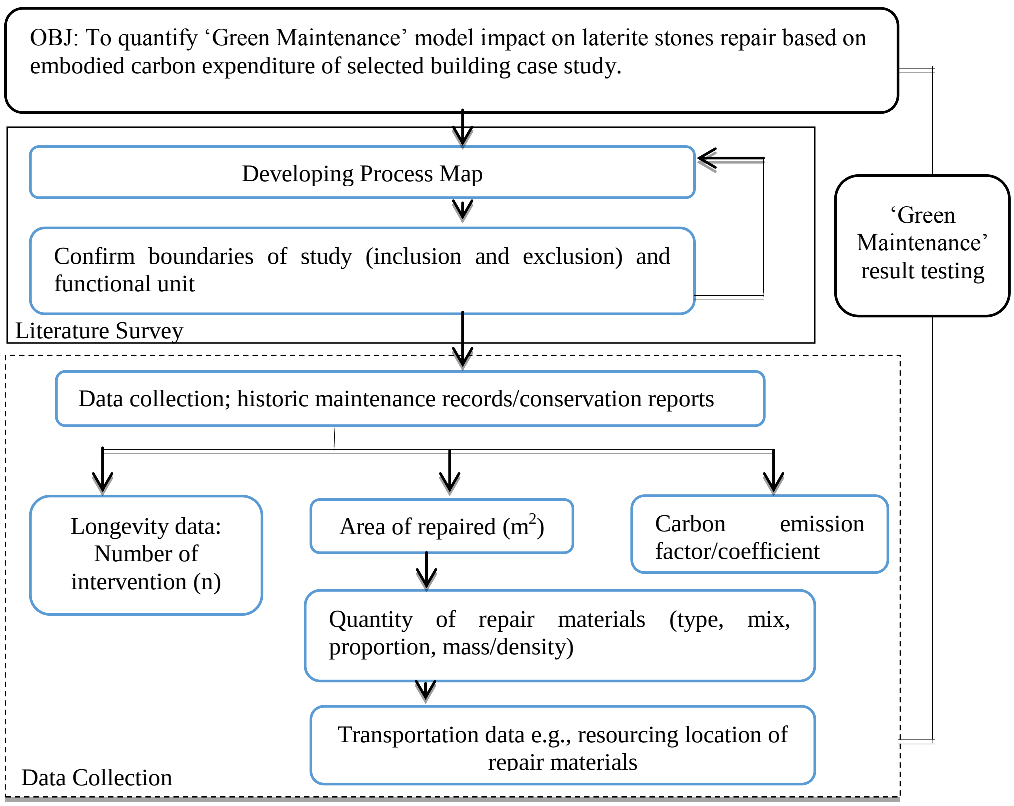

Figure 3 Research flow

3. PROFILE OF ST. PAUL'S CHURCH

St. Paul's Church is the oldest European building in Southeast Asia, located on the summit of St. Paul's Hill in the Historical City of Melaka, Malaysia, which is representative of the network of Portuguese, Dutch, and British colonials who settled the area (see Figure 4). First built in the 1560s by Duarte Coelho, St. Paul's Church was later expanded by Jesuits using laterite stone blocks as the main building material. The building was complex, described as a beautiful, hip-roofed structure that could accommodate twenty people in a single meeting space (Tan, 2015). The shape of the building is symmetrical and rectangular, containing two verandahs, a large hall, two rooms on the upper floor, and an unfinished chancel and sacristy (Tan, 2015).

Figure 4 St. Paul's church, Melaka, Malaysia

Historically, St. Paul's Church adapted too much change through its use as a college then a hospital. Due to its prominent location, which made it the prime target of Portugal's enemies, it was eventually converted into a military structure. During this time, many repairs were needed in order to strengthen the structure, using coral rock as filler between the Portuguese installment of laterite stone and the yellow-colored bricks and plaster laid during Dutch's occupation (Khoo, 1997). After the establishment of Christ's Church, however, St. Paul's Church was left as a graveyard. The British continued its military use during their occupation until the demolition of Melaka Fort. Thereafter, the church was largely neglected until a series of renovations led by the Melaka Historical Society in the 1930s (Tan, 2015). Its history proves the capability of laterite stone as a sustainable building material, standing nobly for more than 500 years through countless conflicts and wars.

Regarding the evaluation of its maintenance, an external wall of St. Paul's Church was chosen to provide consistent measurements of the variables highlighted by Green Maintenance, such as building exposure and detailing. Under the hot and tropical climate, the building tends to weather rapidly, which is exacerbated by the lack of a roof to protect the interior (see Figure 5). However, the most common repair technique used in the interior is repointing rather than stone replacement, which indicates direct relationship between the severity of deterioration and the rate of exposure, which should be investigated in future research.

Figure 5 Exposed interior of St. Paul's Church, Melaka, Malaysia

Table 1 summarizes the profile of laterite stones used in the external wall of St. Paul's Church, which was generated from site surveys and mathematical calculations. It is believed that the laterite stones were locally sourced from Ilha das Pedros (Pulau Upeh, Melaka, Malaysia) and Cape Ricado (Port Dickson, Negeri Sembilan, Malaysia), as evidence of laterite cuttings can be seen across the island and surrounding areas, as well as from materials salvaged from other buildings built by the Portuguese and the Dutch (Khoo, 1997). However, there are no active stone quarries within the area at present (Zulasmin & Ibrahim, 2007).

Table 1 Construction material of St Paul's Church

	Laterite Stone	Dutch Brick
Type of Stone		
Total Wall Surface	603.52m^2	13m^2
No. of Stone Blocks Used	2,736 blocks	1,300 blocks
Size of Stone (mm/block)	700mm×300mm×300mm	215mm×125mm×40mm
Mass of Stone (t/block)	±0.1 t/block	±0.002 t/block

Lime-based mortar is the most common building material found in the bedding, pointing, and finishing of many heritage buildings, including St. Paul's Church (Mydin, 2017); however, there is no exact ratio for the mortar mixes recorded in any of the building's maintenance documents. To achieve the aims of the present study, Khoo's (1997) observations are taken as a reference, who distinguished between two cross-cutting generations of concrete and mortar. The earlier mortar mix is composed of lime and sand; a thin layer of smooth, rounded laterite pebbles; and some other material (e.g., coral, angular pieces of charcoal, or exfoliating oyster shells). The later mortar shows better workmanship to an extent, as its sand matrix is more evenly sorted, containing coarse granules but not the fine granules found in the earlier mortar. However, the original structure was also cemented in modern mortar (see Figure 6), which obscures the earlier and later mixes.

Figure 6 Modern mortar for the pointing of St. Paul's Church

To quantify these mixes, the earlier mortar is comprised of a 1:3 ratio of limestone and sand, while the later mortar contains a 1:1:2 ratio of limestone, brick dust, and sand (Matias et al., 2016). "Modern mortar" refers to a lime-based material used by the Bastion Middleburg, which, according to guidelines underlined in its reconstruction, is constructed from a 1:1:3 ratio of limestone, white cement, and sand. It must also be noted that the nature of the repair of St. Paul's Church is different from that of other laterite structures within the Historical City of Melaka, particularly due to several interventions occurring between 2000 to 2012. During this period, some interventions were done with guidelines and were better documented due to the establishment of the Malaysian Department of National Heritage in 2008. The Green Maintenance concept and methodology outlined in this paper may aid decision makers, such as conservationists and government authorities, on selecting the most sustainable strategies that can handle the varied nature of the maintenance and repair of heritage buildings.

4. LATERITE-STONE REPAIR SCENARIOS

There are four common repair techniques in the maintenance of heritage buildings, known as stone replacement, plastic repair, repointing and pinning, and consolidation, which are selected according to their relative levels of intrusion on the original material. There are several repair options (i.e., scenarios) that may be beneficial in merging the technical and philosophical aspects of masonry conservation. For example, the repeated repointing of deteriorated mortar joints would have a limited effect on the adjacent laterite structure. In contrast, the removal of deteriorated laterite stone and replacement with new stone blocks logically requires the removal of greater quantities of the original material. It must be noted that certain combinations of laterite stone repair techniques are more common than others. Stone replacement could be practically done only once, while plastic repair is commonly followed by natural stone replacement within a given maintenance period. Conversely, it would be highly unusual to replace the stone and then conduct a plastic repair intervention within the same period (Kayan, 2013). From an extensive examination of the collaborative partners that are responsible for the upkeep of St. Paul's Church, such as the Melaka Museums Corporation and the Malaysian Department of National Heritage, both of which verified the results, there were three repair techniques found to be modeled on the building's EMI over the last 100 years (Forster et al., 2011). The laterite stone structure of St. Paul's Church has lasted for more than 500 years and is still in good condition; thus, to estimate the best technique for longevity, an average maintenance period of 100 years is used in the present study. Figure 7 defines four scenarios for the maintenance of a laterite stone structure over this period.

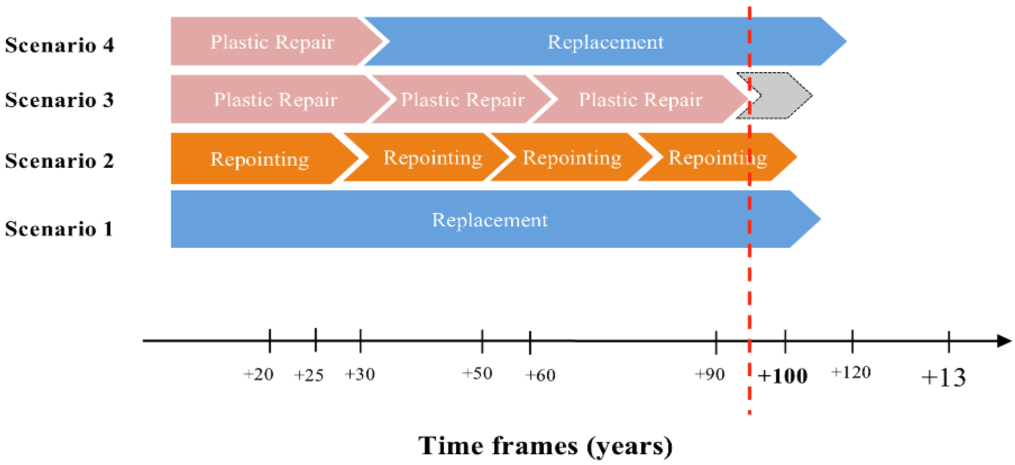

Figure 7 Repair scenario and timeframe (adapted from Forster et al., 2011)

3.1. Stone Replacement

Stone replacement is a repair technique that involves seriously decayed stonework, in which the decayed stone is dug out then replaced with a newer matching one (Hyslop, 2004). In the case of St. Paul's Church, it was found that bricks were sometimes used to replace the original laterite stones (see Figure 8). The material life expectancy of 100 years may lead to fewer maintenance interventions in the study period (see Scenario 1 in Figure 7).

Figure 8 Bricks for stone replacement

3.2. Plastic repair

Plastic repair, also known as mortar repair, involves seriously decayed stonework as well, but it only affects the surface area (Dime & Ashurt, 1998). Typically, the decayed stone must be cut back, then lime-based mortars are applied to the surface (Hyslop, 2004). In the present case, this technique is limited to plastering and patching (see Figure 9). The effects of this technique generally lasts for only 30 years and thus must be periodically reapplied (see Scenario 3 in Figure 7; Forster et al., 2011; Kayan, 2013). In some cases, such as in Scenario 4, the decayed stone may not withstand repeated plastic repair and thus must be replaced with new stone.

Figure 9 Mortar patching over the laterite wall surface

3.3. Repointing

Repointing is the most common technique for the repair of loose, open, crumbly, and/or washed-out bedding and jointing mortar in a wall (see Figure 10; Dore et al., 2013).

Figure 10 Repointing technique used on St. Paul's Church (50–100mm thick)

Normally, the mixture consists of binders and sand, which is available in a pre-mixed package. To repair defects and decay, repointing involves the removal of the failed jointing mortar (to a depth of at least ¾ inch) and applying new mortar as a finishing to replicate the original mortar style (Durnan & Muir, 2006). If more than 25% of the wall needs to be repointed, the rule of thumb is to repoint the entire wall structure, which must involve the correct tools, such as a thin chisel or pointing tools, and skilled craftspeople (Historic Scotland, 2007). The durability of the repointing will depend on several factors, including the mortar used, the finished profile of the mortar joint, and the workmanship, all of which may affect the frequency of repair and lead to a higher number of CO_2 emissions. The normal frequency of repointing is at least 25 years, which, in the study period of 100 years, would incur four times as many emissions as the stone replacement technique (see Scenario 2 in Figure 7; Kayan et al., 2017). The bulk volume of material may also be crucial, especially when dealing with a large area of repair.

3.4. Calculating EMI

Based on the data collected, each repair scenario is defined by the mass of stone used (tons/*t*; a dimension of the stone replacement technique), the lime–mortar jointing ratio, the pointing thickness, the depth of the wall, the minimum depth undercut or cutback basecoats, and the later patching finishes (specifically for plastic repair). Several inputs are required in the calculation of embodied carbon emissions within the cradle-to-gate and gate-to-site assessments, as shown in Equation 1. The material data, or embodied carbon from cradle-to-gate, was derived from Crishna et al. (2011), while the embodied carbon coefficient (ECC), or cradle-to-gate impact, was adopted from Hammond and Jones (2008) (see Table 2). A moderate ECC was applied to the salvaged materials (i.e., laterite and brick), as they needed to be processed (re-cut) and transported a very short distance. It should be noted that while the variations in foreign data are influenced by national differences in fuel mixtures and electricity generation, open access to industry-generated values contained in Inventory of Carbon & Energy database would increase the quality of the present study. The transportation data (gate-to-site), derived from Department for Environment, Food and Rural Affairs (2008), is based on a CO_2 emission factor of 1.32×10^{-4} kilogram, which is the 2005 definition of a heavy goods vehicle (HGV) in the UK. The CO_2 emission factor will be multiplied by weight of goods over distance to building site (i.e., the most direct distance traveled from the resourcing location; see Table 2).

Table 2 Inputs for calculation

Material	ECC ($kgCO_2e/t/m^2$)	Resourcing Location
Laterite Stone	0.781	Salvaged Material/Prachinburi, Thailand (1,797 km)
Brick	0.060	Tajida Industries, Melaka, Malaysia (15.5 km)
Sand	0.005	Bukit Senggeh, Melaka, Malaysia (37.7 km)
Brick Dust	0.220	Alai Kandang, Melaka, Malaysia (8.7 km)
Limestone	0.017	Kuari ISB, Alor Gajah, Melaka, Malaysia (46.1 km)
White Cement	0.469	Klebang Besar, Melaka, Malaysia (7.6 km)

4. RESULTS AND DISCUSSION

From the mathematical calculations, the embodied carbon expenditure (1 m^2) and the total EMI (616.52 m^2) of the overall exterior wall of St Paul’s Church was generated (see Table 3 and Figure 11). These values are based on the foundational knowledge provided in LCA studies, which is derived from the functional unit or can be applied to the whole external wall elements to provide an alternative scenario in long run (Dixit et al, 2010; Padfield et al., 2012).

Table 3 Total embodied carbon expenditure ($kgCO_2e/t/m^2$) of repair within a period of 100 years

		Scenario 1 Stone replacement	Scenario 2 Repeated repointing	Scenario 3 Repeated plastic repair	Scenario 4 Plastic repair, then stone replacement
Stone replacement	$kgCO_2e/m^2$	L: 0.406 B: 0.015	-	-	L: 0.406 B: 0.015
	Number of interventions (n)	1	-	-	0.7
	Total Average EMI	L: 0.406 B: 0.015	-		L: 0.284 B: 0.010
Repeated Repointing	$kgCO_2e/m^2$	-	L: 0.063 B: 0.006	-	-
	Number of interventions (n)	-	4	-	-
	Total Average EMI	-	L: 0.252 B: 0.024	-	-
Plastic repair	$kgCO_2e/m^2$	-	-	L: 0.009 B: 0.001	L: 0.009 B: 0.001
	Number of interventions (n)	-	-	3.33	1
	Total Average EMI		-	L: 0.029 B: 0.003	L: 0.009 B: 0.001
Total Average EMI		0.421	0.28	0.032	0.304

*Note; L: Laterite; B: Brick

Table 3 shows an average EMI of 1 m^2 for the exterior wall of St. Paul's Church, also known as the functional unit of embodied carbon per m^2 ($kgCO_2e/m^2/t$). The average EMI could be used as a generic value for future conservation projects. From the results, it can also be concluded that stone replacement creates a significant amount of CO_2 emissions per intervention, compared to repeated repointing and repeated plastic repair in $1m^2$. In addition, the testing of total EMI linked to the cumulative impact of maintenance in a 100-year period, with respect to longevity of repair, revealed a significant increase in CO_2 emissions in Scenario 4, in which stone replacement is conducted immediately after the first cycle of plastic repair, compared to the single stone replacement in Scenario 1. Therefore, the principle of minimal stone replacement, as highlighted in theory, should be tailored to reduce CO_2 emissions.

In practice, the scale of conservation projects in Melaka depend on the budget, and most projects are conducted as a single intervention; thus, the evaluation of embodied carbon expenditure should be extended to large scale conservation projects. The value of the functional unit will be used in the calculation of total EMI for St. Paul's Church, which consists of multiplying the EMI with the total surface area of the exterior wall (616.52 m^2).

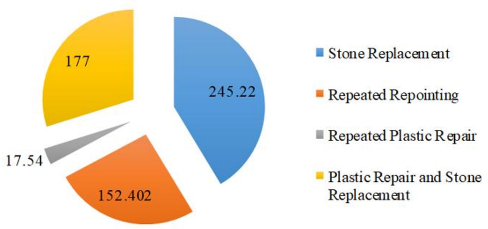

Figure 11 Total EMI ($kgCO_2e/t/m^2$) of the exterior wall of St Paul's Church

As evidenced in Figure 11 and Table 3, stone replacement had the highest embodied carbon expenditure, both per 1 m^2 (0.421 $kgCO_2e/t/m^2$) and across the total wall surface (245.22 $kgCO_2e/t/m^2$), over the study period of 100 years, whereas the repeated plastic repair technique contributed a small amount of CO_2 emissions (17.55 $kgCO_2e/t/m^2$) across all interventions under study. In practice, however, the plastic repair technique requires supplementary techniques and/or interventions (e.g., stone replacement) due to its low longevity of repair, as illustrated in Scenario 4 (see Figure 7), which results in a relatively high amount of CO_2 emissions (177 $kgCO_2e/t/m^2$) over a period of 100 years. Additionally, based on the total generated EMI in Figure 11, the results reveal that repeated repointing contributed 152.402 $kgCO_2e/t/m^2$, although Table 3 shows a low initial embodied carbon expenditure per functional unit in 1 m^2 (0.28 $kgCO_2e/t/m^2$) compared to other scenarios and techniques. In this case, it is important to consider the repair strategies that are most suitable for dealing with the particular area of deterioration. For example, the quantity of repair materials required for repointing highly depends on the thickness and depth of the original pointing. The thicker and deeper the pointing (in this case, between 50–100mm), the more lime mortar needed (kg). Considering the large area of deterioration and high rate of exposure of buildings such as St. Paul's Church, this could significantly impact the embodied carbon expenditure. In plastic repair, the quantity of lime mortar can also be viewed in terms of the different mixtures required to match the façade, which depend on the depth, undercoat, topcoat, and thickness of the patch. In this case, lime mortar is not cost effective in the long term when dealing with a large area of deterioration. Instead, white cement is used in several interventions, as it is cheaper and more readily available than lime-based materials; however, it is technically incompatible with the original material and will thus limit the longevity. Clearly, the selection of low-carbon repair materials should not only consider the single value of embodied carbon expenditure but also the durability.

Based on this discussion, the Green Maintenance methodology, when used to determine the value of CO_2 emissions in the maintenance of St. Paul's Church, shows that the total surface area being repaired, the longevity of repair, and the workmanship has a strong influence on which repair technique is the most sustainable. Thus, among the techniques under study, stone replacement is the best solution due to its high longevity, applicability as a single intervention within a period of 100 years, and ability to deal with large area of deterioration. Although stone replacement will emit a high amount of CO_2 emissions due to its processes of quarrying, manufacturing, and transporting material, these processes are done only once within the given period. In principle, the more frequent the maintenance interventions, the higher the embodied carbon expenditure (Kayan et al., 2017). The less durable materials used in other techniques may not consume as much energy as stone replacement; however, they may require more frequent application, thus resulting in a higher expenditures. Furthermore, as mentioned earlier, frequent interventions are largely unfeasible in Malaysia, due to the nature of maintenance projects based on budget allocation.

When considering stone replacement, an issue arises concerning the scarcity of laterite stone. As shown in Table 1, brick has been used to replace the deteriorated laterite in many areas, sparking a philosophical debate over the use of like-for-like materials and honesty as the pillars of Malaysian society. This creates demand for expert perspectives on the "trade-off" between the loss of historical materials and the reduction of CO_2 emissions (Forster, 2010). When they are initially applied, repairs can clearly be seen; however, the blurring of the old and new materials may occur as patination develops. If like-for-like repair strategies are selected, the use of salvaged material is proposed to reduce CO_2 emissions generated during the transportation phase. In another case study, conducted by Azizul (2015), it was revealed that the laterite stone used in the reconstruction of the Bastion Middleburg, imported from Prachinburi in Thailand (1,797 km), was one of the highest contributors to the CO_2 emissions generated from that project. It was also found that the use of salvaged material is not as easily incorporated in building practices that typically require locating the source early and planning from the start of a dilapidation survey. In this case, Kayan et al. (2018) suggested that significant efforts should be made toward reopening the old quarries, known as snatch quarrying, which would entail a temporary opening to obtain a limited supply of laterite stone, rather than using bricks with unknown durability. The large availability of laterite stone at an old quarry located in Pulau Upeh, Melaka, Malaysia (see Figure 12) could be optimized to ensure the feasibility and quality of future stone-replacement projects. As the Green Maintenance methodology has provided a base repair area of 1 m^2 when quantifying CO_2 emissions, the typical amount of laterite stone required to fill this area is around five blocks. Ideally, the process of extracting and quarrying laterite stone will not be the main cause of CO_2 emissions per se, as the embodied energy expenditure reported by Praseeda et al. (2014) was solely caused by the diesel-operated machinery used in the initial cutting process, either in soil or on a bed of laterite (0.0069 MJ/kg contributed for 1 block of laterite with the dimensions of 400×200×250 mm). Comparatively, if the process is handled manually, there will be zero impact on CO_2 emissions due to extraction and quarrying. Therefore, it is possible to significantly reduce the CO_2 emissions contributed by stone replacement.

Figure 12 Old laterite stone quarry at Pulau Upeh, Melaka, Malaysia

5. CONCLUSION

In creating a better future, the Green Maintenance model can be used to generate the embodied carbon expenditure of a maintenance project, thus aiding in the selection of the most sustainable technique for the repair of laterite stone structures, such as St. Paul's Church. Ultimately, it provides an environmental point of view toward the repair scenarios available, revealing those that have the lowest amount of CO_2 emissions. Stone replacement is considered the most sustainable repair technique, compared to plastic repair, pointing, repeated plastic repair, repeated repointing, and plastic repair combined with stone replacement. However, stone replacement requires further discussion regarding its philosophical implications (e.g., like-for-like materials), as the usage of compatible materials will ensure higher longevity compared to new materials, due to their unknown durability. The present study can be used as a launching pad for further discussion on compatible yet imported materials versus incompatible yet locally sourced materials, using a variety of maintenance projects at different scales. In addition, although stone replacement is costly due to the amount of materials and skilled labor (workmanship) required, if the maintenance project is planned properly through the Green Maintenance concept and methodology, the cost could be reduced over a longer period. The amount of total embodied carbon expenditure, as measured by the EMI, will enable decision makers to conduct a deeper analysis of the philosophical, economic, and environmental concerns involved in the maintenance of heritage buildings. To develop wider understanding in academia and industry, further studies on Green Maintenance must be undertaken to produce rigorous evidence regarding low-carbon buildings and present such evidence in an accessible language.

6. ACKNOWLEDGEMENT

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