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# Environmental and Economic Analysis of Selected Pavement Preservation Treatments

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**Abstract**

Pavements are one of the highest assets and represent massive investment. The need to design and provide a sustainable maintenance service is becoming a priority and this comes mutually with the intentions to reduce impacts caused by maintenance treatments to the environment. This paper through a case study presents a Life Cycle Cost and Assessment technique during a 30 year analysis period to measure the cost effectiveness, embodied energy and carbon emissions of selected preservation treatments. These treatments can either be applied separately or in combination during the preventive maintenance of road pavements. This study entails three life cycle phases of material extraction and production, transportation and construction of maintenance activities. Through a literature review, raw materials energy and emission inventory data was averaged followed by the analysis of the equipment involved by using the specific fuel consumption to calculate the energy and emissions spent by the machine and finally the selected treatment energy and emissions was computed. Results show that preservation treatments can have an LCC of 30-40 % and embodied energy and carbon emission of 3-6 times lower than the traditional approach. This study bridges gaps in literature on integrated evaluation of environmental and economic aspects of preservation treatments.

*Keywords:* Pavements; Sustainability; Life Cycle Assessment; Life Cycle Cost; Preventive Maintenance.

## 1. Introduction

The road network has an important role to play in the development of a country for social and economic growth. A good road network is also important for connectivity, movement of goods and job creation. Zambia has a total gazette road network of 67671 km of which 60% comprises the Core Road Network (CRN).The CRN infrastructure in Zambia consists of a sparsely interconnected network of Trunk (T), Main (M), District (D), Primary Feeder (PF) and Urban (U) roads [1].

The Government of the Republic of Zambia (GRZ) has implemented three notable initiatives in the road sector. Firstly, to improve inter-urban and urban connectivity and accessibility; this will see over 12000km of roads rehabilitated or upgraded to bituminous standard at a total cost of US$8.5 billion. Secondly, GRZ has developed a ten year (2015 – 2024) National Maintenance Strategy which aims to reduce road maintenance backlog and to improve the general condition of CRN. The estimated cost of implementing the entire strategy over the 10 years is US$1.5 billion [2]. Thirdly, the Output and Performance Based Road Contracting (OPRC), which underpins sustainability in road maintenance, is a major key decision adopted [2-3].

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The pre-occupation over the years has mostly been with new constructions and upgrading at the expense of road maintenance. The rehabilitation technique most currently used for asphalt pavements on highways is an asphalt overlay. Pavements in Zambia have structurally deteriorated to a great degree because implementation of the pavement maintenance strategy has not yet been fulfilled. It is clear that with such a large pavement network, the GRZ is challenged to maximize available funds to maintain the network in the best condition possible [2].

It is clear that under the current policies and funding levels in the road sector, it would be inevitable to expect further deterioration in the quality of pavements. It is therefore wise to start implementing cost effective methods of preserving the existing pavements. Various studies have shown that waiting for the pavement to deteriorate beyond its service life before attempting to repair is tantamount to having major rehabilitation and reconstruction activities which would come with huge sums of money that a developing country like Zambia does not need at the moment [4-8]. In Figure 1 below, Galehouse et al. estimated that $1 invested towards pavement preservation at the beginning of the pavement life cycle could save in excess of $5 in the future [7].

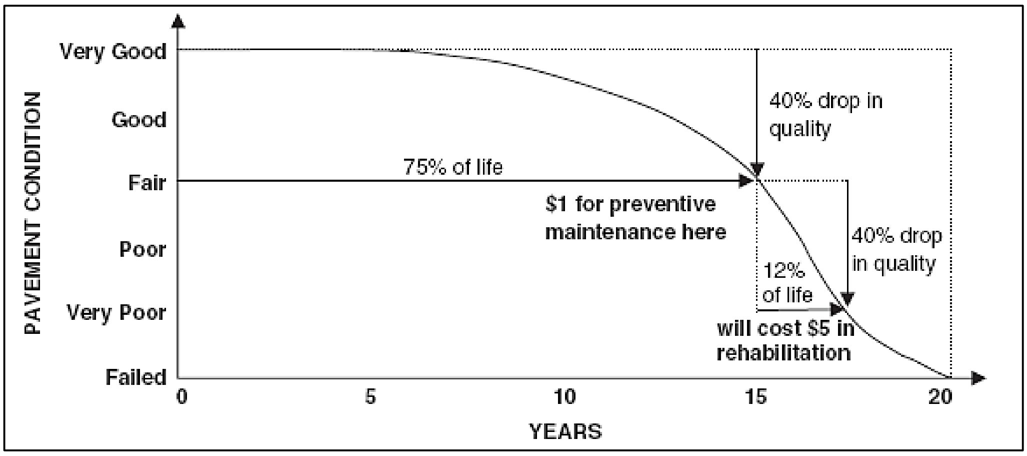



**Figure 1. Relationship between pavement condition and life cycle costs**

With the impeding energy crisis and climate change impacts the world is facing, reducing the environmental impacts of pavement preservation treatments has become mandatory. Most published papers on environmental LCA have been conducted in Europe, USA, China but limited work has been done in Africa. The predominance of these studies lacks an integrated evaluation of both environmental and economic aspects of pavement preservation treatments [9-11]. The few studies which have conducted such analyses show variations in the base data, goal and scope definitions and analysis methods and thus comparison among such processes cannot be readily made [12-15]. It is for this reason that a life cycle assessment of cost, embodied energy, carbon emission ($CO_2e$) has been developed encompassing eleven treatment scenarios suiting the Zambian landscape. This LCA model not only considers the material extraction and production, construction maintenance but also the disposal into its system boundary.

The main objective of this study is to conduct; i) an LCCA by finding the cost effectiveness of selected preservation treatments (Micro-surfacing, Chip+Fog Seal, Thin Hot Mix Asphalt (HMA) Overlay, Mill & Fill) to be applied on Zambian roads by identifying and evaluating the cost benefits of the preservation treatments compared to the "do nothing" alternative; ii) an LCA of maintenance activities by comparing the embodied energy consumptions and carbon emissions of the studied treatments.

The goal of this paper is to quantify and compare the life cycle environmental and economic performance of multiple maintenance preservation treatments in order to improve the pavement sustainability in Zambia. The scope follows a cradle to grave approach and takes into account guidelines outlined by International Organization for Standardization 14044.

## 2. Literature Review on Preservation Treatments, Life Cycle Cost and Assessment Techniques

### 2.1. Preservation Treatments

Pavements are one of the highest assets and represent tremendous investment. With the vast amount of resources dedicated to pavements, topped with the fact that they are under constant public scrutiny, it is imperative that the serviceability of pavements be maintained in an efficient and effective manner to get the most out of investments [16]. The most effective method for maintaining pavement serviceability is to implement a preservation program, which is a planned system of pavement surface treatments designed to extend the life of a pavement using the fewest possible resources (money, materials, energy and time). To sum up the objective of pavement preservation program: it is deciding on "the right treatment on the right pavement at the right time" [16-17].

Preventive Maintenance, as defined by American Association of State Highway and Transportation Officials (AASHTO), is "a planned strategy of cost effective treatments to an existing roadway system and its appurtenances that preserve the system, retards future deterioration and maintains or improves the functional condition of the system without substantially increasing structural capacity" [18]. Preventive maintenance is a tool utilized for pavement preservation. It is specifically utilized on pavements that are in good condition with a considerably long service life. There are three main components of pavement maintenance: routine maintenance, preventive maintenance and minor rehabilitation [18]. The pavement maintenance, no matter the choice amongst the three, is to extend the service life of a road, minimize the life cycle cost and reduce the environmental impacts. What is worth noting here is that, these treatments are applied on pavements with a high structural support capacity and having minimal distresses [18]. This paper examines and briefly explains the four types for use on Zambian roads.

### 2.2.1. Micro-Surfacing

A mixture of cationic polymer modified asphalt emulsion, mineral aggregate, mineral filler, water and other additives properly and carefully proportioned, mixed and laid on a paved surface. Micro-surfacing is much more effective than chip and slurry seals. It differs from chip and slurry seals in that the latter uses a thermal curing process while micro-surfacing uses a chemically controlled process. Owing to its robustness and flexibility, micro-surfacing can be used as a preventive, routine and corrective maintenance strategy [19-21].

### 2.2.2. Chip Seal + Fog Seal

This is an application of asphalt binder on existing pavement followed by a layer of aggregate chips. The treatment is then rolled to embed the aggregate into the binder. There are a number of variations of chip seals, the more common ones being single and double chip seals. A single chip seal is an application of binder followed by the aggregate while a double chip seal is a built up seal coat consisting of multiple applications of binder and aggregate. To put it into perspective, a double chip seal involves a spray application of binder, spreading a layer of aggregate, rolling the aggregate for embedment, then applying an additional application of binder, spreading another layer of aggregate usually half the base aggregate gradation and finally rolling [22].

Fog Seal is an application of diluted emulsion to augment the pavement surface and retards ravelling and oxidation. It involves the application of a slow setting asphalt emulsion diluted with water normally in the ratio of 1 to 1 sprayed directly to an existing pavement. The sole purpose is to renew the old HMA that has become brittle and dry. This treatment has been found to not only seal surface voids and cracks but also to inhibit ravelling [23].

### 2.2.3. Thin Hot Mix Asphalt Surfacing

This treatment is used for maintenance and/or rehabilitation, a method used to extend the life of pavements that are structurally sound and have minimal rutting. A thin overlay consists of an overlay of hot mix asphalt of 30-40mm thickness. It is a mixture of well graded aggregates, asphalt binder and filler mixed hot in a mixing plant. The types of thin hot mix asphalt surfacing are Dense-Graded Systems, Open-Graded Systems, Gap-Graded Systems and Ultra-Thin Systems (NovaChip®).This preservation technique requires careful attention to the material mix design procedure. Things to consider include high quality aggregates, the use of a softer asphalt binder or modified binders and the mix design itself should be similar to HMA structural mixes [24-25].

### 2.2.4. Mill and Fill

This is a better preventive maintenance strategy compared to simple HMA overlay, in which 20-25mm of the old asphalt is milled out and then resurfaced with a 40-50mm of new HMA. Milling is not expensive and has low emissions, but is nonetheless more beneficial to a pavement with irregularities. The advantages of milling include; compatibility of the new pavement with the existing drainage system, maintaining the required clearance for vertical obstacles and protection of new layers from the propagation of the distress existing in the previous layers. The final pavement of a mill and resurface has the same effect as a thin overlay with an added advantage of preventing the accumulation of asphalt layers thereby improving the vertical load transmission to the deepest layers [25-26].

## 2.2. Life Cycle Cost Analysis (LCCA)

This is a decision support tool often used by road agencies to compare total user and agency cost for different treatment alternatives. It is an economic analytical tool that compares benefits and costs of the selected alternatives and allows decision makers to choose the best option. There are basically two types of approaches that could be employed in LCCA: deterministic and probabilistic. In the deterministic approach, input variables are considered discrete fixed variables. The biggest drawback of this traditional approach is that it does not account for the variability associated with the LCCA input parameters. This level of uncertainty is mainly a combination of four reasons as highlighted by a study done by Tighe [27-28]. These uncertainties can be combatted using the probabilistic approach or a sensitivity analysis. The use of computer simulation software (RealCost) is the most utilized method for probabilistic approach [28].

LCCA is a method based on the principles of economics to evaluate the long term economic benefits of the different investment options. This method is been utilized by a large number of agencies worldwide due to its ability to analyze pavement economics realistically [29-31]. The Federal Highway Administration (FHWA) technical bulletin lists the steps involved in conducting a life cycle cost analysis [29].

The cost components for use in the analysis are initial costs, maintenance cost, rehabilitation, user costs and salvage value. The equations to be used for the economic analysis will be the Net Present Value (NPV) and the Equivalent Uniform Annual Cost (EUAC).The reason for choosing these two equations is the fact that they are the most widely used economic indices available worldwide [27, 32-33].

Equation 1 shows the NPV formula.

$$NPV = Initial\ Cost + \sum_{K=1}^{N} Future\ Cost_K \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}}\right] \quad (1)$$

Where:

N = number of future costs incurred over the analysis period,
i = discount rate as a percentage,
$n_k$ = number of years from the initial construction to the $K^{th}$ expenditure,
$n_e$ = analysis period in years.

Since the Zambian budget is presented annually, it is imperative that our cost matches the budget timing. It is for this reason that the present and future expenditures are converted to a uniform annual cost in the form of EUAC. Equation (2) shows the EUAC formula.

$$EUAC = NPV \left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \quad (2)$$

Where:

NPV = Net Present Value
i = discount rate,
n = years of expenditure.

Finally, after the computations of the LCCA of pavements, the present values of the differential costs are compared across competing alternatives.

### 2.3. Life Cycle Assessment (LCCA)

Life Cycle Assessment (LCA), as defined by the International Organization for Standardization (ISO) 14040 and 14044, is a tool that makes it possible to assess the environmental impact of a product. It is a process or an activity, through identifying and quantifying the flows of energy and material, evaluating the consumption of energy and materials as well as emissions generated, and identifying and evaluating possible measures for improving the environment [34-36].

This LCA approach formalized by ISO 14040 series divides the LCA framework into four interactive stages: i) goal and scope definition; ii) life cycle inventory analysis (LCI); iii) life cycle impact assessment (LCIA); iv) interpretation. The goal and scope outlines the reasons for conducting the study as well as the intended application and audience. In this stage the system boundaries which involve the picking of activities or processes to be incorporated in the LCA and functional unit has been defined as quantifying a stated amount of a system for use as a reference unit is well expounded. The LCI, which is the second stage, compiles the inputs and outputs from the product over its life cycle in relation to the functional unit. The LCIA aims to form a link between the system and the potential to cause human and environmental damage. Finally, the results from all the previous stages are evaluated and interpreted in relation to the goal and scope definition in order to identify analysis refinements and improvements and to reach a conclusion to recommend and aid in the decision making process [34-35]. Currently, the three methods of LCA commonly employed include: Economic Input-Economic Output (LCA-EIO), Process based LCA, and Hybrid LCA [37].

The LCA-EIO employs a top down approach to critically relate production of goods and services to the production outputs of the sectors of an economy. It does not require a system boundary but traces all direct and indirect economic inputs required to produce a unit of output from a given economic sector [37].Horvath and Hendrickson used this method to compare the energy consumption of Hot Mix Asphalt (HMA) and Continuously Reinforced Concrete Pavement (CRCP). The study mainly dwelt on extraction and production of different surface materials and the qualitative analysis of construction phase and end of life. They concluded that the HMA consumed 40% more energy than the CRCP [38]. The process based method involves the principles refined by Society of Environmental Toxicology and Chemistry (SETAC) and U.S. Environmental Protection Agency (EPA) [36, 49]. It provides a transparent bottom up approach for assessing process based environmental contributions like carbon emissions within the defined boundary. Stripple utilized it and studied Jointed Plain Concrete Pavements (JPCP) and asphalt pavements constructed using both hot and cold production techniques. This study concluded that without the feedstock energy, JPCP consumes more energy than its counterparts [39]. The hybrid assessment combines process based and LCA-EIO in a manner that exploits the strength and minimizes the limitations associated with the previous two methods. By using this method, the limitations and errors of using the conventional methods are reduced [37]. Park et al. used this method to study the environmental load of asphalt concrete and ready mix concrete in South Korea [40].

Important literature on pavement preservation LCA processes include a study done by Chehovits and Galehouse which studied the energy use and Greenhouse Gas (GHG) emission of preservation treatments for asphalt pavements. Common techniques like slurry seal, chip seal, Hot In Place Recycling (HIR), crack seal etc. were used. Results show that on a per annum basis, different maintenance treatments consume different amounts of energy per year of pavement life. It went on to show that new construction, thin HMA and HIR have the highest energy usage rate while slurry, chip seal and micro-surfacing have lower amounts of energy per year [11]. A study conducted in Chile about different asphalt pavement maintenance and rehabilitation techniques found out that Cold In Place Recycling (CIR) uses the least amount of energy and the haulage distance is the most sensitive factor on the total energy consumption. The different techniques included asphalt overlay, reconstruction and CIR [9]. A study by Yu and Lu compared environmental effects on three overlay systems by considering six modules; material, distribution, construction, congestion, usage and end of life. They found out that in the usage module, materials, traffic congestion and usage are the main factors for energy consumption and air emissions and that recycling materials reduces energy consumption for HMA [41].

Tatari et al. did an LCA to evaluate the environmental impacts of different types of Warm Mix Asphalt (WMA) and compared them to conventional HMA pavements. It was concluded that the WMA was less sustainable in terms of total energy [42]. A more elaborate study on asphalt concrete pavement and CRCP was studied by Hoang et al.; the energy use, emission of $CO_2$ and use of virgin aggregate and bitumen were the main components of this study. The results showed that CRPC consumes around 40% more energy than asphalt pavements and three times more $CO_2$ emissions [43]. One of the backbone literatures for LCA on pavements was studied by Chapat and Bilal; they evaluated twenty different construction techniques for calculating energy consumption and GHG emissions. The study found that heavier traffic loads require pavements of better bearing capacity and also have an increased need for maintenance operations. So it was concluded that the energy and GHG emission caused by traffic was far more than that in the construction phase [10].

## 3. Research Methodology

### 3.1. Case Study

An environmental and economic analysis was performed on an existing HMA pavement in Central Province, Zambia. The project site is the 65.5km stretch between Kabwe and Kapiri-Mposhi towns which is part of the Great North Road (T002).The existing section of the road comprises of a 3.5m single lane carriageway (both directions) and 2 m wide shoulders (inner and outer). The pavement structure consists of a 50mm asphalt concrete layer, a 150mm crushed stone base, a 150mm granular sub-base and a 300mm subgrade layer. In this case study, selected preservation treatments were evaluated over the 30 years analysis period integrating both the economic and environmental implications. The pavement design approach follows the principles contained in the 1993 AASHTO pavement design guidelines were Pavement Serviceability Index (PSI) and 80KN Equivalent Single Axle Load (ESAL) are the main parameters defining performance. These parameters are all related to the material properties, drainage and environmental conditions and performance reliability which are used to calculate the pavement structural strength through an index known as the structural number (SN). Figure 2 below shows the location map of the project.

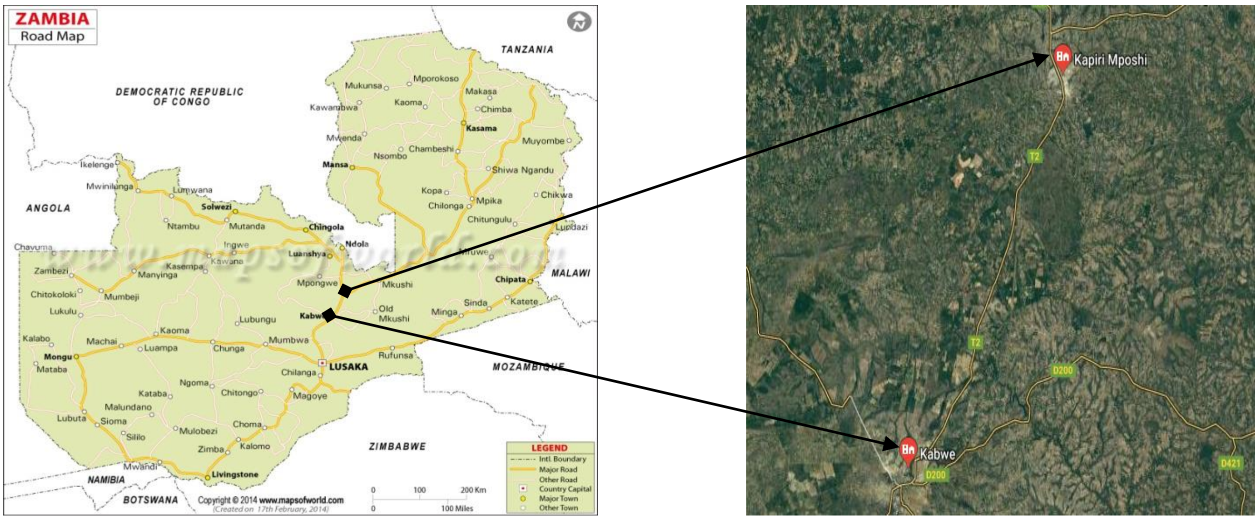



**Figure 2. Case study location map**

### 3.2. Energy and Carbon Emission Calculation

***a) Goal and Scope***

The goal of this paper is to quantify and compare the life cycle environmental and economic performance of multiple maintenance preservation treatments in order to improve the pavement sustainability in Zambia. The scope follows a cradle to grave approach and takes into account guidelines outlined by ISO [34-35].

***b) Functional Unit***

It is defined as a 1km road of 3.5m lane width with an analysis period of 30 years.

***c) System Boundaries and Assumptions***

Figure 2 shows the phases and components included within the system boundaries of the proposed LCA model. The model entails three life cycle phases: materials extraction and production; transportation; and construction of maintenance treatments. The work zone traffic management and usage phase were not included in the model because of lacking a well-defined standardized method and the incognizance of the enormity of the emissions.

The construction assumptions of a maintenance project are based on case study parameters in Zambia:

- 1500 km between the refinery for bitumen production/bituminous products and mixing plant/storage place;
- 100 km between cement plant to the mixing plant/storage place;
- 50 km between aggregate quarry and mixing site/stockpile;
- 10 km between the mixing plant/stockpile/storage place and the construction site;
- 10 km between water supply and construction site;
- 20 km between construction site and the land fill.

In general, embodied energy consumption and carbon emissions occur during two main phases of pavement construction i.e., materials production and construction. The materials production phase includes the extraction and initial processing of aggregates, asphalt and other materials. The processes within this phase include raw material acquisition, transportation of raw materials to and from the plant and material manufacturing. The transportation of manufactured materials to and from the construction site is usually considered into the construction phase [10].

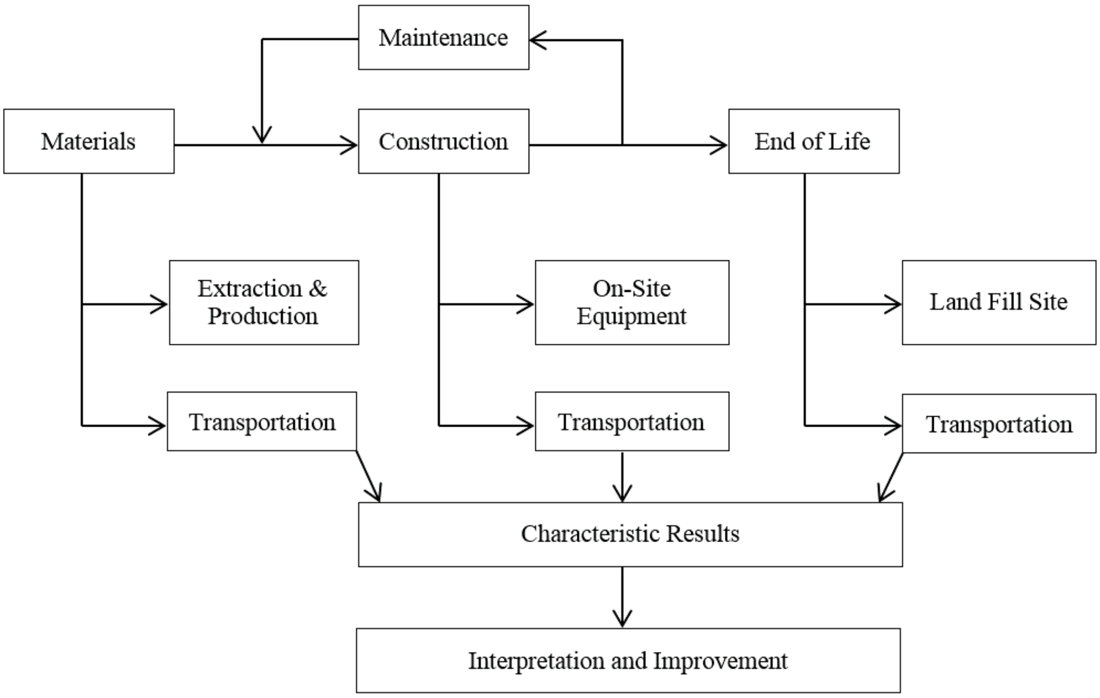



**Figure 3. LCA of pavement**

#### 3.2.1. Embodied Energy and Carbon Emissions for Construction Materials

The first step in calculating the embodied energy and carbon emission of pavement preservation treatments is to determine the material components of the treatments studied. An LCI data analysis through a literature review was conducted and averages are computed in order to calculate a reasonable final value of the materials of importance as shown in Table 1 below. It should be noted that the entries listed in the table considers all stages and processes to attain the final product as ready for use.

**Table 1. Embodied energy and carbon emissions LCI data for construction materials**

| Material | Arithmetic Mean | | Sources |
|---|---|---|---|
| | Embodied Energy [MJ/ton] | Emission-$CO_2$e [kg/ton] | |
| Bitumen | 4832.8 | 303.6 | [39] [44] [45] [46] [47] |
| Bitumen Emulsion (60%) | 3187.0 | 225.0 | [39] [45] |
| Polymer Modified Bitumen | 5490.0 | 350.0 | [45] |
| Emulsifiers | 63250 | 600 | [39] [48] |
| Cement | 5252.5 | 677.5 | [39] [44] [47] [48] |
| Hydrated Lime | 1244 | 245.0 | [10] |
| Crushed Aggregates | 43 | 6.8 | [39] [44] [47] [48] |
| Pit-run Aggregates | 28 | 4.7 | [39] [44] [46] |
| Potable Water | 10 | 0.3 | [39] |

### 3.2.2. Embodied Energy and Carbon Emissions for Construction Equipment

After the LCI phase through a literature review, the next step is to consider and calculate the average fuel consumption of diesel oil machines. Machinery/Equipment for the successful laying of the studied treatments like Millers, Pavers, Rollers, Chip Spreaders, Micro-surfacing Machinery, Bitumen Distributors and Trucks were investigated to identify and quantify emissions and embodied energy in road preservation treatments and activities. The primary source of emissions, in fact, is due to the engine exhaust system, depending on the total amount of fuel consumed in each phase of the preservation process. However, the true quantity of fuel consumed while applying maintenance treatment on a road is hard to estimate. The method employed in this paper is adapted from the relationship made by U.S. Environmental Protection Agency [49] to convert the calculated fuel consumption into emissions produced and energy spent. The step by step guide is outlined by Guistozzi et al. [50]. The machinery/equipment company model studied is widely used and accepted in Zambia, the outcomes calculated and analyzed from the machineries/equipments are hereby provided.

**Table 2. Embodied energy and carbon emissions for construction equipment**

| Model | Engine Rating (kW) | Width (m) | Speed (m/h) | Productivity ($m^2$/h) | F (l/h) | $F_{sqr}$ (l/$m^2$) | $CO_2$e (g/$m^2$) | Energy (MJ/$m^2$) | Company |
|---|---|---|---|---|---|---|---|---|---|
| ***Pavers*** | | | | | | | | | |
| DF145C | 153 | 5.5 | 1200 | 6600 | 38.43 | 0.0058 | 15.43 | 0.20 | Dynapac |
| Super1603 | 100 | 3.5 | 1200 | 4200 | 25.12 | 0.0060 | 15.85 | 0.21 | Voegele |
| ***Micro-surfacing Machineries*** | | | | | | | | | |
| M206 | [a]74;186 | | 2400 | 3600 | 41.70 | 0.0116 | 30.70 | 0.417 | Bergkamp |
| M210 | [a]74;224 | | 2400 | 3600 | 42.40 | 0.0118 | 31.75 | 0.424 | Bergkamp |
| ***Milling machine*** | | | | | | | | | |
| PL2100S | 447 | 2.1 | 1800 | 3780 | 104.77 | 0.0277 | 73.45 | 0.97 | Dynapac |
| W120F | 227 | 1 | 1800 | 1800 | 53.20 | 0.0296 | 78.33 | 1.04 | Wirtgen |
| ***Double Drum Steel Rollers (6 and 3 passes)*** | | | | | | | | | |
| CC421 | 80 | [b]1.42 | 4000 | 946 | 20 | 0.0190 | 50.35 | 0.684 | Dynapac |
| CC421 | 80 | [b]1.42 | 4000 | 1893.3 | 20 | 0.0106 | 27.99 | 0.371 | Dynapac |
| ***Pneumatic Tire Rollers (6 passes)*** | | | | | | | | | |
| CP142 | 74 | [b]1.50 | 10000 | 2493.3 | 14.5 | 0.0058 | 15.41 | 0.204 | Dynapac |
| CP274 | 82 | [b]1.96 | 10000 | 3258.3 | 16.2 | 0.0050 | 13.18 | 0.175 | Dynapac |
| ***Vibrating Smooth Wheeled Rollers (6 passes)*** | | | | | | | | | |
| 213DH-S | 115 | [b]1.81 | 4000 | 1207.0 | 18.7 | 0.0155 | 41.06 | 0.544 | Bomag |
| 177DH-S | 76 | [b]1.43 | 4000 | 952.0 | 28.2 | 0.0297 | 78.61 | 1.041 | Bomag |
| ***Motor Grader*** | | | | | | | | | |
| 120K | 111 | 3.7 | | 2007 | 27.30 | 0.0136 | 36.05 | 0.48 | CAT |
| 160H | 134 | 4.1 | | 2247 | 38.50 | 0.0171 | 45.40 | 0.60 | CAT |
| Chip Seal Machine (Spraying and Compaction) [51] | | | | | | | 46.2 | 0.6 | |
| Bitumen Distributor for application of emulsion (60%) [39] | | | | | | | 0.036 | 0.491 | |
| Truck Transportation (Full Load Hauling and Empty on Return) [50] | | | | | | | 0.062 | 0.901 | |

*a The first value is mixer engine rating and the second value is truck engine rating*

*b The effective width shown for rollers is the 85% of the actual roller width*

### 3.2.3. Embodied Energy and Carbon Emissions for Preservation Treatments

The last step in our LCA is to calculate the embodied energy and emissions for the selected preservation treatments. Considering the materials, activities and equipment/machinery involved, it was easy to calculate the emissions and energy consumption. The fractions or the mix designs of each treatment were established in order to determine the quantity (kg) of each component per ton. Based on this value together with the density and thickness, it was possible to quantify each element in tons per square meter. The procedure for Chip seal and Micro-surfacing was slightly different as the aggregate application rate from the mix design is in kg/m$^2$, so converting to tons per square meter was easy. The values obtained were then multiplied by the emissions and energy consumption data listed in the previous section to give the total emissions and energy consumption for each preservation treatment. It is important to note that the above explained procedure is not necessary in regard to equipment/machinery calculations as their data is already expressed per square meter [9, 11, 21, 50].

The mix designs for HMA asphalt, reconstruction and chip seal with their respective thicknesses is based on data from projects in Zambia while for micro-surfacing, data from the Georgia Department of Transportation was used [19]. A spreadsheet tool was created for easy calculation and automation in taking into account different possible treatment combinations. The specifics of each treatment case are shown and discussed below.

***a) Thin Hot Mix Asphalt Overlay***

A typical mix design was chosen clearly showing the percentages of bitumen, aggregates and filler in the asphalt. The intervention thickness is 40 mm asphalt concrete; this will greatly help us calculate the total volume of materials used per square meter of the treatment. The mix design is 4.8% of 60/70 Penetration Grade Bitumen, 1% Hydrated Lime, 50.2% Pit Run Aggregate and 44% Crushed Aggregate. The production of HMA follows the usual procedure consisting of drying the aggregates (coarse and fine) by heating at high temperatures then mixing the materials (bitumen, aggregate (coarse and fine) and filler). Results show carbon emissions of 5.28/m$^2$ and embodied energy of 74.83/m$^2$ as Table 3 highlights the calculation procedure for this type of treatment.

***b) Micro-surfacing***

A similar procedure similar to the one outlined above was used for applying a micro-surfacing mixture on a square meter of a road pavement. The design is a Type III Aggregate gradation containing 81.6%, 7.4% of Modified Emulsion (3.5% SBR), 1% Cement Filler and 10% of Potable Free Water. The objective is to get a 19mm thick surface layer which is capable of providing adequate surface protection and maintaining a high pavement serviceability level. Results show carbon emissions of 2.48 kg/m$^2$ and embodied energy of 39.32 MJ/m$^2$.

**Table 3. Embodied energy and carbon emissions of preservation treatments**

| **HMA Mix Design Input Parameters** | | | | | |
|---|---|---|---|---|---|
| | Asphalt Concrete | Bitumen | Crushed Aggregate | Pit-run Aggregate | Filler (H. Lime) |
| Bulk Specific Density (ton/m$^3$) | 2.48 | 1.01 | 2.80 | 2.80 | - |
| % of Individual in Mix | 100 | 4.8 | 44 | 50.2 | 1 |
| Pavement Thickness (m) | 0.04 | | | | |
| (ton/m$^2$) | 0.0992 | 0.0048 | 0.0436 | 0.0498 | 0.001 |
| Thin HMA Overlay 0.04 m | Quantity [ton/m$^2$] | Carbon Emission [kg/ton] | Embodied Energy [MJ/ton] | Total Carbon Emission [kg/m$^2$] | Total Embodied Energy [MJ/m$^2$] |
| **Materials** | | | | | |
| Bitumen | 0.0048 | 303.6 | 4832.8 | 1.45 | 23.01 |
| Crushed Aggregate | 0.0436 | 6.3 | 38.62 | 0.27 | 1.69 |
| Pit-run Aggregate | 0.0498 | 4.8 | 28 | 0.24 | 1.39 |
| Hydrated Lime Filler | 0.001 | 245.0 | 1244 | 0.24 | 1.23 |
| HMA Production | 0.0992 | 19.0 | 299.5 | 1.88 | 29.71 |
| Tackcoat (SS60) | 0.001 | 225.0 | 3187.0 | 0.23 | 3.19 |
| **Machinery/Equipment** | | | | | |
| | Fuel Usage [l/h] | | | | |
| Tackcoat Sprayer (HM 10HD) | | | | 0.000036 | 0.491 |
| Paver (Dynapac DF145C) | 38.43 | | | 0.01543 | 0.2 |
| Roller Dynapac CC421 | 20 | | | 0.05035 | 0.684 |
| Roller (Pneumatic) | 14.5 | | | 0.01541 | 0.204 |

| | | | | |
|---|---|---|---|---|
| Transport HMA (10 km) | 0.0617 | 0.901 | 0.061 | 0.894 |
| Transport Bitumen (1500 km) | 0.0617 | 0.901 | 0.441 | 6.435 |
| Transport Tack Coat (1500 km) | 0.0617 | 0.901 | 0.093 | 1.352 |
| Transport C. Aggregates (50 km) | 0.0617 | 0.901 | 0.135 | 1.966 |
| Transport P. Aggregates (50 km) | 0.0617 | 0.901 | 0.154 | 2.243 |
| Transport H. Lime (150 km) /km | 0.0617 | 0.901 | 0.009 | 0.134 |
| **Total** | | | 5.28 | 74.83 |

***c) Chip Seal with a Fog Seal***

A double surface dressing with 13.2 mm and 6.7 mm crushed aggregates was chosen with an aggregate application rate of 1.632 kg/m$^2$ and 15 kg/m$^2$ respectively and a 80/100 penetration grade bitumen application rate of 0.8 l/m$^2$ was used as a binder. A fog seal which is simply an emulsion is applied at a rate of 0.5 l/m$^2$ and is eventually sprayed on top of the chip seal to complete the treatment. Results show carbon emissions of 1.68 kg/m$^2$ and embodied energy of 23.07 MJ/m$^2$.

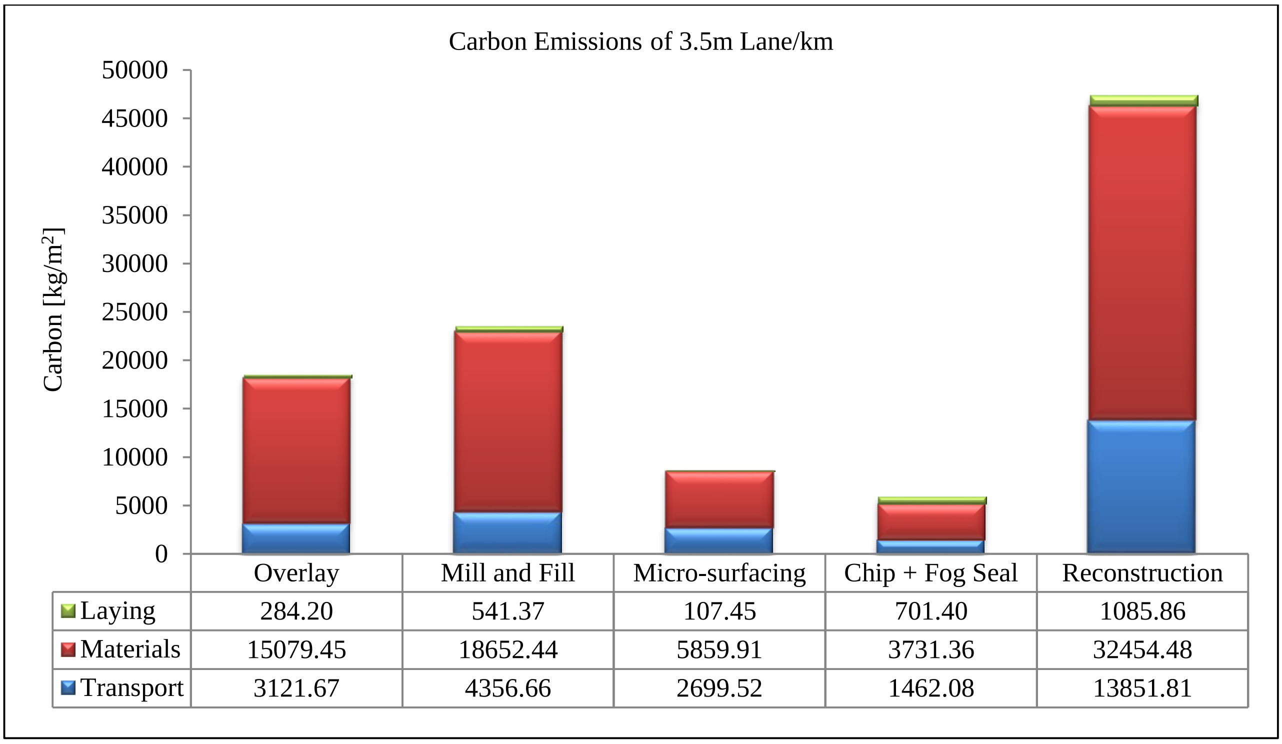
***d) Mill and Fill***

This treatment option involves the milling of 20 mm of the asphalt layer and then resurfacing it with 50 mm new asphalt. The procedure and calculations are the same with the Thin HMA overlay. Results show carbon emissions of 6.73/m$^2$ and embodied energy of 95.21/m$^2$.

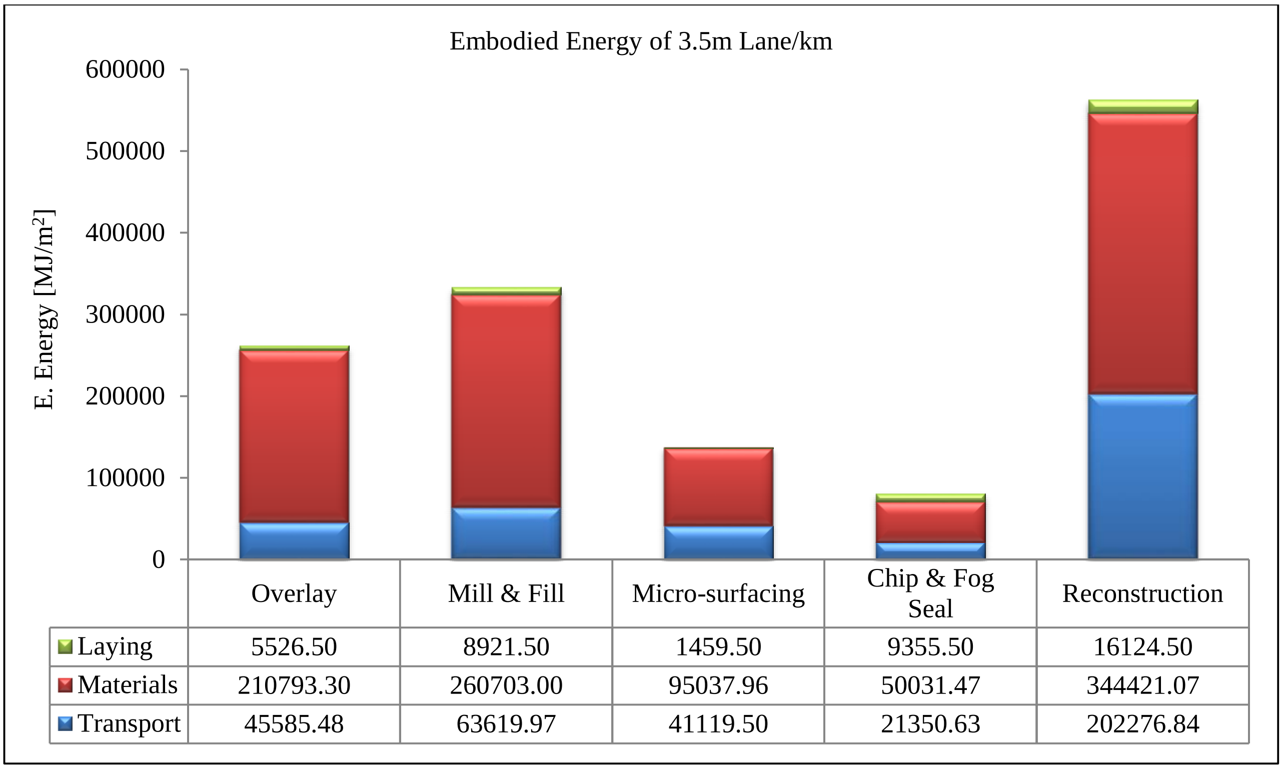
***e) Major Reconstruction***

This is a last resort intervention when during the pavement design life no maintenance strategy was employed on the pavement. It consists of milling the 40/50 mm existing AC layer then milling/scarifying the 150/200 mm underlying base layer and replacing them with a new 150 mm gravel sub-base and a 120mm cemented base or a 150/200 mm crushed stone as the new base and finally laying a new 50 mm AC layer. This is done in order to achieve a pavement structural number consistent with the new traffic loadings at the time of rehabilitation. Results show carbon emissions of 13.54/m$^2$ and embodied energy of 160.81/m$^2$.

Figure 3 below summarizes and shows the embodied energy and carbon emissions of a 1km 3.5m lane road.




**(a)**




**(b)**

**Figure 3. Carbon emissions (a) and embodied energy (b) for treatments of 3.5m lane/km**

## 3.3. Life Cycle Cost Calculation

The LCCA process either probabilistic or deterministic is initiated after a road section has been earmarked to be worked on and a range of possible alternatives have been identified in the quest to improve the pavement. Then the activity timing follows; this timing of treatments should be based on existing performance records or literature to achieve maximum cost benefits. The effectiveness of the treatment is also a fundamental input for a good LCCA [5, 17-26]. After determining the activity timing and effectiveness of selected treatments as listed in Table 4, the estimation of costs follows. In this paper only the costs demonstrating differences between alternatives are considered. These are the cost of the individual treatments and are obtained from the World Bank ROCKS software since the World Bank is one of the biggest road projects funders and moreover this data shows less variability and is similar to costs quoted in Zambia [52]. The cost has been converted to its April, 2019 value using the inflation index suggested by the United States Bureau of Statistics and then converted to Zambian Kwacha (ZMW) [53]. Zambia as a developing country and according to the World Bank uses 12% as a discount rate. Finally, the computation of the life cycle cost using the formulas given in the previous section is done and summarized in Table 5.

**Table 4. Effective treatment life and treatment cost**

| Treatment Type | Effective Treatment Life (Years) | Treatment Cost (US$/m$^2$) | Treatment Cost (ZMW/m$^2$) | Cost (ZMW/km) with 3.5 m of width |
|---|---|---|---|---|
| Full Depth Recon. | 20 | 46.24 | 568.29 | 1989013.60 |
| Mill & Fill Overlay (MF) | 10 | 19.52 | 239.90 | 839652.80 |
| HMA Overlay (TO) | 7 | 12.63 | 155.22 | 543279.45 |
| Micro-surfacing (MS) | 6 | 4.96 | 60.96 | 213354.40 |
| Chip + Fog Spray (CF) | 5 | 4.20 | 51.62 | 180663.00 |

**Table 5. Cost, NPV and EUAC of different treatment scenarios**

| Treatment Type | Year of Application | Cost (ZMW/km) with 3.5m lane | NPV (ZMW/km) with 3.5m lane | EUAC (ZMW/km) with 3.5m lane |
|---|---|---|---|---|
| HMA Thin Overlay (TO) | 9 and 17 | 1086558.90 | 2264048.82 | 277573.83 |
| Mill & Fill Overlay (MF) | 12 | 839652.80 | 2204535.68 | 271775.88 |
| Micro-surfacing (MS) | 7 and 13 | 426708.80 | 2134418.89 | 263131.86 |

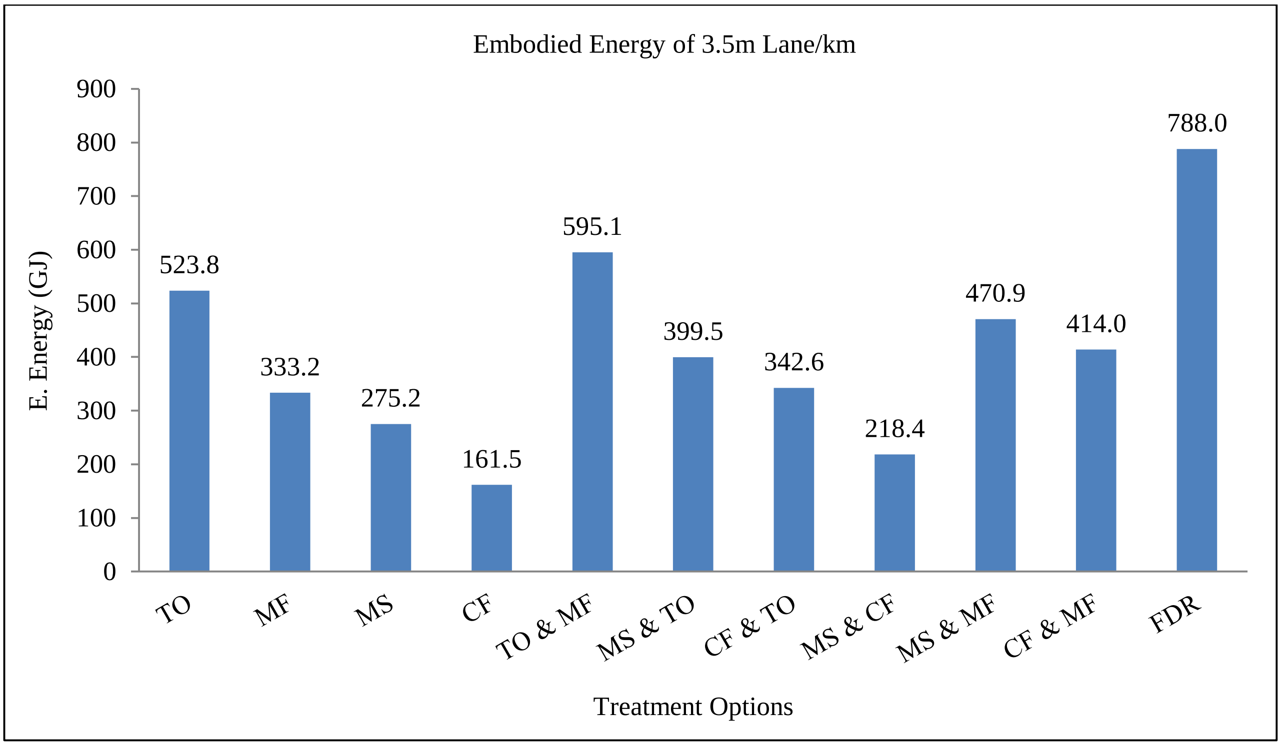
| | | | | |
|---|---|---|---|---|
| Chip & Fog Seal (CF) | 6 and 12 | 361326.00 | 2126915.47 | 264043.07 |
| TO & MF | 8 and 15 | 1382932.25 | 2361837.87 | 287765.36 |
| MS & TO | 7 and 14 | 756633.85 | 2196690.30 | 270017.85 |
| CF & TO | 6 and 12 | 723942.45 | 2219991.86 | 273681.32 |
| MS & CF | 6 and 13 | 394017.40 | 2138507.88 | 264503.61 |
| MS & MF | 7 and 14 | 1053007.20 | 2257334.22 | 275539.56 |
| CF & MF | 7 and 12 | 1020315.80 | 2296064.98 | 280846.91 |
| Full Depth Reconstruction | 20 | 2983520.40 | 3292821.96 | 399431.24 |

## 4. Results and Discussion

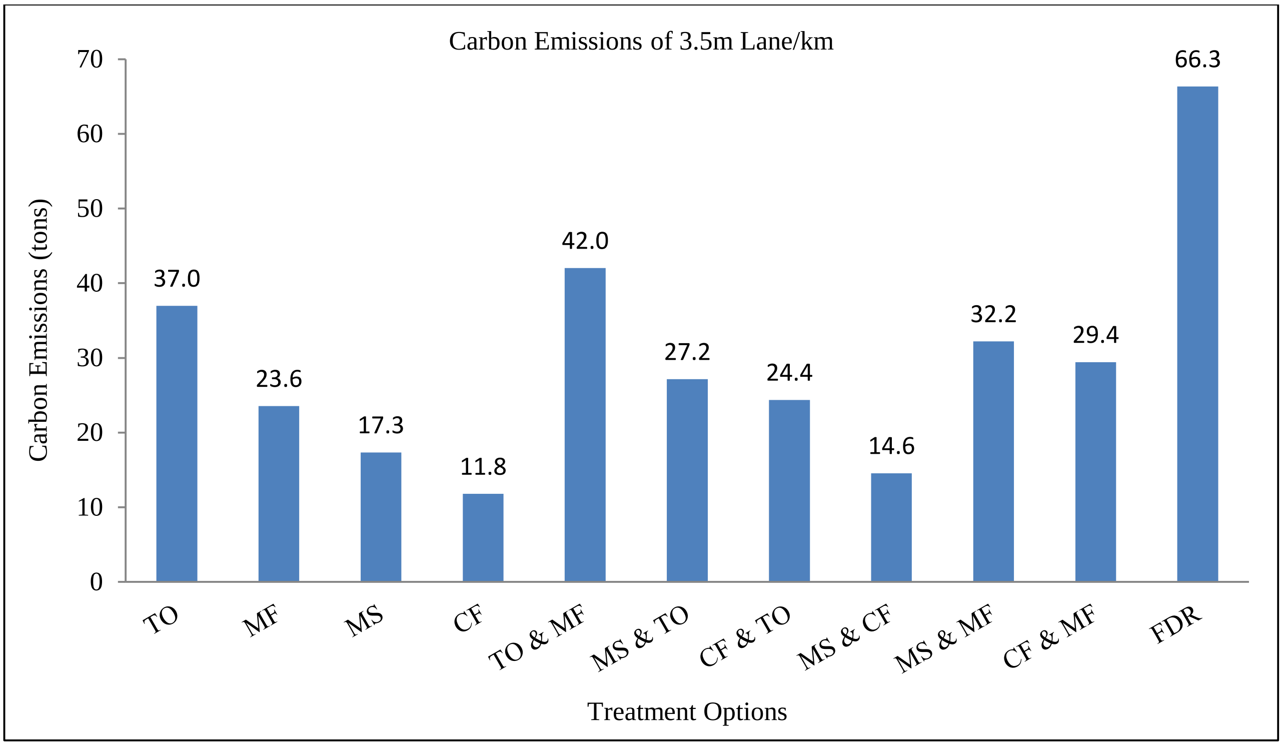
### 4.1. Energy and Carbon Emission

The Figure 4 below shows that full depth reconstruction, a combination of thin overlay and mill and fill and thin overlay consume the largest amount of embodied energy of 788GJ, 595.1GJ and 523.8GJ respectively. These values are a bit high due to a simple reason that the production process and transportation of materials is the highest in the energy chain. The treatments that require a lot of aggregate heating and having the largest quantity of materials per unit area use the largest amounts of energy. The results show embodied energy amounts of 3 to 4 times that of chip + fog seal, micro-surfacing and a combination of chip + fog seal and micro-surfacing treatment having values of 161.5GJ, 218.4GJ and 275.2GJ respectively. The embodied energy consumption difference between the greatest and the least treatment option is 646.3GJ which can be used on 4km of road pavement using the least treatment preservation option.

Taking into account the carbon emissions, the figure shows that full depth reconstruction, a combination of thin overlay with mill and fill and thin overlay are the largest emitters with values of 66.3tons, 42tons and 37tons respectively. The values are in excess of 3-6 times the three least treatment emitters of chip + fog seal, micro-surfacing and a combination of chip + fog seal and micro-surfacing having values of 11.8tons, 14.6tons and 17.3tons respectively. The carbon emission difference between the most and the least treatment option is 54.5tons which can be used on 5km of road pavement using the least treatment preservation option. Generally, chip + fog seals showed the lowest variability with micro-surfacing following it. The carbon emissions and energy for micro-surfacing can be further reduced if the percentage of plastics in the modified binders is reduced. The modified emulsions have high percentage of carbon emissions and have thus increased the overall performance of micro-surfacing in terms of emissions impact to the environment. Research and development in better understanding of the binder will provide a basis for better preservation design optimization, hence greatly reducing the energy consumption and carbon emissions.




**(a)**




**(b)**

**Figure 4. Embodied energy and carbon emissions of 3.5m lane/km**

## 4.2. Life Cycle Cost

The results obtained from the LCCA after the necessary calculations are shown in Figure 5.The NPV shows marked differences among the costs of the scenarios.

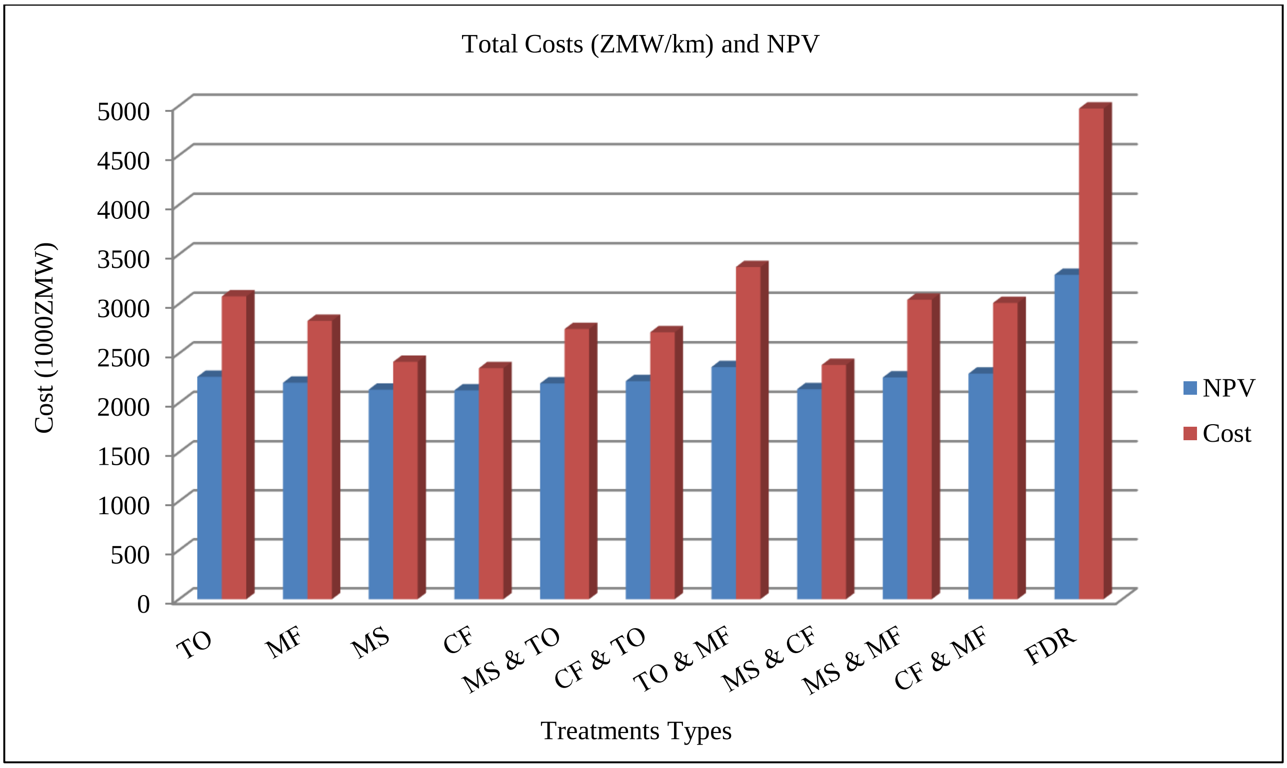



**Figure 5. Total costs and NPV (ZMW/km) of 3.5m lane road**

Based on the costs and NPV, the figure shows that the most economical were the chip + fog seal and micro-surfacing then followed by a treatment whose options included the above two treatments and the least economical was a combination of mill and fill with thin overlay and then full depth reconstruction. Chip + Fog seal has the lowest life cycle NPV of ZMW2126915.47 then followed by micro-surfacing with ZMW2134418.89. The most expensive treatment was full depth reconstruction at ZMW3292821.96 while a combination of mill and fill with thin overlay followed at ZMW2361837.87. It is worth noting that the three most economical treatments show an LCC of 30-40% lower than the full depth reconstruction. Agencies should bear in mind that when the LCC among treatment options show a difference of less than 10%, it would be wise to consider the treatment options to be equivalent or consider the work zone traffic influence and other parameters as tie breakers.

## 5. Conclusion

An economic and environmental analysis among selected pavement preservation treatments through a case study was calculated and compared. Based on the costs and NPV, results showed that the most economical were the chip + fog seal and micro-surfacing and the least economical was full depth reconstruction and a combination of mill and fill and thin overlay. Although the LCCA appears to show that chip + fog seal is overall the best preservation treatment, the selection of the treatments depends on different factors based on the characteristics of each treatment option. These factors include environmental conditions, availability of required materials, as well as traffic volumes or loads. The environmental analysis showed that different treatments require different amounts of embodied energy and emit carbon differently during the analysis period of 30 years. Full depth reconstruction and a combination of thin overlay and mill and fill treatment options have the highest embodied energy consumption while chip + fog seal and a combination of micro-surfacing and chip + fog seal utilize the least amounts of embodied energy. Similar result patterns apply to carbon emissions with full depth reconstruction being the biggest emitter and chip + fog seal as the least emitter. The results show and agree with other literature that treatments that do not require aggregate heating and those having the lowest amount of materials per unit area use the least amount of energy and have the lowest carbon emissions [9-11].

The raw material extraction process is the highest in the energy and carbon emission chain. This highlights the need to have the quarry site, treatment plants and construction site to be in close proximity in order to avoid excess energy use and carbon emissions which result in high economic costs. In light of the above results, an expertly defined LCA system for preservation treatments of roads is the only way forward to the path of a "green" procurement and optimal use and recycling of materials in the construction of roads. This system can also be made useful in the implementation of the carbon tax in the road construction sector.

As this study only considered selected preventive maintenance treatments and the life cycle cost and assessment scope was narrowed, it is recommended that elements of user costs including accident costs, work zone costs and environmental costs be extended for a better estimation of the total life cycle costing. Additionally, vehicle emissions derived from pavement condition and work zones should also be considered in accounting the carbon emissions from the application of preservation treatments. Expensive and deeper strategies of rehabilitation can be avoided by the application of perpetual pavements which would require less maintenance interventions thus reducing the embodied energy, carbon emissions and economical cost of treatments. Finally, it should be recommended to track the maintenance strategies carried out as a result of the application of this model so as to validate, adjust or dismiss the parameters considered.

## 6. Conflicts of Interest

The authors declare no conflict of interest.

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