USING MULTICRITERIA ANALYSIS TO SELECT ALTERNATIVE SURFACINGS FOR LOW VOLUME ROADS

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ABSTRACT

A large portion of the road network in developing countries in Africa consist of Low Volume Roads (LVRs). Funding for upgrading and maintenance of these roads pose a challenge for roads authorities as their limited budgets are mainly aimed at highways and major corridors. Isolated communities bear the burden of inaccessibility to markets, education and health facilities.

As part of a study that was launched by the Research for Community Access Partnership (ReCAP) an investigation into alternative surfacings to gravel roads was conducted in Ghana, Liberia and Sierra Leone. A stakeholder engagement process, designed around several workshops, was used to gain insight into the needs of the community. The local roads authorities, local engineers and technical pavement experts were involved in the selection of surfacing options which would be most suitable for implementation.

Several other aspects of the surfacing types were investigated such as the initial construction cost, anticipated maintenance costs and life cycle cost. An exclusive multicriteria analysis, which used the outputs from the different costing scenarios and the workshops was conducted, and a Monte Carlo simulation was completed to select the most appropriate surfacing solutions.

1. INTRODUCTION

West African countries are known for their tropical climate and high rainfall. Impassibility of rural low volume roads (LVRs) poses a large problem during the rainy season leaving people severed from basic services and disrupting market access (Brito, 2011).

Low Volume roads can be defined as roads carrying less than one million equivalent standard axles over a design period of 10 to 15 years. These roads have a base year daily traffic of not more than 300 four-wheeled motorised vehicles, inclusive of 20-25% commercial vehicles (Road Development Agency, 2019).

An investigation into alternative surfacings (to a gravel surface) was launched by the Research for Community Access Partnership (Hartman & Pretorius, 2019). The purpose of the investigation was to identify surfacing options suitable for the social, economic, and environmental conditions present in Ghana, Sierra Leone and Liberia.

Data gathered during stakeholder workshops was used as part of an all-inclusive multicriteria analysis supplemented by a Monte Carlo simulation. The multicriteria analysis combined data gathered from all stakeholders including the road user, expert engineers (people who ~~will~~ design the infrastructure) as well as the individuals from transport authorities (statutory bodies who will implement legislations and fund projects) to present surfacing options which would potentially satisfy the needs of all parties.

The Monte Carlo simulation was used as a tool to ensure that the full range of different scenarios were considered and that the optimal solution to the surfacing problem was selected.

2. BACKGROUND

2.1 Low Volume Roads

In most developing countries the greatest portion of the road network comprises of Low volume roads (LVRs) (Brito, 2011). One of the main characteristics of LVRs is that the pavement performance is largely influenced by environmentally induced distresses rather than load-associated distresses (SADC, 2003).

Compared to highways the traffic volume of LVRs is small, but these roads serve a socio-economic function in that the “first-mile” of travel, for marketable goods and people, mostly materializes on LVRs. It is important to consider the following contributions that rural roads make towards economic growth and social prosperity (Coghlan, 1999):

- LVRs are the primary links to the highway transportation system.
- Homes and farms are connected to markets by means of LVRs.
- Raw materials from mines and forests are connected through LVRs to distribution points to allow materials to be transported to the second phase of processing in the supply chain.
- LVRs allow the public to access essential health care and educational facilities.
- LVRs afford people who live in rural areas the opportunity to join in on recreational activities.

2.2 Surfacing Solutions

A brief discussion of the various surfacing options that were investigated follows.

2.2.1 Single Seal, Sand Seal and Slurry Seal

A single seal is constructed by spraying a bituminous binder on a primed base and adding stone chippings on top. Sometime the chippings are covered with a second coat of bitumen or a fog spray (Sabita, 2016). The single seal is suitable for low volume roads as no expensive equipment is required for construction and it has good skid resistance. Some of the disadvantages of the single seal is that it is thin and prone to mechanical damage and requires regular maintenance, particularly in severe climates (Sabita, 2012).

2.2.2 Choked Seal

A choked seal is similar to a single seal. However, the seal is choked with a smaller aggregate without the application of a second penetration coat (SANRAL, 2007).

The choked seal requires less binder and can be constructed relatively quickly.

2.2.3 Double Seal, Inverted Double Seal and Triple Seal

A double seal and triple seal are constructed by applying a bituminous binder on a primed base, followed by a layer of aggregate that is rolled. A second coat of binder and a second layer of aggregate is applied after the first layer. The triple seal then gets a third coat of binder and aggregate. The size of the aggregate usually decreases as the layers are constructed but for the inverted double seal the smallest aggregate is placed at the bottom (Sabita, 2012). The double and triple seal are more durable than the single seal and can resist more extreme climatic conditions.

2.2.4 Otta Seal

The Otta seal consist of a 16 mm to 32 mm thick mixture of graded aggregate which is placed on a thick film of soft binder. Rolling of the surface and general traffic movement causes the binder to migrate upwards. The strength of the seal is dependent on mechanical interlocking and bitumen binding (Botswana Roads Department, 1999).

The main advantages of an Otta seal are that it can be constructed using natural gravel (instead of crushed stone) and the surfacing requires less maintenance that some of the other seals. It does however require relatively expensive equipment (bitumen distributor and heating facilities) to construct.

2.2.5 Hot and Cold Mix Asphalt

Hot-mix asphalt is produced by mixing aggregate with bitumen at high temperatures (140°C to 190°C) at a hot-mix production facility. The mix is transported via truck to site. Cold-mix asphalt is a mixture of aggregate, cutback bitumen, and mineral filler, and is delivered in bags or mixed on site with bitumen emulsions for application at ambient temperatures (Sabita, 2016).

Cold mix asphalt is more environmentally friendly and energy efficient than hot mix asphalt and it can be constructed using labour intensive methods. The adhesion properties and moisture resistance of cold asphalt mixes are not always sufficient. whereas hot mix asphalt provides excellent performance under almost all conditions. It is very labour intensive and can be constructed with inexpensive equipment, albeit to a lower final surface roughness.

2.2.6 Concrete Pavements

The use of concrete as a durable and economical surfacing solution for LVRs has been investigated extensively (Cook, et al., 2013). Concrete as a surfacing solution has very low maintenance costs, however, the initial cost of construction is excessive. Several different concrete surfacing options are available. These include plain jointed reinforced and unreinforced concrete pavements, dowel jointed reinforced and unreinforced concrete pavements, continuously reinforced concrete pavements, ultra-thin reinforced concrete pavements and roller compacted concrete pavements (Marais & Perrie, 1993; Rasmussen et al., 2009).

2.2.7 Interlocking Concrete Paving Blocks and Clay Bricks

Interlocking concrete block paving is a surfacing system that produces a hard-wearing continuous structure. Interlocking paving blocks can be used for a multitude of applications ranging from pedestrian traffic and parking areas to heavy-vehicle loading.

The application of clay bricks is similar to that of concrete paving blocks. The difference is that fired clay bricks are the product of firing-moulded blocks of silty clay (Cook, et al., 2013).

Clay and concrete pavers can be used in all climates and can be constructed in a labour intensive fashion (Cook et al., 2013).

2.2.8 Cobbles

Cobblestone surfacing is similar to concrete block paving, but for stone surfacing natural stones rather than manufactured concrete blocks are used (Don Bosco Foundation, 2015). A cobblestone road is generally suitable for low to medium traffic densities. The application is very useful on roads with steep longitudinal grades. Unfortunately, the surface finish of a cobble road is not smooth and the roughness of the road is higher than the other surfacing solutions.

2.2.9 Geocells

Plastic cell-filled concrete block pavements (PCCBP), or geo cells, are an alternative to block paving, with better structural performance and less maintenance. The Don Bosco Foundation Training Manual (Don Bosco Foundation, 2015) refers to geo cells as an appropriate surfacing option for rural low-volume roads.

Geocells can be used in all climatic conditions and are suitable for roads with steep grades. Quality control is a critical aspect of geo-cell construction, and the surface finish is sometimes not as smooth as with interlocking concrete pavers (Singh, 2011).

2.3 Multicriteria Analysis

Multicriteria decision making deals with the selection of the best alternative from several possible alternatives. Decisions require the balancing of several criteria which could be complex and sometime conflicting in nature. (Pavan & Todeschini, 2009). The starting point for a multicriteria analysis is to convert often intangible outcomes into several criteria. There are two issues to be considered, firstly, measuring the intangible outcomes and secondly, how to combine these measurements to produce an inclusive ranking which will assist in the final decision analysis (Pavan & Todeschini, 2009).

The first step in establishing a set of criteria is to study the result of actions that are relevant (De Brucker et al., 1995). After the establishment of criteria, the relative importance of a criterion in respect to the other criteria needs to be established. The final step in the process is to rate the alternatives in terms of their conformance to the criteria.

3. EXCLUSIVE MULTICRITERIA ANALYSIS

Analytical methods such as Life Cycle Cost Analysis (LCCA), multicriteria analysis and social cost-benefit analysis are occasionally viewed as mutually exclusive appraisal methods. These methods can, however, be used to complement each other. An exclusive multicriteria analysis can be conducted by integrating the outputs of several other analytical tools (De Brucker et al., 1995). The exclusive analysis differs from standard multicriteria analysis in two regards:

- Outputs of other analytical methods are used as inputs for the analysis.
- Fundamental questions regarding the desirability of a specific project can be answered.

The exclusive multicriteria analysis for the current alternative surfacings project combined several project dimensions, including the following:

- Multicriteria analysis on surfacing alternatives per country.
- Multicriteria analysis on surfacing alternatives from local pavement experts.
- LCCA when a well-defined maintenance plan is followed (per country).
- LCCA when no maintenance plan is followed (per country).
- Initial construction cost of each alternative (per country).

Uncertainty regarding the importance rating of the project dimensions led to the development of a Monte Carlo simulation. For each country the exclusive multicriteria analysis and a Monte Carlo simulation was performed. The importance rating for each of the project dimensions were varied during the Monte Carlo simulation.

3.1 Development of Criteria for Multicriteria Analysis

During the first workshop, stakeholders were asked to identify and rank challenges that the road industry in their said countries faced with regards to road construction and maintenance. Using the challenges identified, a set of design criteria that would satisfy the needs of all stakeholders was developed. The design criteria relating to road surfacings include:

- The surfacing had to require low maintenance costs during its life.
- The surfacing had to be resilient to the environment (e.g. precipitation, temperature).
- The surfacing should be constructable using labour-intensive construction methods.
- The skills required to construct the surfacing should be transferable to other industries (e.g. concrete mixing and placing skills can be used in the buildings industry).
- The materials used to construct the surfacing should be locally available.
- The surfacing should be constructible by a low skilled contractor.
- The surfacing should be constructible even with a low level of supervision, and rules out many options.
- A low design skill level should be required to develop the design of the surfacing.

3.2 Life Cycle Cost Analysis

The total cost of facility ownership can be assessed using the LCCA method. All costs related to acquiring, owning and disposing of the asset is considered. LCCA is a valuable tool to assess project alternatives that fulfil the same function but has different construction, maintenance and disposal costs (Fuller, 2016). By calculating the life cycle cost of different alternatives, projects can be viewed on the same monetary scale and the alternative with the lowest life cycle cost can be selected for implementation.

Several methods are available for LCCA. Two methods that were investigated included the HDM-4 software package (University of Birmingham, 2019) developed by the World Bank and the Present Worth of Cost method (Technical and Vocational Training Corporation, 2019).

3.3 Monte Carlo Simulation

A Monte Carlo simulation is a mathematical technique regularly used as part of decision analysis. A range of possible outcomes are assessed by assigning probabilities to these outcomes. All possibilities, including outlier events are evaluated.

Probability distributions are assigned to all factors that are viewed as being uncertain. Depending on the number of uncertainties and the ranges specified for them, thousands of recalculations might be necessary before an outcome is achieved.

There are various probability distributions that can be used for the analysis, including normal, log normal, triangular, uniform, PERT and discrete (Palisade, 2018).

For this project a discrete distribution was selected. The importance ratings for the various elements of the exclusive multicriteria analysis was uncertain and user defined ratings were assigned to each attribute.

A Monte Carlo simulation has several advantages over a single-point analysis, including the following (Palisade, 2018):

- Interdependent relationships between inputs can be modelled. This can be used to show how some factors go up when others go down.
- Results show not only what can happen, but also the likelihood of a specific event.
- It is easier to conduct a sensitivity analysis and to determine which factor influences the outcome the most.
- Because of the data-intensive output, it is easy to display results graphically.

4. RESULTS

4.1 Multicriteria Analysis

Through a design-led-thinking workshop, the stakeholders in each country developed a set of design criteria to which the most suitable LVR surfacings should comply. The stakeholders were asked to give the design criteria an importance rating out of five (five being ‘very important’ and one being ‘not that important’). The stakeholders of each country as well as a group of pavement experts were then asked to select three surfacings that would best conform to each of these design criteria.

The frequency of selection for the different surfacings in relation to the different criteria was computed and multiplied with the importance rating. The purpose of this exercise was to gauge the overall suitability of the surfacings for all developed criteria.

When comparing the weighting of the different selection criteria from the different workshops, as shown in Figure 2, the following criteria ranked high in all cases:

- Requires low maintenance.
- Is resilient to the environment.

Ghana, Sierra Leone and Liberia experience high rainfall which puts severe pressure on the serviceability of low volume roads. Lack of an adequate maintenance management system and secure funding for maintenance puts additional strain on the roads. Surfacing options with low maintenance requirements which are resilient to environmental conditions (such as excessive rainfall) would ensure all year round accessibility.

Ghana and Liberia rated “locally available material” as an important factor. These two countries indicated that funding for LVRs was one of their biggest challenges. The issue arises because bituminous products which are used for surfacing seal construction are not locally available and must be imported. The same issue comes to light during concrete manufacturing. Imported materials are exposed to fluctuating currencies and markets making planning efforts even more challenging.

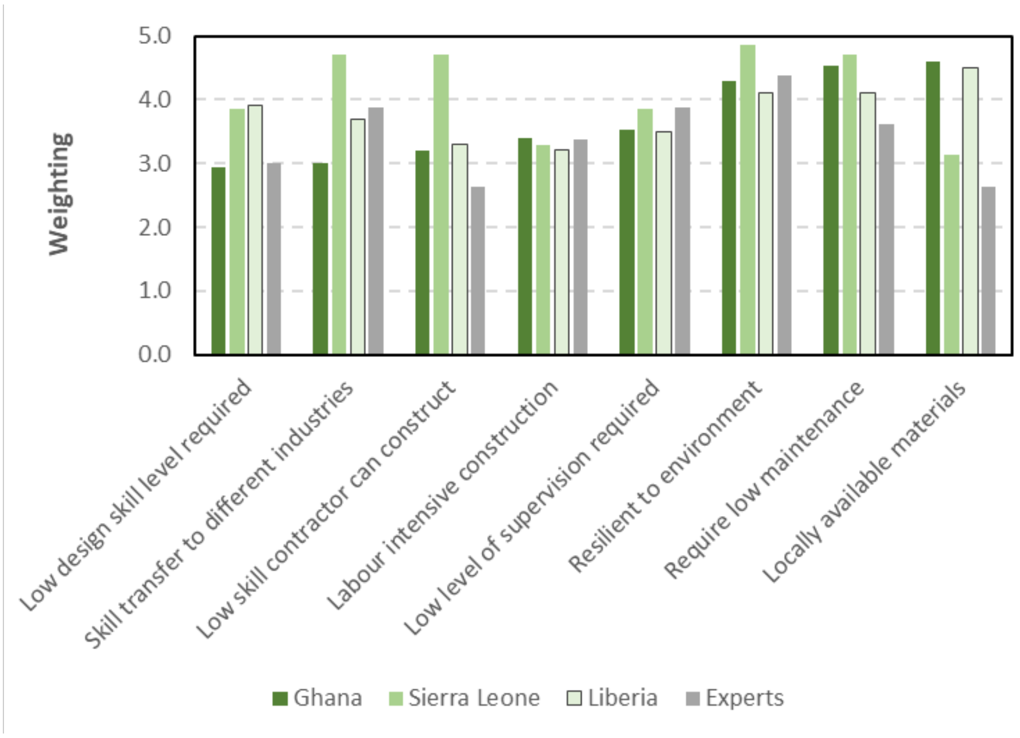

Figure 2: Weighting of the various criteria from all workshops

In Figure 3, the combined technical rating of the different surfacing types is presented. From a combined technical perspective, the following are the top four surfacing types:

- Concrete block paving.
- Plain-jointed concrete.
- Concrete strip roads (Caveat: only for relatively low traffic levels due to unacceptable road safety issues).
- Otta seal (Caveat: Not suitable for use on excessive slopes.

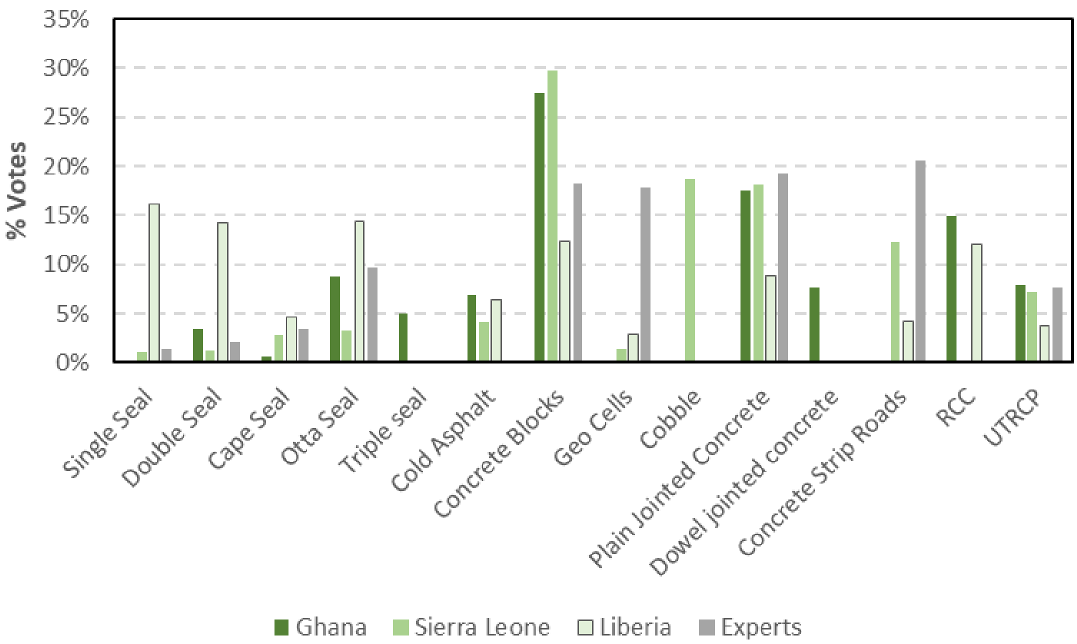

Figure 3: Combined results for all workshops

4.2 Life Cycle Cost Analysis

The purpose of pavement design is to develop a pavement structure with sufficient structural capacity to carry the design load while optimising the life cycle cost of the structure. In the initial stages of development, several alternatives are identified considering elements including, the level of service, the structural capacity, and the availability of material. The alternative selected for implementation depends on the outcome of the economic analysis. An economic analysis considers all the cost over the entire life cycle.

There are mainly two strategies that should be evaluated. The first strategy includes a high initial construction cost with small (less frequent) spending on maintenance. The second option consist of a smaller capital expenditure with more frequent (and sometimes larger expenditures) on maintenance actions.

An integral part of the LCCA is an understanding of the behavioural differences of the alternative surfacing types. Maintenance and rehabilitation requirements of the different surfacing types would be vastly different across the spectrum of surfacings. It is critical to know how the various pavement materials behave under different loading and environmental conditions.

4.2.1 HDM-4 Analysis

The use of HDM-4 as a tool to evaluate different surfacing types was problematic as not all the required input data was available at the time of the study. The HDM-4 tool is more suited for project level analysis than for an overview of generic options such as that required for this project. Elements that were noted in the study included:

- Due to the low traffic volumes associated with rural feeder roads the relative savings on road user costs between the different surfacings became negligible in comparison to the maintenance and construction costs.
- The analysis indicated that a concrete surfacing would result in higher road user and maintenance savings than bituminous surfacing on steeper road sections.
- Deterioration models embedded in HDM-4 lean more towards maintenance triggers for traffic volumes over a time period than towards deterioration due to environmental effects. Because the traffic volumes were so low, maintenance actions were not triggered, and a scheduled maintenance approach had to be followed.

HDM-4 was deemed unsuitable for this project and a Present Worth of Cost method was accordingly adopted. The PWC method did not specifically evaluate the appropriateness of the different surfacings on excessive slopes although it was indirectly accounted for through the selected criteria mentioned in Section 3.1.

4.2.2 Present Worth of Cost

The PWOC method is an uncomplicated method to compare the LCC of different pavement types. An accurate economic assessment is only possible if a realistic life cycle strategy that includes timely rehabilitation and maintenance inputs is available. For the current study a life cycle strategy was developed for each of the surfacing options.

To make the different surfacing types comparable, all the future maintenance costs for all alternatives must be discounted to the present value. Based on recommendations of several international institutions (Campos et al., 2015), a discount rate of 12% was selected for the current study. The PWOC method discounts all the maintenance inputs over the pavement life-cycle as well as the salvage value of the road at the end of the service life to a present-day value.

To be able to synthesise the PWOC model the following information was required:

- Traffic Loading Class (TLC 0.01, TLC 0.3, TLC 1.0).
- Subgrade condition (3% ≤ CBR ≤ 7%, 8% ≤ CBR ≤ 14%, CBR ≥ 15%).
- Surfacing types.
- Road width (a width of 7 m was used for all surfacings except dual concrete strips).
- Road length (a length of 1 km was analysed).
- A maintenance schedule that was specifically developed for each surfacing type.
- A Bill of Quantities (BOQ) populated by a local representative, considering costs from previous projects.

Traffic classes appropriate for low volume road design was selected in line with several manuals including the following:

- Pavement and Materials Design Manual, 1999, the United Republic of Tanzania, Ministry of Works.
- Design Manual for Low-Volume Sealed Roads Using the DCP Design Method, 2013, Republic of Malawi, Ministry of Transport and Public Works.
- Pavement Design Manual: Volume 1: Flexible Pavements, 2013, the Federal Democratic Republic of Ethiopia, Ethiopian Roads Authority.

Two maintenance scenarios were considered. In the first scenario maintenance costs were allocated according to a well-constructed maintenance schedule. For the second scenario, no maintenance actions were considered, and full reconstruction of the surfacings were required after several years. The timeline in which a surfacing deteriorates to a point where there is a zero salvage value and the surfacing need to be completely reconstructed would differ for the alternatives. Deterioration would be different as certain surfacing are more durable than others.

It was also impractical to consider only the costs of the surfacing and not the entire pavement structure. A seal, for example would be relatively cheap compared to a concrete option. The seal has no structural bearing and its function, in most cases, is purely to prevent water from entering the base and subbase layers. The concrete layer, on the other hand, contributes to the structural capacity of the pavement. To ensure comparability of the surfacings, the cost of the supporting structures was also considered.

Several manuals were consulted to design pavement structures for the different surfacings which are suitable for low volume road conditions (CSIR, 2008; Cement and Concrete Institute, 2009; Ethiopian Roads Authority, 2017; Geddes & Goldie-Scot, 2018; Jofre & Zabala, 1998). Not the latest manuals on LVR design. For each of the surfacing types a different pavement design was developed for three subgrade condition and three traffic classes.

With all of the available information a total amount of 18 PWOC models were required for each surfacing.

4.3 Monte Carlo Simulation

To be able to select the most appropriate surfacings in each of the countries a Monte Carlo simulation was used. Both the technical and financial evaluations were considered. The ranking provided by the experts, with their in-depth knowledge of the different surfacing types, had a greater focus on the surfacing products and their capabilities. Rankings by the stakeholders represented a view of what was locally possible. Funding was highlighted as a critical concern in all the countries. Political agendas would lean towards the construction of longer lengths of road rather than focusing on options that are more durable. From a sustainability point of view, the life-cycle cost would be the most important consideration.

The main parameters (criteria) driving the final surfacing selection are thus:

- Construction cost.
- Life-cycle cost – with maintenance.
- Life-cycle cost – without maintenance.
- Technical analysis (experts).
- Technical analysis (local stakeholders).

Considering the uncertainty in the weighting of the different parameters listed above a Monte Carlo simulation was performed to determine the top five surfacing options.

4.3.1 Analysis to Determine Final Surfacing Selection

To prevent bias as to which of the above-mentioned criteria should be considered most important, a weighting was assigned to each of the various criteria. The weighting was varied across the criteria and always summed up to one.

A total of 352 scenarios were assessed for each traffic and subgrade class and each country (352 x 9 x 3 = 9504 simulations). The surfacing options were ranked according to their *position* based on the least expensive option for costs and the highest ranking for technical analysis. The rankings were multiplied by the assigned weighting, and the top three alternatives for each scenario were selected. The number of times that a certain option ranked in the top three were counted across the various scenarios. From these, the top five alternatives were determined.

The top five surfacing alternatives selected for Ghana, Sierra Leone, and Liberia after the completion of the Monte Carlo simulation are shown in Figure 5.

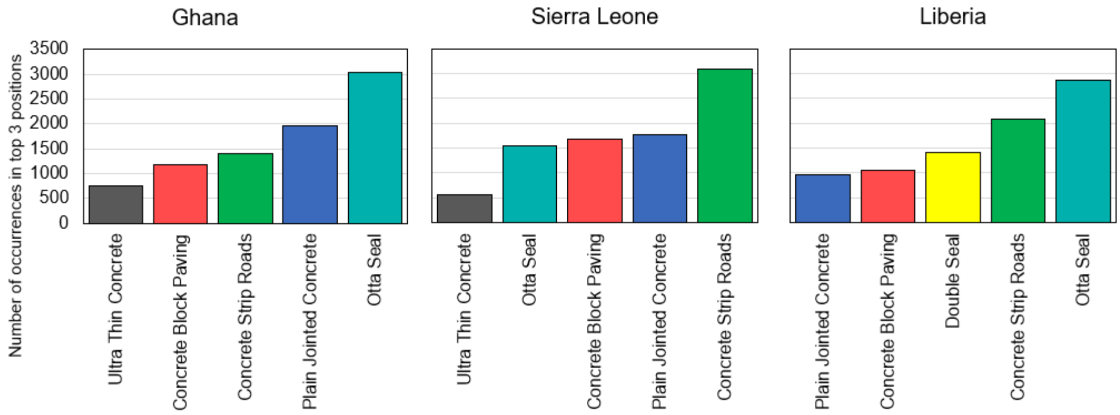

Figure 5: Final surfacing selection

5. CONCLUSION

The dire state of rural roads in Ghana, Sierra Leon and Liberia is not only hampering the connectedness of communities but has an influence on the economy at large. To facilitate trade, countries are required to have an efficient transport infrastructure network.

Low volume roads mainly deteriorate due to environmental conditions rather than load associated distresses. The tropical climate present in West Africa aggravates the rate of deterioration due to persistent high rainfall.

Development of surfacing suitable for low volume roads which can be constructed in a labour-intensive fashion can alleviate impoverished living conditions that some people have to endure. In Liberia and Sierra Leone, more than half of the population is living below the poverty line. These people would benefit in multiple ways from labour-based road construction projects.

In a series of workshops, stakeholders identified challenges that the roads departments in their countries faced. Coupled with data gathered from interviews, the challenges were turned into design criteria that surfacing alternatives must comply with.

Using tools including a Life Cycle Cost Analysis, a Multicriteria Analysis and a Monte Carlo simulation, 22 available surfacing options were reduced to five alternatives per country that were viable options for low volume roads. The outcome should not be viewed as the ultimate ranking in performance of the different surfacing types, but rather it produced a reduced set of surfacing options that were incorporated in their low volume road design manuals. For a specific project the designer would thus consider the topography, traffic, geometry, available materials and select an appropriate surfacing solution for each section of road.

Table 1 shows the final selected surfacing types.

Table 1: Surfacing options for Ghana, Sierra Leone and Liberia

Rank	Ghana	Sierra Leone	Liberia
1	Otta Seal	Concrete Strip Roads	Otta Seal
2	Plain Jointed Concrete	Concrete Block Paving	Concrete Strip Roads
3	Ultra-Thin Concrete	Plain Jointed Concrete	Double Seal
4	Concrete Block Paving	Otta Seal	Concrete Block Paving
5	Concrete Strip Roads	Ultra-Thin Concrete	Plain Jointed Concrete

6. ACKNOWLEDGEMENT

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