MULTI-CRITERIA DECISION MODELING FOR INFRASTRUCTURE DEVELOPMENT: A CASE OF ETHIOPIAN HIGHWAY REHABILITATION PROJECTS

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Abstract

Several Ethiopian highways need reconstruction, but the government doesn't have enough finance to upgrade or rehabilitate all of them in a given fiscal year. Therefore, it has to make prioritization. The decision on highway investment, however, involves several stakeholders and many attributes. Hence, Multi-criteria Decision Method (MCDM) becomes vital. We used Analytic Hierarchy Process (AHP) and relative weighting to rank the highways for rehabilitation. 68 major highways covering the entire nation were selected first. Then four core criteria namely: social benefits, economic benefits, administrative importance, and capital cost were used. The criteria were further subdivided into 22 measurable indicators for which the data were transformed into utility values before arithmetic operation. The criteria and indicators were weighted by AHP and MCDA methods respectively. The score of each of the highways was calculated through stepwise aggregation of the weighting and utility values. The result shows that highways radiating from Addis to: Gondar, Mekele, Awassa, and Nekemt ranked 2nd, 3rd, 5th, & 6th in AHP; and 1st, 2nd, 4th, & 5th in MCDM; respectively. This means, the relative priority among the alternatives for both approaches is the same. In the model the 4th criterion (capital cost) is inversely proportional to road length. Running the model without the 4th criterion would then result in a benefit-maximized rank of highways. Therefore roads such as: Dembidolo-Gambella-Jikawo, Goba-Bitata, Metu-Gore-Gambella, shashememe-Goba-Robe, Degahabur-Gode, and Gimbi-Asosa became: 1st, 2nd, 3rd, 4th, 5th, and 6th rank; respectively. This shows that rehabilitating these regional highways would equally be very feasible as those which radiate from Addis Ababa. The final rank of the highways was highly sensitive to changes in: data quality, transformation functions, and utility value assignment approaches. The model can be used as a prerequisite for feasibility studies.

1 INTRODUCTION

1.1 Background

Ethiopia is a second populous developing country in Sub-Saharan Africa. Arguably, it is experiencing fast economic growth which is also accompanied with a huge demand for transport infrastructure. Despite the undergoing ambitious railway development, the sector of road transport remains the nation's single most important means for travel and transport; and it accounts for more than 95% of the country's domestic passenger and cargo traffic (Authority 1998; Worku 2011). However, the average road density was only about 38.6 km per 1000 km² in 2007 (Shiferawa et al. 2012) which is still less than the average of 50 km per 1000 km² for sub Saharan Africa. Moreover, Ethiopia currently has only two express ways. These are: Addis Ababa ring road and Addis - Adama express way which is now under construction. The regional highways have only two lanes; one in the opposite direction of the other. The share of improved national road length was grown: from 31% in 1995 to 40% in 2007 (Shiferawa et al. 2012) and this value was projected to be 50% in 2012. Majority of the highways, however, are still either in poor condition or under construction. All these evidences indicate that the country is struggling to attain the high necessity of improving the quality of road infrastructure.

Efficient use of available finance is crucial in road construction industry because resources are scarce. Road quality improvement[1] is one of the ultimate goals of Ethiopian Roads Authority-ERA. In Ethiopia, a number of highways need to be either upgraded or rehabilitated[2]. A report of road development plan performance in ten years: 1997-2007 (Africa and Authority ; Worku 2011) informs us two major challenges (Shiferawa et al. 2012). At the *first* place the number of highways to be rehabilitated has been increasing. And *secondly,* those highways which deserve urgent improvement must be prioritized within themselves because they are many. Both cases are challenges to Ethiopian road sector development program - RSDP. Let's explain them in a clearer manner.

Challenge 1 In Ethiopia several highways need improvement: As the country's growth becomes swift, ERA has become busy with building several new regional highways while the quality of existing once reduces through time. Ethiopian highways need continuous improvement because roads do wear out fast. This is mainly because of the low quality of construction: Evidently, more than 55% of federal road are not in a good quality, more than 85% of the total road surface is unpaved and there exists unbalanced axial load which has a damaging role to the highways(Authority 1998). In addition to that, the capacity of the government for rehabilitating all the roads is pretty low. For instance, from 1997 to 2007, the share of expenditure on highways from foreign financial sources was 52.56% (Worku 2011). This implies that the county's financial capacity is very scarce to rehabilitate or generally to improve highways. Therefore, for effective use of both internal and "unpredictably" external finance, Ethiopia has to prioritize highway rehabilitation projects.

Challenge 2 Ethiopia lacks a decision support tool for prioritization: Ethiopia has never had a well reputable reference document on road transport planning until 2006. The first comprehensive

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[1] *Road quality improvement means: construction, upgrading, rehabilitation, or maintenance*
[2] *New road construction, reconstruction, and routine maintenance are not concerns of this document*

planning manual which was prepared and published by Ethiopian Roads Authority – ERA was launched in May 2006, (Becker and Demissie 2006). This implies that the nation couldn't have a well established decision making model in regard to prioretizing highways for any sort of improvement (upgrading, rehabilitaion). The manual contains guidelines for multi-criteria decision making but we couldn't get any experience done by the guideline since its publication time. Therefore, it is justifiable to build a multi-criteria decision making model to prioretize road improvement projects with a particaular emphasis to rehabilaitaion. In short, developing a decision support tool is necessary. A number of multi-criteria decision making – MCDM (Diakoulaki et al. 2005) methods can be applied to address the challenge. But the most appropriate once can be Analytic Hierarchy Process - AHP (Abrishamchi et al. 2005; Chao et al. 2006) and Multi-Attribute Decision Making – MADM (Moges 2007). AHP is the simplest for the decision makers to understand despite its inability to accommodate feedback. On the other hand relative weighting of criteria is too subjective in MADM. Therefore, the combination of both methods is applied in this model to take advantage of each.

1.2   Statement of the problem

For a fair and effective decision output, a decision must either be multi-objective or multi-attribute or both. The theoretical research problem of this research, therefore, lies on necessity of establishing a multi-criteria decision making model for road infrastructure projects of developing countries. In Ethiopia a number of highways need to be rehabilitated or generally improved. Only about 12% of the highways are in good condition, more than 80% of the total road surface is unpaved, and person-road length ratio is the lowest in even in African standards. So, there is a huge demand for road quality improvement. But the government doesn't have capacity to do it in short period of time. For instance, in the last 10 years: 1997-2007, more than 50% of the expenditure on road development was funded by foreign aid. In such a big gap between the need to road quality improvement and the real financial capacity, Ethiopia lacks a comprehensive decision making model to prioritize road projects in order to benefit from effective investment of the little money at hand. This is the real research problem now prevailing in the nation and necessitates the establishment of a comprehensive multi-criteria decision making model to prioritize highway projects for any sort of quality improvement (e.g. heavy maintenance, rehabilitation, upgrading, or reconstruction).

1.3   Research objectives

The main objective of this research is to propose a full-fledged, comprehensive, and semi-automated model that can prioritize all highways of Ethiopia for rehabilitation. There are two specific objectives under this major aim. These are: to design a multi-criteria decision model for national road project prioritization and to implement the proposed model with real data of Ethiopia and see the results.

2 METHODS AND MATERIALS

2.1 General procedure of the research

Any decision making process begins with the recognition and definition of the decision problem. This task has already been done in the previous section. In this sub-section, the methodologies followed for data collection, data analysis and data presentation will briefly be explained. In Figure 2-1 Design of the research methodologyFigure 2-1, the entire process starting from problem definition and ends up with a final outcome which is solution. The list of highways was first extracted from the entire road network and named as 'alternatives'. Then the criteria were set along with the measurable indicators within them. The modeling part continues with the AHP and MCDA (Moges 2007) methods which also include data transformation, weighting, and aggregation. The final outcome is the ranked list of the highways showing which of the highways should be given 1st, 2nd, 3rd, and so...on priority for rehabilitation.
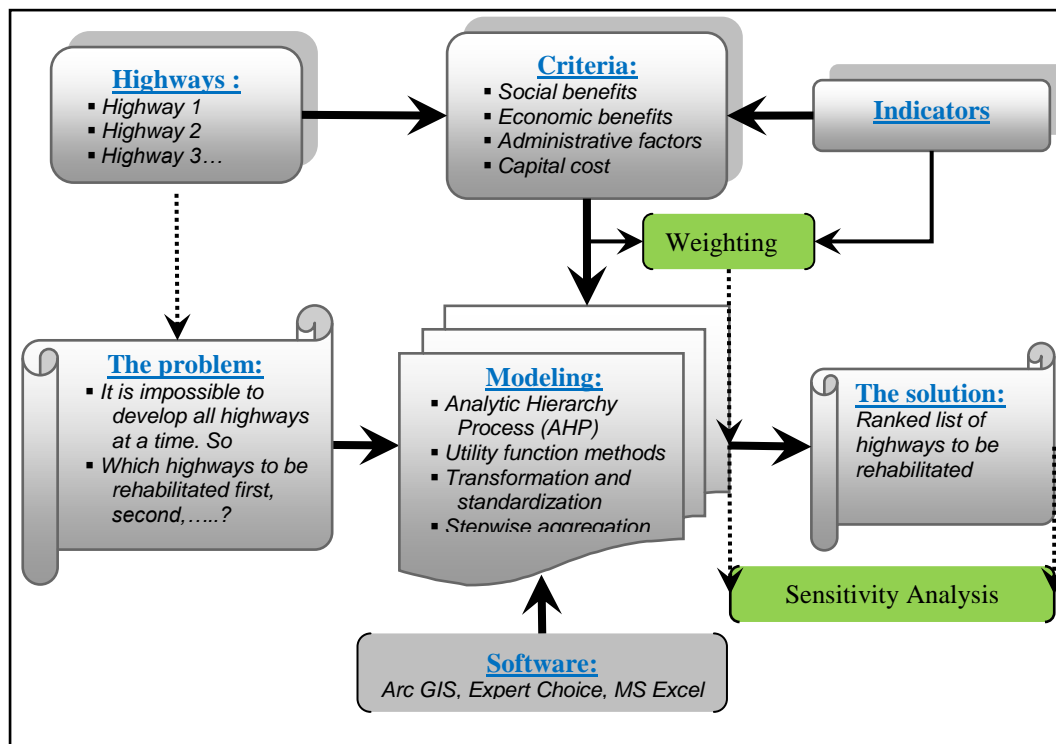

Figure 2-1 Design of the research methodology

ArcGIS software combined with MS Excel (Malczewski 1999) in the modeling part. Sensitivity analysis was done in order to observe the level and direction of changes in the rank of highways in response to any variation in model parameters. Sensitivity parameters in this case were: data transformation functions and weights. In Figure 2-1, the bold arrows indicate the major flow direction of the research task while the broken lines indicate the possible activity or step.

2.2 The multi-criteria decision modeling

This process is the core of the research and it encompasses seven major steps. These are: selecting the alternatives (i.e. highways), setting the core criteria, identifying indicators under each criterion, weighting the criteria, weighting the indicators, transforming indicator data per alternative, and aggregation and ranking. Each of these tasks is briefly explained as below.

The **first** activity was to identify the highways which compete for rehabilitation. Highways differ in their: type, size, pavement, length, and hierarchy. For instance, we can't compare second generation (Gwilliam and Kumar 2003) highways with a small local street (Riverson et al. 1991). Therefore, we followed a two-staged listing of highways and named them as: 1st order and 2nd order alternatives. Some rules were set for selecting few representative highways from the entire road network system of the country. We used two simple rules for selecting 1st order alternatives. As can be observed in Figure 2-2, if a highway is classified as TRUNK[3] by Ethiopian Road Authority and if it radiates from Addis to major regional city, then it is grouped as 1st order alternative. More rules were set to select 2nd order alternatives. A road can be selected as 2nd order alternative if it fulfills at least 3 of the following parameters. These are: being a regional road, uses as motorway, has length between 50km and 800km, at least of 4th hierarchy in ERA standards, connects towns with minimum population 30,000 each, directly connects a town to international boarder, directly connects capital city of a regional state to other towns, and directly links two 1st order alternatives. Application of these filtering parameters to the entire national road network gives us 68 highways: 7 as 1st order alternatives and 61 as 2nd order alternatives. They are shown in Figure 2-2.
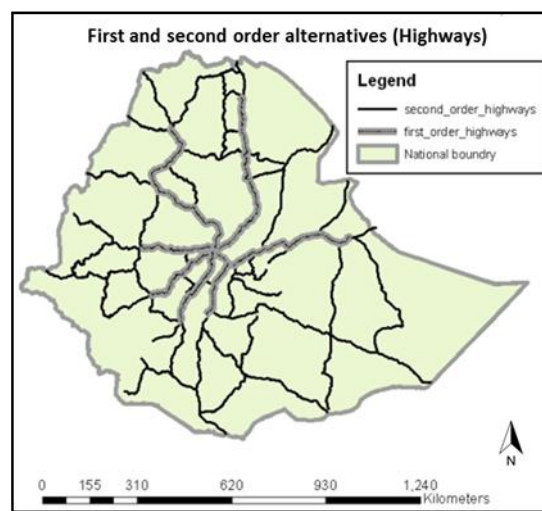

Figure 2-2 In total 68 highways were selected as alternatives for the decision modeling

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[3] *TRUNKS are those highways classified as top hierarchy according to classification by Ethiopian Roads Authority*

The **second** modeling step was to set the core criteria. We referred to main issues of sustainable development in order to set our core criteria. These are: economy, social development, and environment. But since this is not a study for new projects, the issue of environment was left out and two additional criteria namely: administrative importance and capital cost were considered. Therefore, the four criteria to be used in this model are: *social benefits, economic benefits, administrative importance* and *capital cost*. By 'social benefits' we didn't mean the social issues addressed by ERA (Hine et al. 2003), rather we focus on demographic factors. More details are mentioned in further steps below. But the criteria were too crude to measure. So, we had to break them down to measurable facts.

The **third** modeling step was to identify indicators under each criterion. Measuring those 4 criteria only possible where they are further subdivided into measurable indicators as show Figure 2-3. A total of 22 measurable indicators were grouped under the 4 criteria. The number of the indicators under social benefits, for example (see Figure 2-3), economic benefits, administrative importance, and capital cost were: 6, 6, 5, and 5, respectively.
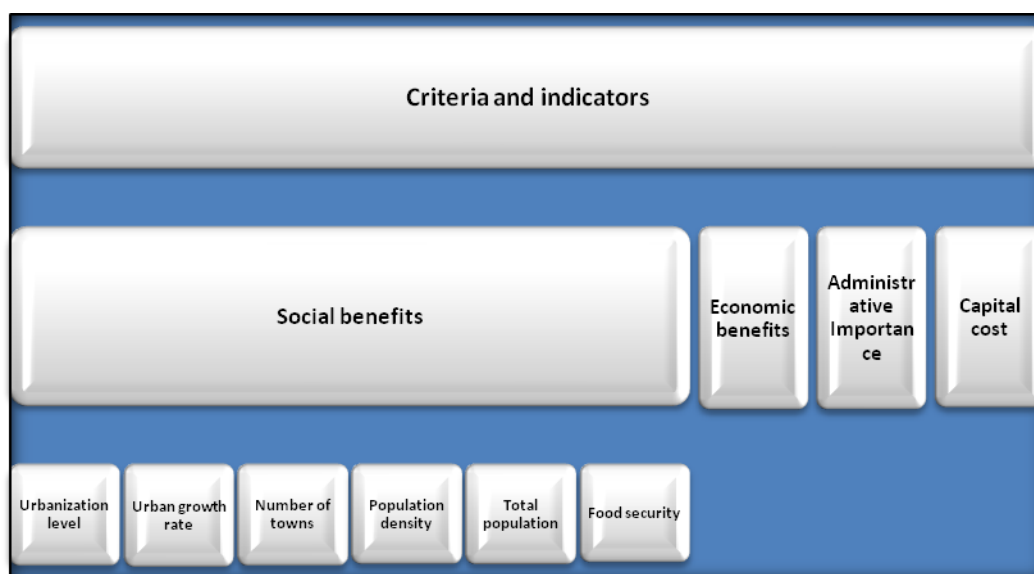

Figure 2-3 Indicators under each criteria (only indicators of social benefits are displayed)

Indicators under social benefits were: percentage of people living in urban centers, rate of urbanization, number of towns, population density, total population, and food security. Indicators under economic benefits were access to: sites of vital national economy, mining sites, irrigable lands, export products producing areas, major crop producing zones, and livestock specialty places. Indicators under administrative importance were: connectivity to a regional capital, connectivity to sea port or boarder highway, connectivity to economically weak regions, effectiveness in road networking, and role of connecting cities. And indicators under capital cost were: road length, road surface type, topography, number of crossed rivers, and hierarchical level of the highway. Each of the 22 indicators were selected and grouped under the 4 criteria in such a way that they can be measured.

The **fourth** modeling step was weighting the 4 criteria. To do this, the procedure of Analytic Hierarchy Process (AHP) (see Figure 2-4) was followed. AHP is a decision making tool that was created by Dr. Thomas Saaty in 1980 (Takano, 2007). AHP allows a set of complex issues that have an impact on an overall objective to be compared with the importance of each issue relative to its impact on the solution of the problem (Álvarez et al. 2013). It uses a matrix of elements (criteria or alternatives) to make a pair-wise analysis and end up with the so called "Eigen vector" which is the relative weight of the elements under consideration. The total sum of the eigen vector is 1. For our research, we used AHP in order to decide the weight of the 4 criteria. In Figure 2-4. The term "Ind" means indicator which is quite measurable.
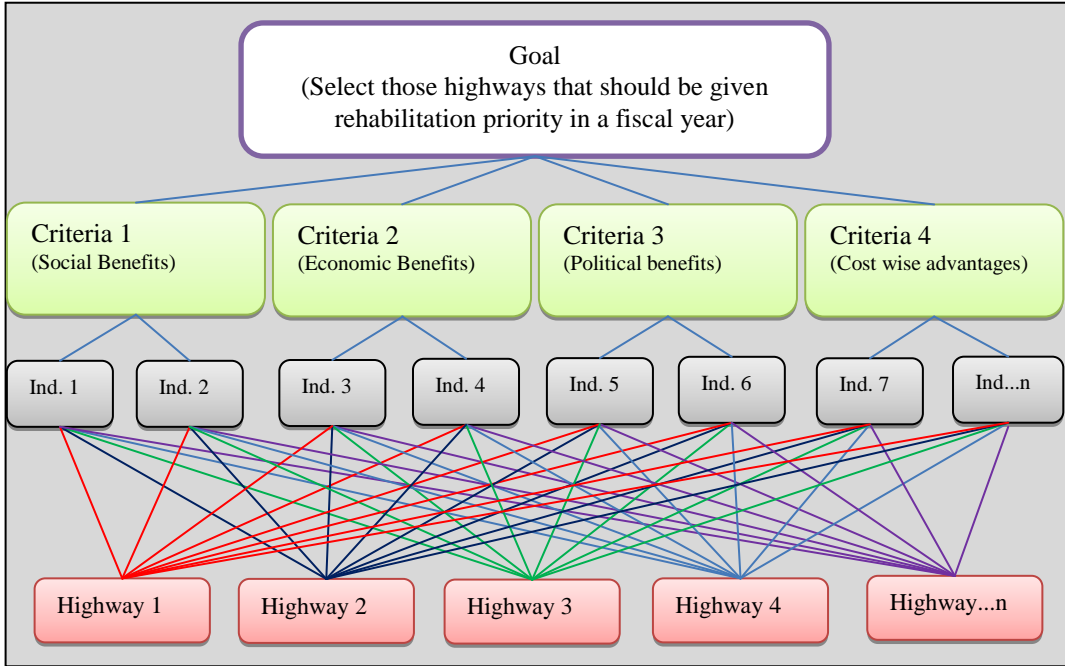

Figure 2-4 Application of Analytic Hierarchy Process (AHP) in highway rehabilitation

In order to set the weights of the 4 criteria, six highly educated Ethiopian experts working in transport sector were given a detailed AHP questionnaire during data collection. The analysis of the data gave us the eigen vector (which is now weight) as: 0.17, 0.38, 0.25, and 0.20 for: social benefits, economic benefits, political benefits, and cost benefits respectively. These weights are also indicated in the third column of Table 2-1.

The **fifth** modeling step was weighting the indicators. The same procedure of collecting expert judgment through AHP was applied for setting the weights of the indicators. We have to note that the sum of indicators weights within a criterion is 1 because the experts were allowed to give values for relative importance of the indicators within a criterion. The result is displayed in Table 2-1.

Table 2-1 weights of criteria and indicators from AHP

Criteria	Indicator	Criteria weight	Indicator weight
Social Benefits	Urbanization rate	0.17	0.1
	Number of Towns	0.17	0.2
	Population density	0.17	0.2
	Total population	0.17	0.1
	Food security	0.17	0.35
Economic Benefits	National organizations	0.38	0.1
	Access to Mining sites	0.38	0.1
	Irrigation potential areas	0.38	0.2
	Export producing areas	0.38	0.15
	Crop producing regions	0.38	0.3
	Livestock specialty areas	0.38	0.15
Political Benefits	Connectivity to a regional capital	0.25	0.15
	Connectivity to a seaport of boarder highway	0.25	0.40
	Connection to economically weak regions	0.25	0.15
	Level of effectiveness in Networking	0.25	0.10
	Role of connecting Cities	0.25	0.20
Cost Advantages	Road length	0.20	0.2
	Road surface type	0.20	0.2
	Topography	0.20	0.15
	Number of rivers crossed	0.20	0.2
	Hierarchical level of the highway	0.20	0.25

The **sixth** step of modeling was to transform indicator data for each alternative. This part of the research involves transformation of data of each indicator into a common format by using relevant mathematical function. We converted the real data into utility value (UV) which ranges from 0 to 1 inclusive. One of the formulas use used to find UV is shown in Equation 2- 1, which was applied to irrigable land. Multiplying this value with 100 gives us a normalized 1 to 100 scale values, which can then be aggregated with data of other indicator transformed in a similar way.

$$UV = \frac{x_i - x_{min}}{x_{min} - x_{max}}$$

Equation 2- 1 Computation of Utility Value from real data

Where, UV is a [0-1] scale transformed value, x_i is the area of irrigable land attached to a highway, x_{min} and x_{max} are minimum and maximum areas, respectively.

The last and the **seventh** modeling procedure was aggregation and ranking. This is a very important one because it wide up the overall research and gives the results we have been looking for. Mathematical expression of the final model is given by Eq... 2:1 the total score is just the summation of the sums of the four criteria. The rank of a highway (alternatives) depends on the

sum the values of indicators; the larger this aggregate value the better the rank, and hence the higher priority for rehabilitation.

$$S_j = \left\{ \sum_{i=1}^{6} (0.17 * w_{isb}) + \sum_{i=1}^{6} (0.38 * w_{ieb}) + \sum_{i=1}^{5} [0.25 * w_{ipi}] + \sum_{i=1}^{5} [0.20 * w_{icc}] \right\} m_{ij}$$

Eq... 2:1 summarizing equation for the total score

Where; S_j is total score of highway (j), *6, 6, 5, and 5* are the numbers of indicators under each of the four criteria, *0.17, 0.38, 0.25, and 0.20* are weights of the criteria from AHP, w_{isb}, w_{ieb}, w_{ipi}, *and* w_{icc} are relative weights of an indicator within the respective criteria, and m_{ij} is transformed measure or utility value of an alternative (j) for an indicator (i).

3   DISCUSSION ON THE RESULTS

The ultimate result of the model is the ranked list of highways. Top 20 and top 10 ranked highways are shown in Figure 3-1and Figure 3-2, respectively. First we displayed and discussed the ranks for each criteria separately and then for all criteria.

In Figure 3-1 **(a)**, where only **social benefits** were considered as criteria, all of the 7 first order alternatives *(black lines)* are part of the top 20 highways to be rehabilitated. This is due to the reason that population and most of the urban agglomerations are located along these seven axes. The rest Majority of the rest highways *(red lines)* are connecting highlands to the desert areas in which case food security issue would be well addressed. And the model also automatically selects few highways at the central part of the country because of the high population density as compared to outer parts.

In Figure 3-1 **(b)**, where only **economic benefits** were considered as criteria, out of the top 20 ranked highways, 4 *(shown by black)* are the 1st order alternatives, and the rest 16 *(red lines)* are the 2nd order alternatives. The four 1st order highways shown on the map are ranked as 2nd, 3rd, 6th, and 8th. This is due to the reason that national organizations with economic importance lie along them. Moreover, most of the livestock and crop producing regions belong to these highways (e.g. Borena and Somali area).

In Figure 3-1 **(c)**, where only **administrative or political benefits** were considered as criteria, all the seven 1st order alternatives *(black colored)* were automatically prioritized by the model. This tells us the vitality of those highways emanating from the capital Addis Ababa in terms of administrative advantages. Majority of out of the top 20 ranked alternatives were at the 3rd hierarchy *(they are called "Access Roads" according ERA)*. Most of these roads have intersection to the international boarder in which case political implication is justified (e.g. access to sea port and border-crossing highways).
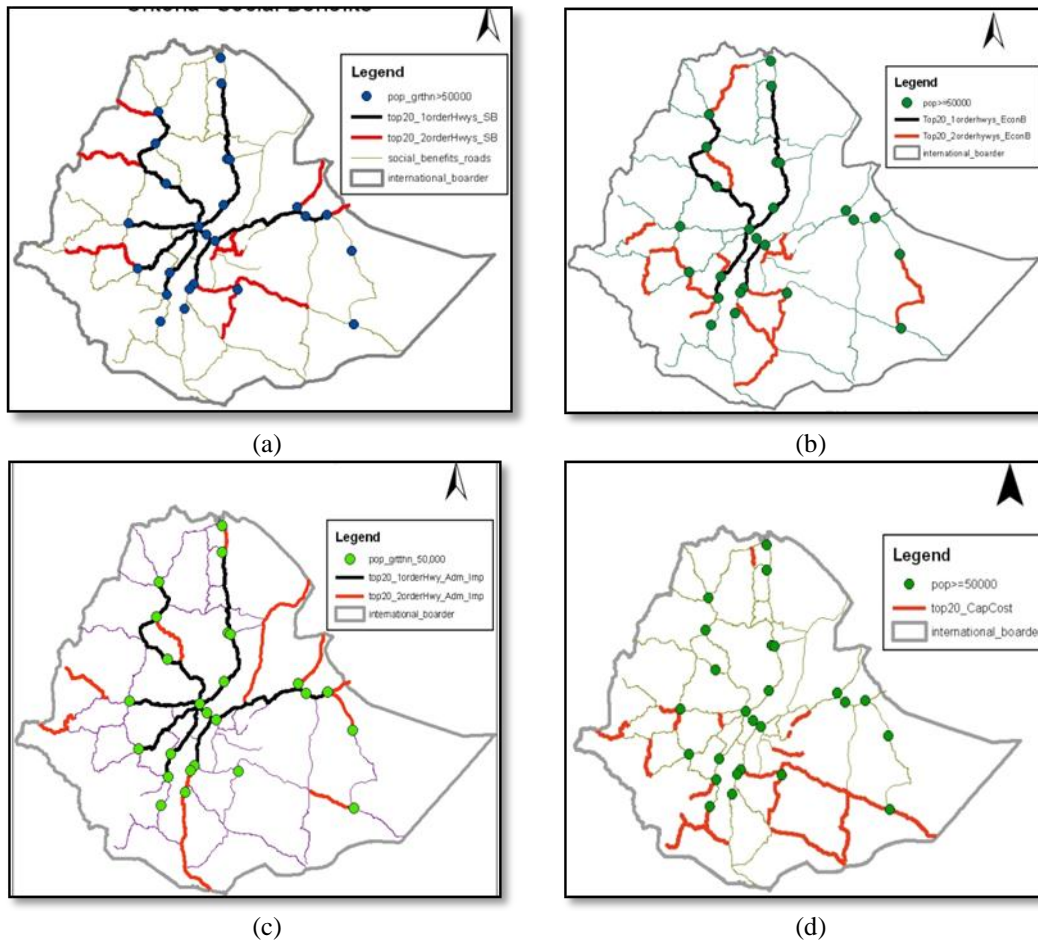
Figure 3-1 Top 20 ranked highways prioritized by using: (a) social benefits, (b) economic benefits, (c) administrative benefits, and (d) capital cost

In Figure 3-1 **(d)**, where only **capital cost** was considered as criteria, majority of the prioritized highways were not long which implies that road length was inversely proportional to cost. Some of the selected highways lie in the flatter parts of the country (e.g. south eastern part of the nation). This shows the influence of elevation as a factor of cost. And most of the highways with high priority for rehabilitation were of the lowest hierarchy *("Collectors" according to ERA classification)*.

The final result, which portrays only 10 highly prioritized highways, is shown in Figure 3-2. As can be seen from the figure, all 1st order alternatives except Addis Ababa-Hossana-Sodo are among the top 10 ranked highways selected for rehabilitation. The result depicts that all roads are not comparable. The rest highways out of the top ten are mainly belong to regions with high crop productivity. And the purple one (in Somali Region) is prioritized mainly because of its relatively flatter landscape, oil potential and large livestock.
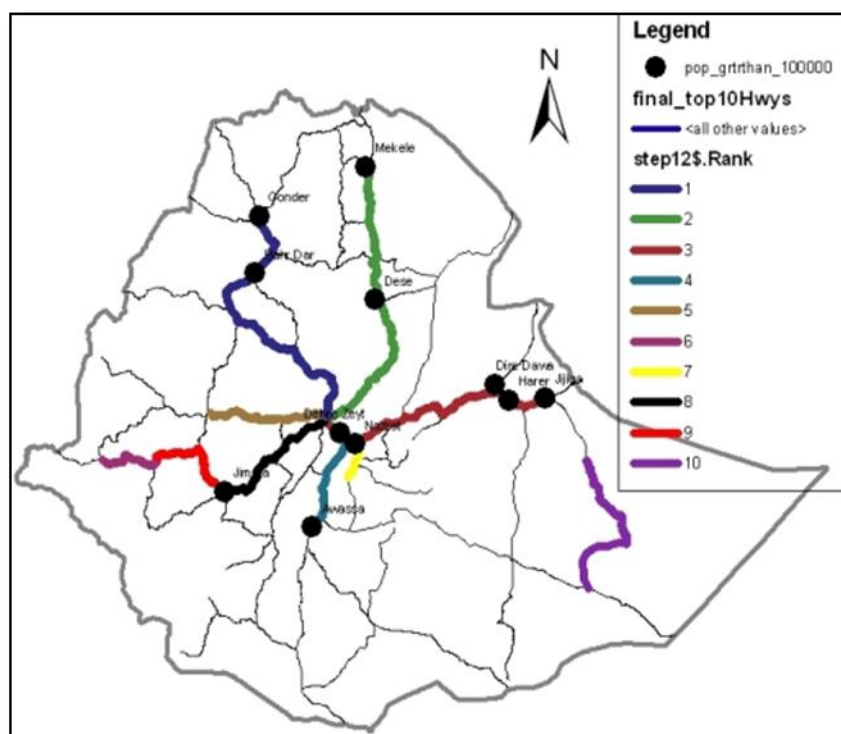
Figure 3-2 top ten ranked highways of multi-criteria decision making model

From the result of the model we found out that the five highways which radiate from the capital Addis Ababa got the highest priority for rehabilitation. The result, however, was highly influenced by capital cost. After removing cost as priority, regional highways got highest rank. Roads such as: Dembidolo-Gambella-Jikawo, Goba-Bitata, Metu-Gore-Gambella, shashememe-Goba-Robe, Degahabur-Gode, and Gimbi-Asosa became: 1st, 2nd, 3rd, 4th, 5th, and 6th rank; respectively. This shows that rehabilitating these regional highways would equally be very feasible as those which radiate from Addis Ababa. The final rank of the highways was highly sensitive to changes in: data quality, transformation functions, and utility value assignment approaches. The model can be used as a prerequisite for feasibility studies.

4   CONCLUSION

Multi-criteria decision making/analysis (MCDM) is not a new concept to infrastructure planning (Modarres and Zarei 2002). But Ethiopia had never used it for highway planning until 2009. Then introduction of MCDM model to Ethiopian Road Sector Development Planning (RSDP) was necessary. This model covers the entire country of Ethiopia in which case Ethiopian Roads Authority may use, amend and modify the model easily for all federal roads under its responsibility. Additional advantage of the model is that it may not only be used for highway rehabilitation but also for similar developments like: new construction, reconstruction, upgrading

…etc with a very little or no modification. The model is composed of 4 criteria, 22 indicators and 68 highway segments which are selected from the entire country. All the remaining highways are of low hierarchy as compared to the 68. The four criteria are social benefits, economic benefits, administrative or political importance and capital cost. Except the missing of environmental aspects, these criteria are believed to represent the concept of sustainable development.

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Acknowledgements

We are grateful to staff members in ERA[4] and ECA[5] as well as all other parties who supported us in data collection. We thank Mr. Stefan Fina[6] for his contribution in GIS software.