Geographic data modeling to define alternative transport corridors to bypass the Metropolitan Region of Belo Horizonte: comparative scenarios

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SUMMARY

This paper aims to present the methodology used to compute feasible corridor alternatives to bypass the Metropolitan Region of Belo Horizonte (RMBH). Its computations were based on predictive scenarios developed with the use of geoprocessing and multi-criteria analysis. The study area encompasses extreme concerns of physical, biological, economic, social and logistic natures. In spite of the full cooperation of nature conservation units, designated areas for managed aquifer recharge, and land with very rugged topography, the region has suffered strong anthropogenic pressure, particularly with the fierce growth of the urban stain, the installation of industries and warehouses, and mining activity. From a logistic point of view, the region is strategically important as it connects the highways BR-040 and BR-381, which interconnect from the RMBH to Rio de Janeiro and São Paulo, respectively. Although a public notice and terms of reference were released in 2011, a study of technical, economic and environmental feasibility and the engineering design of the south segment of the ring road have not been concluded nor submitted. In this sense, and in order to promote elements for analysis, control and discussion, the purpose of this paper is to produce material suitable for qualifying and quantifying different transport corridor alternatives for the development of this delineation in transportation infrastructure. The developed model made use of information from the public notice and the terms of reference of the project, and the data used were all official and pertaining to the public domain. Multi-criteria analysis was implemented in a geographic information system setting using the AHP technique in hierarchical levels of decision-making. Four scenarios were produced that reflect distinct and competing interests: biophysical, environmental restrictions, socioeconomic and commercial/logistic. In each scenario, the cost surface and the feasibility corridors were computed. The corridors were compared in relation to their extension, declivity, urban area, conservation areas and vegetated area. The study displayed considerable applicability potential for external control. The results showed that predictive scenarios can be used to promote qualitative and quantitative analyses as to the viability of linear infrastructure projects, even in the phase of publishing public notice.

Keywords: Geographic information system. Multi-criteria analysis. Decision-making rules. Transparency. Evaluation of public works.

1. INTRODUCTION

Despite its long historical evolution, the development of road infrastructure projects in Brazil faces considerable difficulties to this day, principally during the planning and implementation phases. According to Nóbrega (2013), the majority of projects are marked by inadequacies in their planning phase. In addition, a lack of transparency concerning the data and methods employed in the analyses all cause technical and budgetary problems, which reflect in the rising costs and prolonged periods for completion.

In order to achieve effective results in the activity of transportation infrastructure planning, in a transparent manner in both the public and private sphere, it is essential that the projects be guided by systematic thinking processes. Thus, it is vital that the professionals involved make decisions as a team and consider the interaction of the variables present in all stages of the process. This form of reasoning is based on the principle of multi-criteria analysis, aided by the technique of the Analytic Hierarchy Process (AHP) (Saaty, 1995). This model has been explored with geographic information Systems (GIS) that allow for spatial modeling of variables in the decision-making process.

According to DNIT (BRAZIL, 2012), the proposed construction of the ring road features the project in three segments: south, north and east. Based on the above-mentioned methods of analysis, it is the aim of this paper to investigate the feasibility corridors for the "South Ring", a route whose feasibility study is in development and has yet to present preliminary results. In this context, this article presents the results of geographic data modeling to define alternative transport corridors that represent greater economic, technical and environmental feasibility for the implementation of this transportation infrastructure. In addition to the public notice and the terms of reference (BRAZIL, 2012), we extracted from domain geographic data environmental, logistic, commercial and socio-economic variables to be used in the model.

2. MULTI-CRITERIA ANALYSIS AND GIS MODELING IN TRANSPORTATION

The demand for methodologies to modernize transportation planning is widely known and geoprocessing has been a key factor in integrating, in a coordinated manner, the numerous spatial variables of this process. The inclusion of GIS to assist in the planning of transport corridors requires great deal of data. According to Longley et al. (2013), a GIS is characterized by a set of constructors to represent objects, tools and processes in a computerized environment, usually operating in the form of geographic data models.

One of the models discussed and used together with GIS to assist in the decision-making process is multi-criteria analysis. It provides a structured integration of geographic variables, the opinions of the agents involved, even if different or divergent, and weight of the variables in the decision-making rules, with the goal of reproducing diagnostic and prognostic scenarios. In order to subsidize multi-criteria analysis, methodologies have been developed to optimize the workflow, which are then implemented in GIS modeling. Worth mentioning in this context is the analytic hierarchy process AHP, a technique developed by Saaty (1995) to ensure that subjectivity originating from human decisions is minimized by applying mathematical rules in the process of assigning importance to the given variables. According to Sadasivuni et al. (2009), this technique is applied as a method of variable comparison for multi-criteria analysis and uses mathematical modeling to determine priorities--defined as something important in relation to the organization of disparities in the values, opinions and interests of the agents involved in the planning of transport corridors.

While the AHP method uses paired values as input data, alternatively its output information corresponds to a numerical ranking, which lists, orders and assigns importance to the given preferences. The main role of GIS has been in relation to the composition of values assigned to pixels in digital maps in matrix format (NOBREGA et al., 2009).

Although significant advances in the geographic contextualization of decision-making processes in transportation were achieved in the 1990s and the first decade of the twenty-first century, AHP methodology, coupled with GIS, became an area of interest for practical projects of feasibility corridors only a few years ago. In Brazil, the combined use of GIS and AHP in the planning of transport corridor projects is not exclusive to the academy. Recent studies applied to the planning of railways were developed under federal administration with transport and control managers (BERBERIAN et al., 2015). These initiatives show the interest of transportation managers and technicians in the modernization of the planning process. The results demonstrate the potential of geoprocessing in catalyzing not only a huge range of variables involved in transportation planning, but also in helping to model solutions in the face of the complexity of the public, environmental and transportation policies involved in the process.

3. STUDY AREA

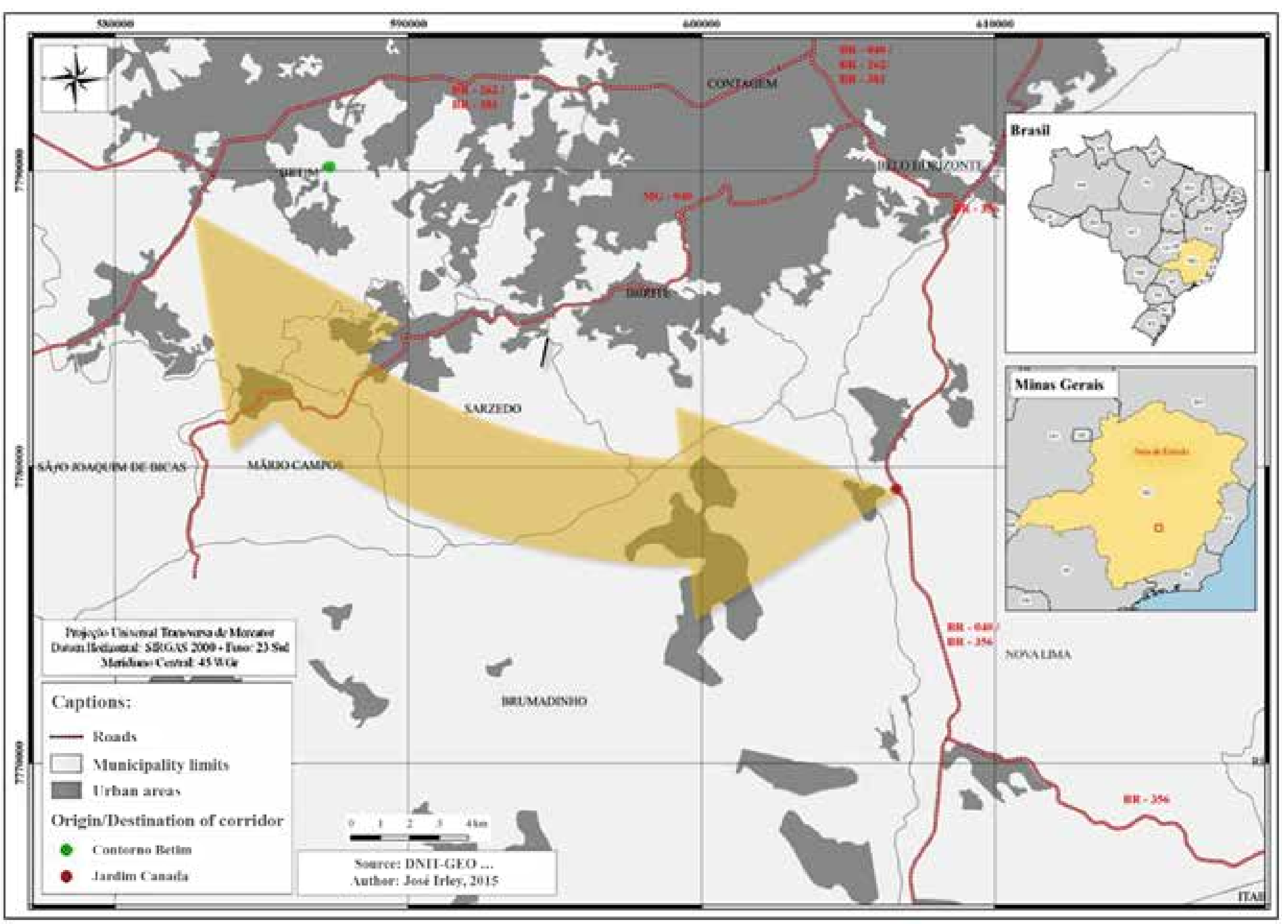
RMBH is composed of thirty-four municipalities. It is an area of high traffic flow density due to its high transportation demands to meet the needs of commerce, industry, mineral prospection activities and services.

Important federal highways such as BR-040, BR-262, BR-381 and BR-356, on which small, medium and large sized vehicles circulate, intercept it. Seeking to mitigate traffic congestion and security problems related to excessive amounts of vehicles which necessarily intersect these urban areas, a ring road was proposed in order to provide an alternative beyond the RMBH. According to DNIT (BRAZIL, 2012), the South Ring Road is part of a highway interchange project including the North Ring Road (the Krupp-Ravenna intersection, 67 km long) and the East Ring Road (Olhos D'agua-Sabará, 22 km long). The region elected for the southern section of the ring road has high population density, industrial activities, vulnerable areas and environmental conservation areas. According to the public notice and terms of reference, DNIT elected the location points in Contorno de Betim and Jardim Canadá in the municipal of Nova Lima, to be the origin and destination of the South Ring Road. Figure 1 illustrates the proposal, linking the traffic flows of BR-040 and BR-381, and their respective exits to Rio de Janeiro and São Paulo.

4. METHODOLOGY

In order to develop this study, data collection and the construction of the database, both tabular and geospatial, were necessary. In regards to technical documentation, the following was used to guide the corridor modeling: "Terms of reference for the study of the delineation and development of the engineering executive project for the southbound highway of the metropolitan region of Belo Horizonte BR-040/MG" (BRAZIL, 2012). This document is identified as Annex I – Basic model for service contracting according to subparagraph (I), paragraph 2, Art. 7, of law No. 8,666 of 21/6/93, under process number 50600.032686/2011-78 (BRAZIL, 2012).

Figure1:
location of the study area



These terms serve to guide the determination of variables found in the text itself, as well as indicate additional manuals and technical documents for consultation, such as the Service Instructions (SI) and Basic Scopes (BS), while also having been used as guidelines for the geographic modeling of this paper.

The geographic bases (Chart 1) of this study were acquired through telephone contacts and personal visits. To facilitate organization, the data were separated into subsets, as described in the terms of reference of the South Ring of RMBH, stating that the delineation should simultaneously consider "the environmental, cultural, social, community, geographical, financial and engineering issues involved in the study of the project" (BRAZIL, 2012). The architecture of the model followed the guidelines of Nóbrega (2014).

4.1 TREATMENT AND PROCESSING OF DATA

One essential procedure that preceded the processing of spatial data was the standardization of the system of coordinates, considering that the simple and correct use of map projection can prevent inconsistencies in the measurements of a linear engineering project. In this study, all the data were redesigned for the Sirgas 2000 Geodetic System with UTM-23S projection.

Subsequently, due to the need for the use of data in matrix format for the multicriteria analysis utilized in the model, the original data in vector and tabular format (Chart 1) were converted to matrix format. The transformation of vector data (discrete) into matrix data (continuous) makes it possible to produce algebra maps. Figure 2 illustrates an example of data transformation from vector to matrix format and their integration with other matrix data for elaborating the accumulated cost surface through algebra maps.

4.2 MULTICRITERIA ANALYSIS, COST SURFACES AND FEASIBILITY CORRIDORS

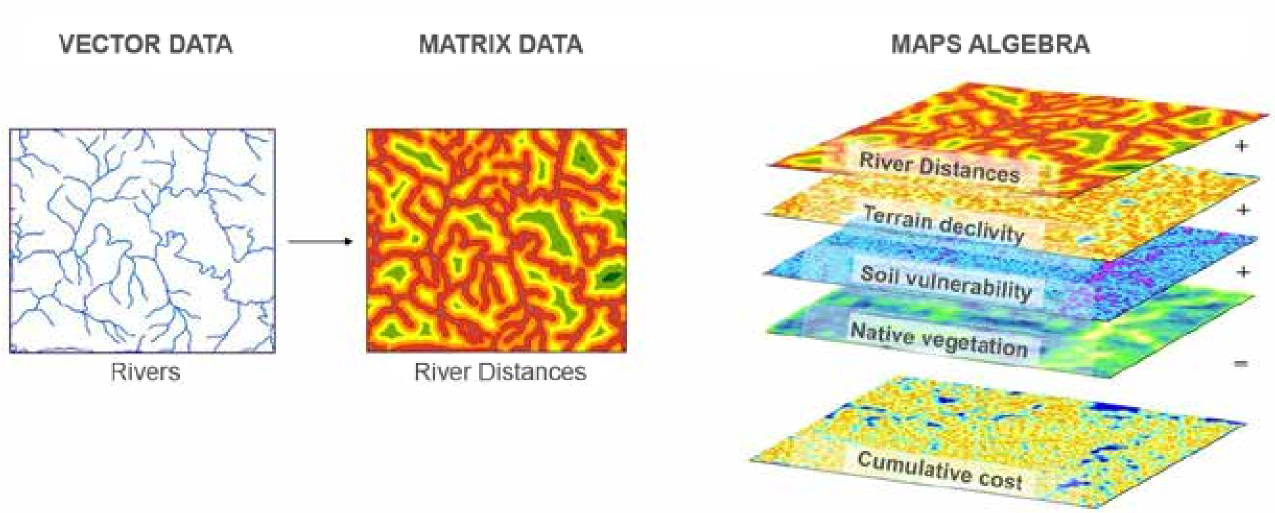
This step consisted of the application of the AHP technique to standardize variables and construction of the accumulated cost surface. This implementation occurs at three levels: intravariables, intervariables and intergroups, the latter being responsible for the integration of the final cost surface. The crux of this process consists in assigning importance ratings to variables of the model that require multidisciplinary knowledge.

At the intravariable level, each incoming data was analyzed before it could be converted into information plans for the model. The technical documentation of the project was consulted to see how each variable

Chart 1:
Database organization

Data	Scale	Source	Date	Type	Subset
Urbanized areas	1:50000	ZEE-MG (2009)	2009	Vector	Socioeconomic
Population	1:500000	IBGE (2010)	2010	Chart	
Rural settlements	1:10000	INCRA (2015)	2015	Vector	
Archaeological heritage – Distance	1:50000	IPHAN (2015)	2015	Chart	
1. Historical, artistic and cultural heritage – Distance	1:50000	Prefectures (2015)	2015	Chart	
Highways – Density	1:10000	DNIT – GEO/Vectorization	2015	Vector	Marketing and logistic support
Urban streets – Density	1:50000	Open Street Map	2015	Vector	
Gas networks – Distance	1:10000	GASMIG	2015	Vector	
Transmission lines – Distance	1:10000	CEMIG	2015	Vector	
Mineral resources	1:1000000	Geodiversity – CPRM	2010	Vector	
Mineral interest	1:1000000	DNPM - SIGMINE	2015	Vector	
VRemaining vegetation	1:150000	Landsat 8 - NDVI	2015	Raster	Biophysical
Springs - distance from water springs	1:1000000	IGAM	2014	Vector	
Hydrography - density and distance of hydrography	1:1000000	IGAM	2014	Vector	
DTM - Digital Terrain Model (Slope)	1:10000	IGTEC	2009	Raster	
Vulnerability to erosion	1:1500000	ZEE-MG	2009	Vector	
Risk of erosion - phyllite, karst and mass movement	1:1000000	Geodiversity - CPRM	2010	Vector	
Reflecting pool	1:1000000	Vectorization	2015	Vector	
Conservation unit – integral protection	1:50000	ZEE-MG	2009	Vector	Environmental restrictions
Conservation unit – Sustainable use	1:50000	ZEE-MG	2009	Vector	
Caves – Distance	1:50000	SECAV	2015	Vector	

Figure 2:
Illustration of the treatment and processing of the data model



could be utilized and to ascertain the level of importance of each class present in the data. For instance, the Euclidean distances of the watercourses in Figure 2 can be seen, while the vector data shows only the presence or absence of a river. The matrix data reveals how far away it is. These distances have been categorized and their importance weighed according to criteria, which indirectly reflect on the possible presence of riparian forest, soft and collapsible soils or in the high costs of crossing. The conversion of vector-matrix data and the use of the AHP technique for each variable were conducted, as shown in Figure 3 (above), thus creating information plans that were integrated by group for the development of the second level of multicriteria analysis, as proposed by Nóbrega (2013).

For the intervariable level, information plans were organized into four groups: environmental restrictions, biophysical, marketing, and logistical and socioeconomic support. Weighting among the different information plans per group resulted from consultations with specialists. Paired comparison analysis was adopted to prevent inconsistencies in the results, as described in Sadasivuni et al. (2009). As a result, cumulative cost surfaces were generated that correspond to the maps in matrix format where each cell is represented by the value calculated from its respective cumulative effort (or implementation cost) of the variables that participated in the composition of each group. Figure 3 (Center) illustrates this process for the variables of a biophysical group. The process was reproduced for the other groups, resulting in four areas of cumulative effort, which served as input for the third level of the AHP process – intergroups.

Figure 3 (below) illustrates the integration of the groups in four different value settings, obtained in turn through distinct perspectives that sought to focus on the feasibility of the corridors in the preservation of self--interests. Each perspective adopted was intentionally focused on defending environmental concerns, reducing costs of engineering, meeting market/logistic demands, or on minimizing negative socioeconomic impacts. As a result, four distinct scenarios were produced, each conservative in their interests, in order for the alternative transport corridors to then be computed.

Once the integrated cost surfaces for each scenario were computed, they were used as the basis for computationally simulating the anticipated effort for connecting the points of origin and destination, the beginning and ending points of the project, located on BR-040 and BR-381, respectively. This calculation is done in two stages, in which the costs of removal of the two extreme points are initially computed (effort vs. distance), to then integrate the two resulting maps on a surface to reveal the corridor of least effort, and consequently of greatest feasibility according to the perspective of the adopted scenario (Figure 4).

5. RESULTS

The methodological development, had the objective of generating transport corridors, the results of

Figure 3:
Intravariable, intervariable and intergroup decision rules used in the model

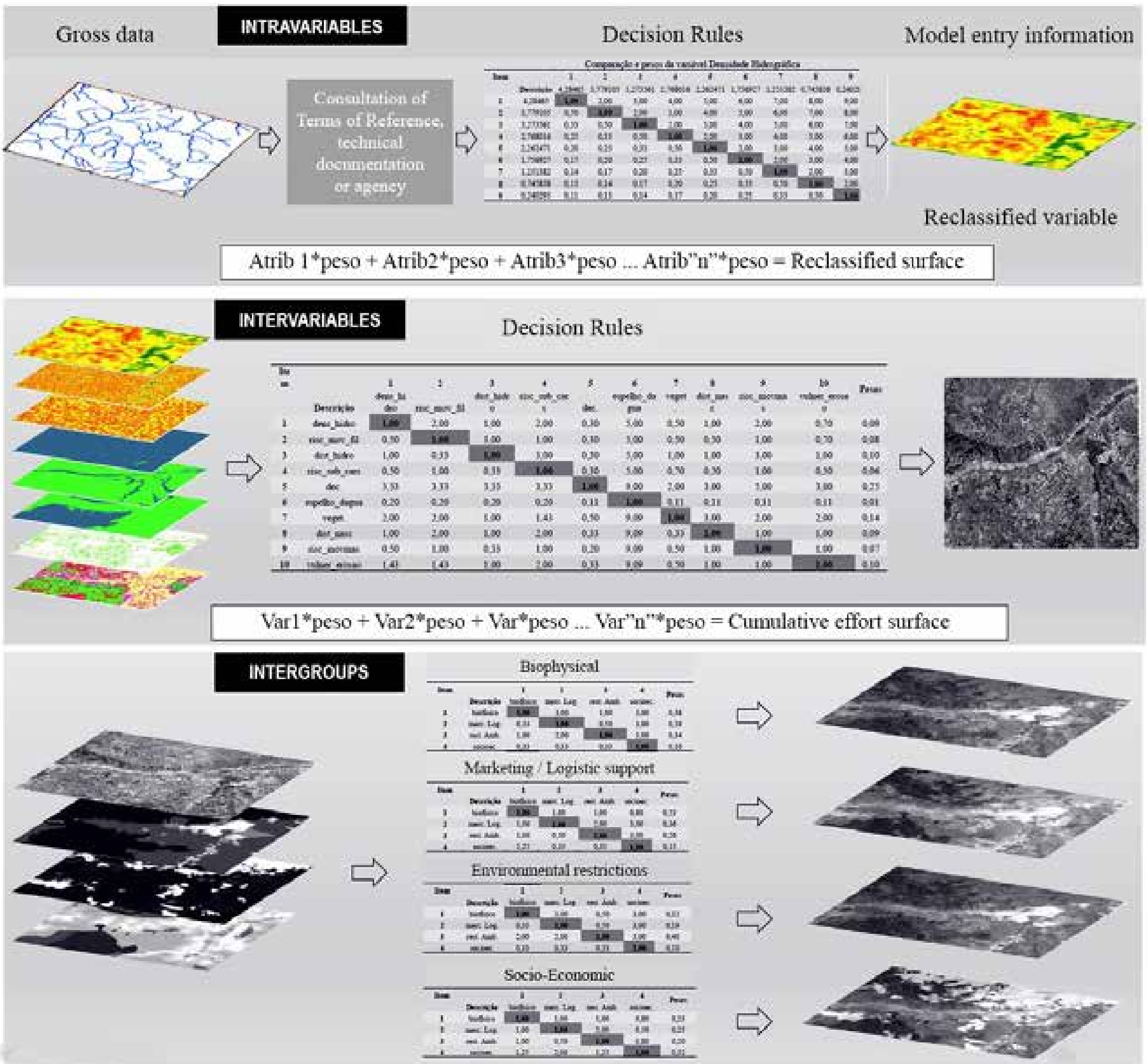
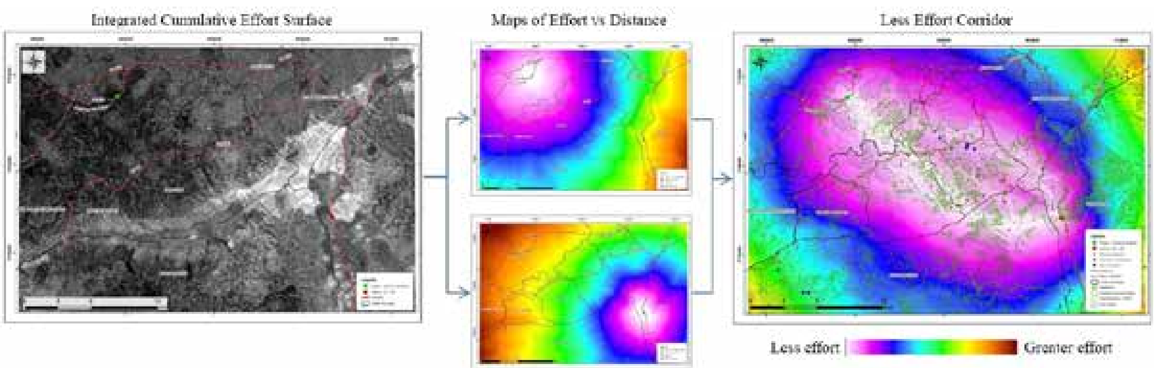


Figure 4:
Illustration of the calculation process of a feasibility corridor



which are presented in Figure 5. As such, four scenarios were produced: biophysical, socioeconomic, environmental restrictions and marketing and logistical support. These scenarios maintained the origin and destination in the terms of reference.

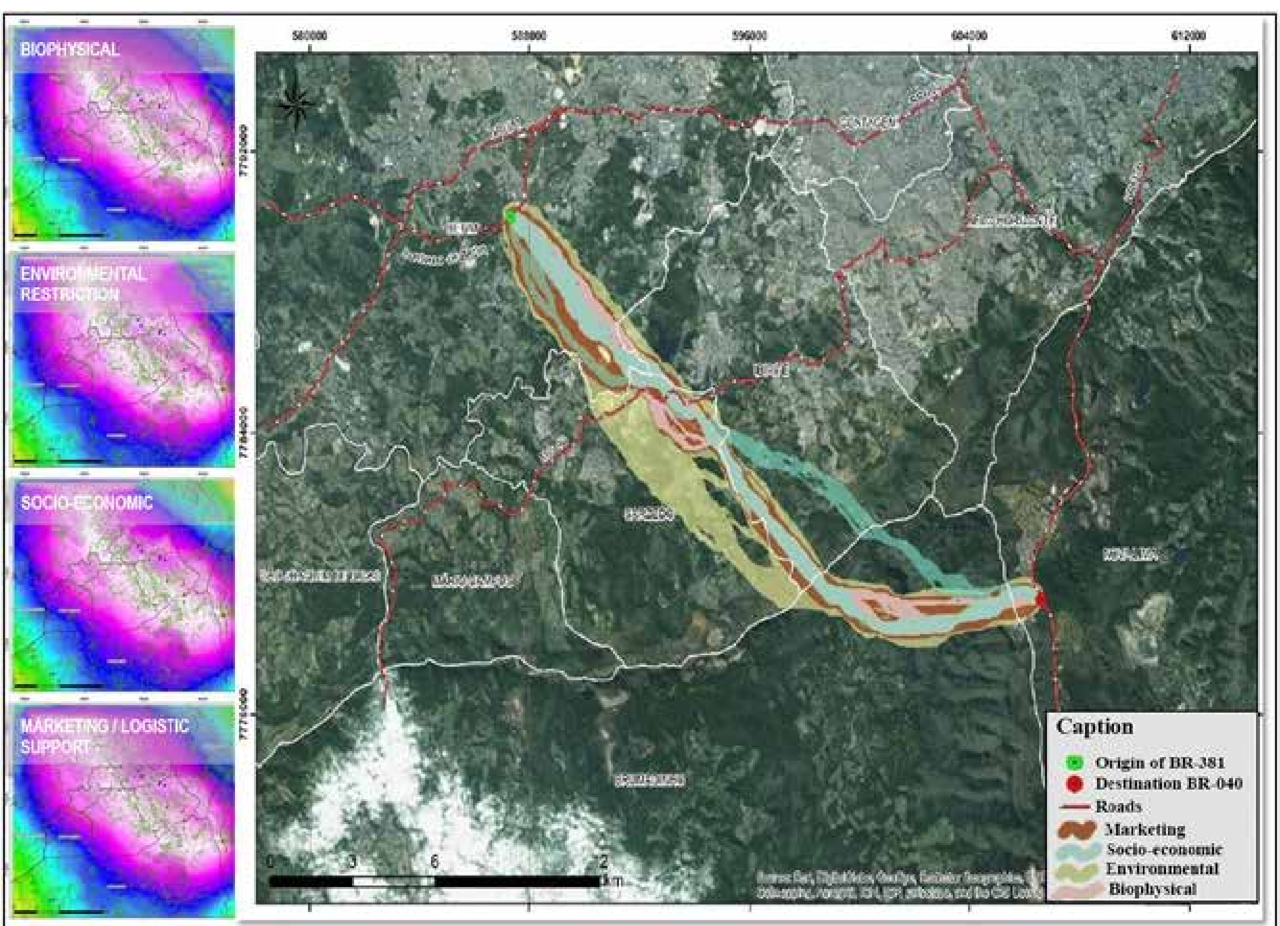
With the design of the transport corridors, it was possible to calculate comparative metrics, such as the full extension of the project and their intersections, with other databases in order to quantify values, assess impacts and compare alternatives. To demonstrate this sensitivity analysis, four variables were chosen which are generally prevalent in transport corridors: slope, urban area, conservation areas and vegetated area. However, the methodology can also be applied to quantify the number of residences to be affected and rivers to be transposed or even to monetize the impact of every alternative corridor, depending on the availability of data present in the study area.

With regard to the extension of the alternatives, the environmental scenario produced a corridor of 24.8 km, the biophysical of 25 km, marketing with 25.2 km and the socioeconomic scenario produced two alternatives of 25.2 km and 23.7 km long, respectively.

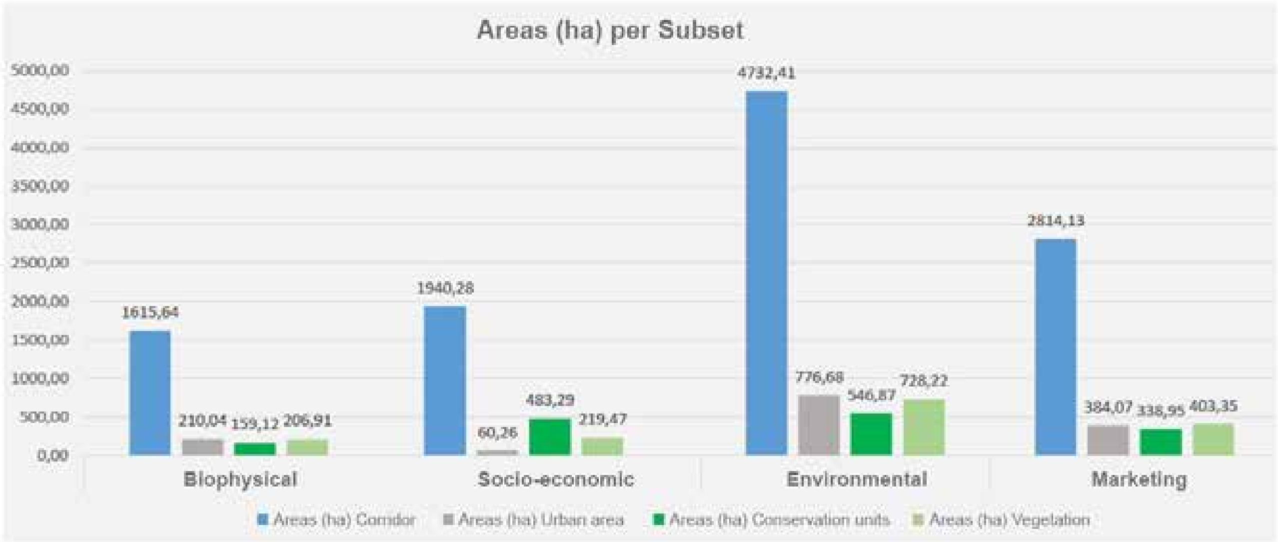
While results from the terrain slope, analysis showed that, inevitably, the delineation of the corridors runs through areas of high declivity, due to the geomorphological nature of the region. However, the model considered the high level of effort to transpose these areas and the construction of the corridors avoided areas with sharp rises in the terrain. A summary of the average slope per corridor of the four evaluated scenarios showed that the biophysical setting scored the lowest average (13.7%), followed by the marketing/logistics scenario (13.9%) and lastly environmental restrictions (14.1%). The socioeconomic scenario presented the highest average (14.6%).

For the variables of urban area, conservation areas and vegetation, the affected areas can be seen in Graph 1. In regards to the biophysical setting, for which weighting of the variables of vegetation and conservation units was

Figure 5: Ttransport corridors computed for each scenario



Graph 1:
Impact metrics for urban areas, vegetated areas and those pertaining to conservation units intercepted by the transport corridors of the analyzed scenarios.



greater, it was observed that when the model was free to construct the corridor, the results showed improvement, corresponding to less impacted areas. In the socioeconomic subset, whose preference for distance from urban areas is evidenced, the results achieved the lowest impact among all the scenarios evaluated.

However, the analyses show the existence of various possibilities for its use once we identify what will undergo intervention and when. The model enables perfected risk analysis and optimized filling out of the environmental impact matrix used to evaluate project alternatives.

Two other proposals were developed taking into account the biophysical and socio-economic scenarios, designating the point of origin as established by DNIT on BR-381 and the destination on BR-040 without defining a specific location (Figure 7). The idea was to verify whether the location on BR-040 published in the public notice corresponds to the location of greatest feasibility according to the criteria adopted in this investigative research. Although not quantified, the preliminary analyses indicate that the point of origin published in the public notice of the project is justified when considered the need for greater distance of the ring road from existing urban areas. Notwithstanding, the model indicated alternative connections between the Ring Road and BR-040 which would cause lesser environmental impacts and possibly lower engineering costs in virtue of running through flatter areas.

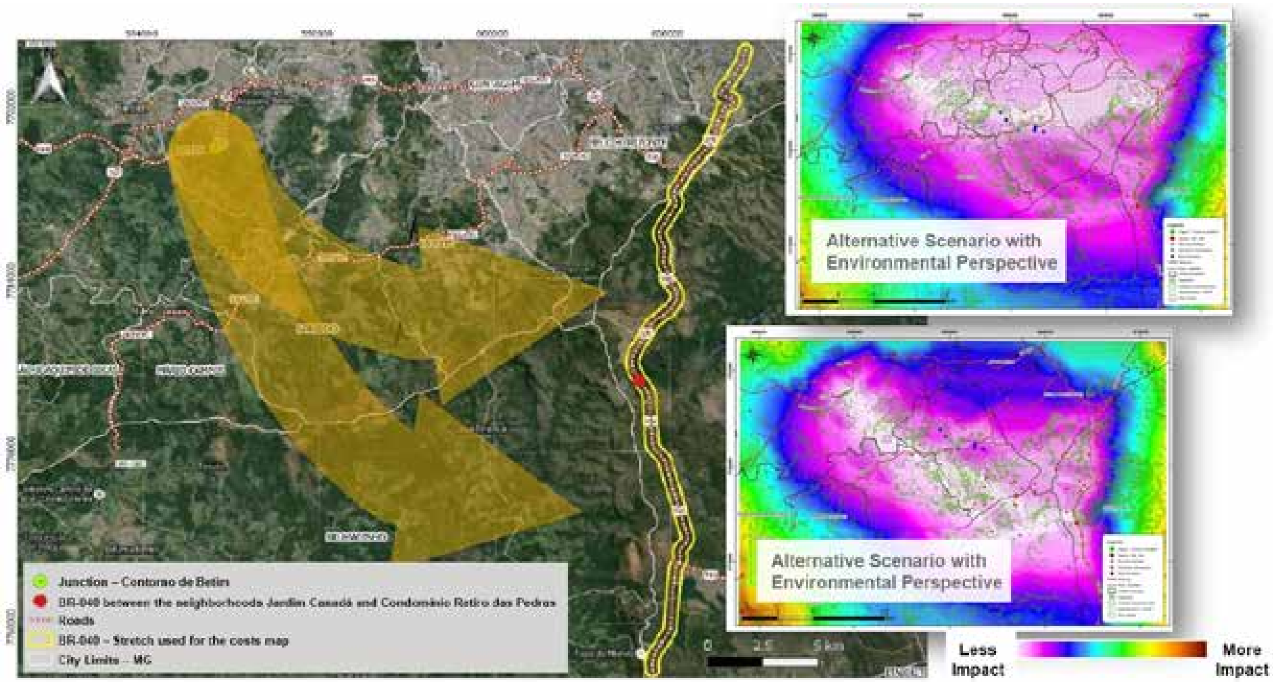
6. CONCLUSION

We faced various challenges throughout this research project regarding interpretation of the terms of reference and the technical documentation as well as data processing. Nevertheless, the central objective of obtaining alternative delineations for the South Ring Road of the metropolitan region of Belo Horizonte by way of distinct, realistic and confrontational perspectives was achieved. Transport corridors were generated considering different variables, supported by the use of geotechnology and multicriteria analysis. The results made possible a harmonic interaction between the application of this technique and the modeling of geographic data. The operational capacity of the model for processing large areas with extensive contextual details of the analyses, as well as time optimization and the analytical capacity of the agents involved in the model, all contribute positively to the modernization of the transportation planning process.

The spatial multi-criteria analysis pilot work showed considerable applicability potential for external control. We believe that, with this model and its operational knowledge, audit activities and external control may be carried out with greater speed and accuracy.

The transport corridors resulting from this study still cannot be compared to the official delineation of the RMBH Ring Road, considering that the latter has not conducted a feasibility study. We expect that the comparative

Figure 7:
Alternative processing to verify adherence of the points of origin and destination as published in the public notice of the project.



metrics can be quantified and analyzed after the project is completed by DNIT or it is presented to the community.

7. ACKNOWLEDGMENTS

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