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Guidelines to devise a multimodal freight transportation network in developing regions under economic growth approach

Cristiano Farias Almeida[a]*, Juliana Gomes Gularte[b], Yaeko Yamashita[c]

[a]*Federal University of Goias, Praça Universitária, Goiânia, Brazil*
[b]*Federal University of Goias, Praça Universitária, Goiânia, Brazil*
[c]*Brasilia University, Campus Universitário Darcy Ribeiro, Brasilia, Brazil*

Abstract

In Brazil, especially at the Amazon Region, the relationship between transport and economic development has been studied since 70s with elaboration of several plans. However, due to many factors, such as the incompatibility between the proposed models of transport planning and territorial planning, the expected results were not reached. Under these aspects, the goal of this paper is to define guidelines in order to devise a multimodal freight transportation network that allows efficient transport of products in a developing region. This network was developed using natural resources and it stimulates the economic growth and development based on the Growth and Development Poles Theory and Graphs Theory. As result three networks related to three different scenarios – *status quo*, investment in transport infrastructure by the governmental programs, and the strategy scenario – have been elaborated and analyzed considering the operational transport costs and their spatial configuration.

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Keywords: Growth and Development Poles Theory; Grahp Theory; Transportation Network.

1. Introduction

Large countries as Brazil comprise developing regions with great amounts of natural resources available such as the Amazon. Because the planning process does not account for all regions equally, these countries cannot achieve desirable levels of growth and development. In this case, the planning approach adopted is mirrors inefficiency in regional planning, mainly in its two principal branches: transportation and territorial planning.

* Corresponding author. Tel.: +55-62-8225-6262; fax: +55-62-3521-1867.
E-mail address: cristianofarias@ufg.br

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Due to the lack of a territorial planning model that accounts for identifying poles where economic activities take place, much inefficiency occurs in the regional planning process (Griffith, 2007). In turn, inefficient planning may be responsible for scattering economic activities geographically causing improper land use (Rodrigue et. al., 2006).

Dispersions, in this case, are mainly caused by incompatibilities between land use and transportation infrastructure available, which results in inefficient processes of regional economic development (Kraft et. al., 1971; Banister & Berechman, 2001). This situation could be solved by means of identifying important economic activities in the region so as to spot Poles of Economic Growth (Andrade, 1987). Such poles would ignite economic growth aided by transportation infrastructure (Perroux, 1964). The combination of these elements (i.e., Poles of Economic Growth and transport infrastructure) would compose a complex transport network, which would contribute to accelerating regional economic growth.

Defining guidelines to devise a multimodal freight transportation network that enables goods to be conveyed efficiently and accelerates economic growth in regions such as the Amazon is supported by two theoretical assumptions: Perroux's Growth Pole and Development Pole Theory; and Graph Theory, which is widely used in network creation techniques.

This paper sets out to define guidelines to devise a multimodal freight transport network that allows goods to be transported, making use of natural resources (e.g., rivers and local production) and infrastructure (e.g., ports, roads, railways). The network presented in this paper was developed for Amazon Region, where the main centers of economic growth were identified.

2. Perroux and the economic regions

From the economic point of view, François Perroux (1964) states that space can be understood from three basic perspectives: (i) economic space as the content of a plan; (ii) economic space as a force field, and (iii) economic space as a homogeneous set of elements. Consequently, there are three types of economic regions: planned, polarized and homogeneous (Clemente & Higachi, 2000).

The concept of space as the content of a plan creates the planning regions. In this context, firms, public entities or any given economic agent, have their own planning region, which both influences and is influenced by their decisions. Regional development plans derive from planning regions framed by the public sector (Clemente & Higachi, 2000). Polarized regions result from the interdependence between several areas, which sometimes belong to different homogeneous regions due to the commercial influence of urban agglomerations (Combes et. al., 2005). The homogeneous aggregate, which is well known to geo-economists, corresponds to the space continuum where each part has features that bring all parts closer together (Boudeville, 1961; Clemente & Higachi, 2000).

A city's power of attraction on the area that surrounds it, which results from its relationships with other areas or cities, causes areas of influence, and, consequently, polarized regions. The economy, by means of processes of trade, is, in essence, an activity that leads to regionalization and determines the radius of a city's area of influence. Thus, highways expand around it, which increases the city's power of attraction (Santos, 1953).

2.1. Growth pole and development pole theory

Perroux developed the Growth Poles and Development Poles Theory based on observation. He noticed that economic growth does not spread consistently throughout the whole area of a country. Instead, it occurs in different intensities at certain points, which are called "growth poles", and then spreads out through several channels, thus, causing different effects on the economy (Andrade, 1987). A growth pole results from a propulsive industry. That industry separates the production factors concentrates capital under the same power and breaks down tasks. Propulsive industries experience higher growth levels in their product than the average growth of the Gross National Product (GNP). Although it is not permanent growth, it can be felt over a period of time (Perroux, 1964).

Propulsive industries makes regional life dynamic as they attract workforce and other industries, thus creating population agglomerations that support the development of agricultural activities in areas that supply food and raw materials, besides encouraging tertiary activities to be carried out. Then, industrial complexes are born; they are characterized by presence of a key industry. Among the companies of an industrial complex, key industries are those, which promote higher growth in sales of other products in contrast with their own sales. Key industries usually deal with raw materials, energy and transportation (Andrade, 1987). In short, Perroux conceives poles as the dynamic economic center of a region, country or continent. Growth stemming from poles is felt throughout their surroundings, as they create flows from the surrounding regions toward the center as well as the other way around.

3. Graphs theory in transportation network study

Graph theory used in the field of transportation are linked to real geographic objects, in which nodes and arcs may represent features of such objects (Castells, 2004). Graph theory stands out as a support tool for solving problems found in the field of transport such as shortest path route (Almeida & Yamashita, 2012). The representation of a transport system in graph theory perspective is associated with the concept of a transport network.

Most analyses in the field of transportation concern the generalized cost of travel, which is the cost of a trip as perceived by the users of a given network. Generalized cost is a measure that encompasses all factors relevant to the decision making process. The most significant components are the direct costs, such as fees and fuel (Bell & Iida, 1997), and expenses that are a function of service quality (indirect cost). This paper does not deal with indirect costs in order to simplify the analysis process. In a representation of a transport network, costs can be assigned to the arcs in terms of movement or restrictions of capacity or operation, especially regarding the limitations associated to the currently available techniques and physical conditions of the road system. The cost notation of each arc is usually a function of the arc's flow (Potts & Oliver, 1972). The arc's flow acknowledged in this study refers to the conveyance of goods. In addition, the operating cost of freight transporting must be analyzed by means of studying the movement of vehicles along the network's arcs. Thus, the cost of transportation in an arc is defined by equation (1).

$$ca_i = cfa_i + cva_i \tag{1}$$

Where: ca_i - cost of transport in arc a_i; cfa_i - fixed cost in arc a_i per day; cva_i - variable cost per kilometer in a_i.

As seen in equation (1), the usual separation scheme between variable and fixed costs was adopted, given that model is popular among most carriers in Brazil. In this case, the equation developed by Almeida & Yamashita (2012) was adopted to calculate the cost of transportation in an arc a_i. Thus, there is equation (2), which is expressed in terms of total operating cost per ton carried through the network's arcs.

$$ca_i = \frac{\left(\dfrac{cfv}{Vm \cdot htd} + cvv\right)}{P} \cdot D_i \tag{2}$$

Where: cfv – fixed cost of the vehicle per day (in Brazilian R$); D_i – length of arc a_i (km); Vm – average vehicle speed in arc a_i (km/h); htd – hours worked per day (h); cvv – fixed cost of the vehicle (in Brazilian R$).

4. Guidelines to devise a multimodal freight transportation network

The guidelines é constituted for eight (8) stages: stage 1 – framing the study area; stage 2 – diagnosis of the regional economy; stage 3 – building a geographic database; stage 4 – identifying growth poles; stage 5 – analyzing the transportation infrastructure; stage 6 – creating a basic transportation network; stage 7 – devising the multimodal freight transportation network; stage 8 – assessing the multimodal freight transportation networks.

5. Devising a Multimodal Freight Transportation Network for Brazilian Amazon Region: the Case Study

This section presents the stages taken in the process of devising a multimodal freight transportation network for Brazilian Amazon Region.

Stage 1: Framing the study area

This paper sets out to study the Brazilian Amazon Region, which covers an area of 5,217,423 km^2. The region encompasses the entire Northern region, a great deal of the Midwestern region and some of the Northeast (ADA, 2007). Figure 1 shows the Amazon Region being considered in this study, which comprises nine states (792 towns).

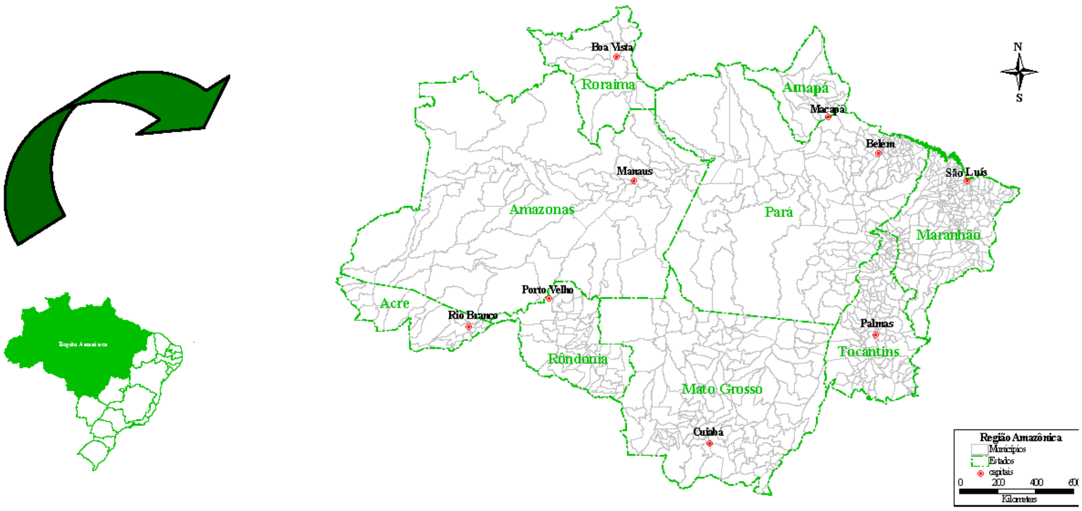


Fig. 1. Geographic boundaries of the Brazilian Amazon Region.

Stage 2: Diagnosis of the regional economy

In order to develop a multimodal freight transportation network, a diagnosis needs to be conducted regarding the regional economy. In that context, it is possible to identify that Amazon Region's economy is supported by mining, forestry and farming (agriculture). These activities are carried out by means of making use of a few unique local products. There are twenty goods supporting the economy, which can be classified in following groups of activities:

- Mining: these activities are characterized by the extraction of various minerals, such as: iron ore, oil, aluminum ore, kaolinite, natural gas and tin. However, iron ore is one of the most important products of the region;
- Forestry: these activities are characterized by the extraction and/or processing timber and latex, mainly;
- Farming (agriculture): a few crops are grown in the Amazon Region, such as: soybean, rice, cassava, cotton, corn and coffee. Among these, more emphasis is given to soybean, rice and cassava.

Stage 3: Building a geographic database (GDB)

A GIS-based database was built with data gathered during the diagnosis. Three types of layers were manipulated:

- A Dot Layer, representing the port subsystem, which encompasses seaports and waterway terminals, as well as their major physical features, such as docks, piers and mooring docks; office buildings and warehouse capacity; width and depth of docks, evolution basins; as well as the access canal;
- A Line Layer, representing rivers as well as their main features, such as name, periods of high and low waters, length, width and depth. Other line layer referring to highways and railways are also created;
- An Area Layer, representing 792 towns of the Amazon was created. A layer is created for each product identified in the diagnosis stage; in total, twenty layers were created. Information was attached to each layer regarding the production value and the amount produced in each town where such economic activities are undertaken.

Stage 4: Identifying growth poles (GP)

In order to identify Growth Poles in the Amazon Region, three main steps were conducted: applying the Perroux’s theory to identify propulsive industries, identifying potential growth pole areas; and, finally, applying the spatial statistics tools to identify the Growth Poles. These steps were devised by combining the theoretical grounds established by Perroux’s Theory with the statistical tools of Spatial Analysis.

Step 4.1: Applying the Perroux's theory to identify propulsive industries

According to Perroux's theory, the starting point is defining the main products produced in the Amazon Region so as to spot the existing economic activities and determine the propulsive industries, which are the key to identifying the growth poles. To identify the products and economic activities, the production values of all twenty products needed to be known and analyzed. The ABC Analysis made it possible to find the most economically important products. The ABC Analysis served to identify the most important products in the Amazon Region, which are the following: soy, iron, rice, oil, cassava, and timber. Extraction and production activities of these products were used to determine the propulsive industries that guided the identification of growth poles in the Amazon Region.

Step 4.2: Identifying potential growth pole areas

At this stage, potential growth pole areas for six products were identified. However, in this paper, the growth pole areas for timber are presented. Here, potential areas are portions of space within the Amazon Region, represented by the towns, which have the highest production values regarding the products that are produced by the propulsive industries identified in the previous stage. In order to identify the potential areas, two activities were conducted: thematic maps of the distribution of the chosen variable were created; and the variable's spatial distribution was analyzed so as to identify potential growth pole areas. Thus, a spatial distribution map of timber's production value (figure 2) was created. Analyses of spatial distribution were conducted on that map to identify geographic areas encompassing sets of towns that have the highest production values.

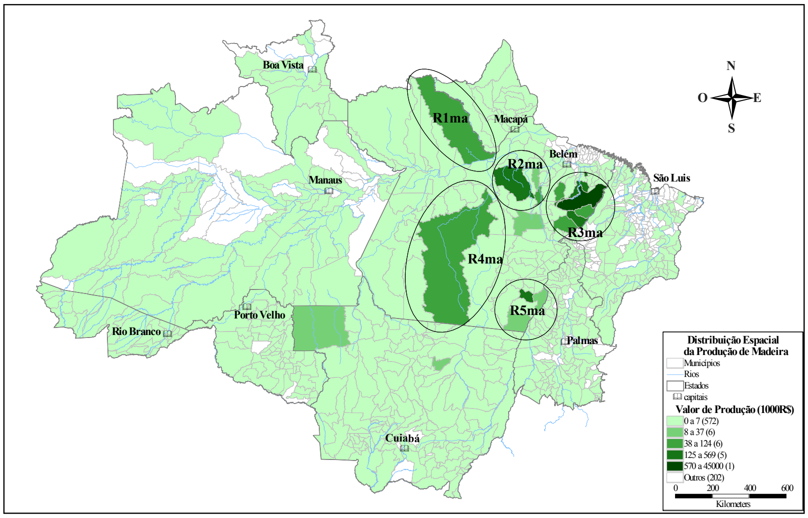


Fig. 2. Spatial distribution of the production value of timber in Amazon Region.

In figure 2, there are five bounded regions (R1ma, R2ma, R3ma, R4ma, R5ma), which had the highest production values. Note that even though the production of timber is spread throughout most of the Amazon Region, the highest production values are found in the state of Pará State (South, Southeast, extreme North and Midwest). In a first analysis, these regions can be considered potential poles. However, spatial analysis techniques can confirm and spatial statistics can validate whether these areas are actual growth poles.

Step 4.3: Applying spatial statistics tools to identify growth poles

This step resorts to spatial statistics indices and maps, which provide a basis for decision-making. The first index we calculated was the Global Moran Index, which expresses the degree of homogeneity or heterogeneity of the area under study. This value was determined with a free software that provides spatial statistics tools. The calculated index was 33%, which indicates that the region under study has spatial dependence, but a low degree of homogeneity, which means that there are few areas showing the same aggregation pattern. Next, a Box Map was created so as to determine the way in which the areas under study relate to each other, as shown in figure 4 (a). The Box Map shows that is a well-defined cluster of areas with the same aggregation patterns. Aggregate areas shown in a red color, which are most strongly related (high-high) due to the attributes' values, overlap the areas previously identified as potential growth poles.

Moran Map (figure 3 [b]) shows significant areas at 95% certainty. The red areas in the Moran Map are strongly related and are significant, while the other areas do not have the same pattern because they are located in an unstable region. Note that some of the significant areas shown in figure 3 (b) overlap the areas initially identified as possible growth poles in figure 2. It's concluded that simply visualizing the spatial distribution of the variable is not enough to identify the growth pole areas, that is, we must make use of spatial statistics.

The town of Aripuanã is identified in figure 3 (b) as significant. This is example is worth mentioning because at first it was not identified as a potential area. However, the Box Map indicated that this town has a high positive autocorrelation pattern (High-High). The Moran Map in figure 3 (b) statistically confirmed that the town of Aripuanã is a growth pole. In addition, figure 3 (b) presents some clusters composed of towns that are significant in the production of timber. These clusters are growth poles in Amazon Region in the perspective of timber producers, which are represented by the following towns: Paragominas; Redenção; Portel; Almeirim; Altamira; and Aripuanã. Then, growth poles for all six products (propulsive industries) were determined according to the following criteria:

- Moran Maps were created for the selected products, as these maps show the statistically significant groups of towns. Groups of towns (clusters) that constituted the growth pole were identified on each product's map;
- A town was chosen to represent the growth pole in each cluster;

Towns representing each growth pole were chosen regarding their production value and transport infrastructure.

a b

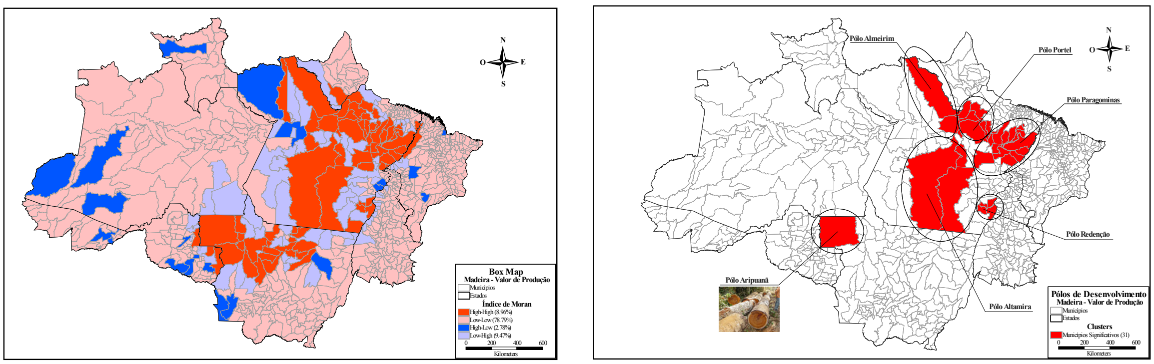


Fig. 3. (a) Box Map of the production value of timber in Amazon Region; (b) Moran Map of the production value of timber in Amazon Region.

Stage 5: Analyzing the transportation infrastructure

Even though projects are still under development, transportation facilities in the Amazon Region are gradually being consolidated. However, expanding the existing infrastructure will depend on the strength of regional economy. First, the current situation of transportation infrastructure needs to be acknowledged so that, later, an analysis can be conducted regarding its maintenance condition and need for expansion. According to the Theory of Growth and Development Poles, transportation infrastructure can be understood as physical means through which growth and/or development coming from the poles spread out; they're known as development corridors. In the perspective of Graph Theory, the development corridors are constituted by transportation infrastructure.

Analyses regarding Amazon Region's transportation infrastructure were needed to identify the desired lines for defining the arcs of the basic transportation network. Such analyses enabled us to identify the main bottlenecks that could affect vehicle flow and the conveyance of cargo. Since each transport mode has its own features, separate analyses were performed for each transportation subsystem. The following tests were considered: the rivers' navigability, the use of highways for conveying cargo and the cargo handling intensity in ports and railways.

Stage 6: Creating a basic transportation network

This stage encompassed three activities: defining the nodes, defining the arcs; and overlapping thematic maps to generate the basic transportation network.

Step 6.1: Defining the nodes

First, two sets of nodes were defined: centroid nodes and connection nodes.

- Centroid Nodes: for each cluster, which is a growth pole, the town with the highest production value is defined as the vertex of its cluster. Vertexes were determined for all the growth poles, totaling twenty-six nodes.
- Connection Nodes: intersection points between two different arcs of the same transportation subsystem, or intersections between different transportation subsystems, which serve as intermodal terminals were defined as connection nodes along with the arcs.

Step 6.2: Defining the arcs

Arcs comprised by the basic transportation network were defined using the transport routes identified previously (i.e., analysis of the transportation infrastructure). To analyze the existing transportation infrastructure, each subsystem was analyzed in a separate thematic map. After that, the thematic maps were exported to another GIS platform, where a new geographical structure was created. This platform consisted of arcs and connection nodes.

Step 6.3: Overlapping thematic maps to generate a basic transportation network

In this step a basic transportation network was generate. The output of this activity was a thematic map of arcs and nodes. The network was created by means of overlapping two thematic maps: one showing nodes and the other, arcs and edges.

Stage 7: Devising the multimodal freight transportation network

This stage is based on Graph Theory so as to design the transportation network. Some activities were conducted to devise three multimodal freight transportation networks: defining basic assumptions to devise the multimodal freight transportation network; calculating the costs of transportation; linking cost of transportation to the basic transportation network; creating scenarios, and graphically representing the transportation networks.

Step 7.1: Stating the assumptions for designing a multimodal freight transport network

The assumptions underlying the process of designing the network were as following:

- Each possible network is represented by a direct graph;
- Centroid nodes correspond to locations where trips are generated;
- A minimum cost route was set for each growth pole. All arcs in the basic transportation network were acknowledged in determining the shortest paths;

- For nodes representing poles of the cassava propulsive industry, state capitals were considered as destinations in the analysis of the transport cost. This was done because most of the cassava is consumed locally and because the population is concentrated in the capital, which could represent destinations of trips generated by those nodes;
- Because the seaports located in the area under study are gateways for exporting goods, they were considered as the destination nodes of trips generated by the centroid nodes representing growth poles;
- Three scenarios were created to represent different situations;
- Operating costs in the arcs and nodes were acknowledged so as to determine the shortest path routes;
- Vehicles were considered for calculating the operating cost. Along with such vehicles, some features were identified: fixed costs (*cfv*) and variable costs (*cvv*); load capacity (*P*); average speed (*Vm*); road's length (D_i);
- Vehicles used in the cost analysis and their features were defined in terms of the roads' physical characteristics.

Step 7.2: Calculating the costs of transportation

This step is central for analyzing minimum cost routes that allow for establishing the transport routes in Amazon. Two costs were considered: costs of transportation and transshipment costs. Both were calculated using equation (3).

$$C'_{rota} = \sum_{i=1}^{I} coa_i + \sum_{j=1}^{J} cn_j \tag{3}$$

Where: C'_{rota} - direct cost of transportation in a route, from an origin to a destination; ca_i - operating cost of transportation in arc a_i per ton (R$/ton); cn_j - operating cost of transportation in node n_j per ton (R$/ton).

Equation (2) was used for calculating the operating cost of transportation in the arcs. The basic network consists of arcs that represent roads, rivers and railways; a commercial vehicle was defined for each mode of transport.

In addition to the operating costs shown above, another cost was estimated to provide a basis for the minimum path analysis: the cost of transshipment. In this study, the cost of transshipment is the cost of transferring cargo between different modes of transport and it was calculated using equation (4). Even though there is a series of fees charged by ports, we chose to use two fees, regarding the use of waterway infrastructure (T_1) and the use of land infrastructure (T_2), because these fees were the only ones found in all ports considered in this analysis.

$$cn_j = T_{1j} + T_{2j} + Op_j \tag{4}$$

Where: cn_j – cost cost of transportation in node n_j; T_{ij} – port fees regarding the use of waterway infrastructure (R$/ton); T_{2j} – port fees regarding the use of land infrastructure (R$/ton); Op_j – cargo-handling services (R$/ton).

Step 7.3: Linking costs of transport to the basic transport network – feeding the database

Operating costs of transportation were calculated for the arcs and nodes. Operating costs in each arc (coa_i) was determined in terms of the road's length or the distance of the arc (Di). Thus, both expressions for specific transport modes and the values calculated for each port were used to feed the database, linking them through GIS-based tools. The expressions were linked to arcs representing paved and unpaved roads, navigable rivers and railways; and the estimated values, to the nodes representing ports or waterway terminals where there transshipment takes place.

Step 7.4: Creating scenarios

Three scenarios were created, and, consequently, three multimodal freight transportation networks were designed: one for each scenario. The aspect that differentiated three scenarios concerns changes in the transportation infrastructure in Amazon Region, which resulted in changes in spatial structure of the networks, namely:

- Scenario 1 - status quo: the current situation of the existing transportation infrastructure in the Amazon Region was acknowledged. Accordingly, this scenario enabled use to visualize the Amazon's actual situation regarding the conveyance of goods through the available infrastructure;

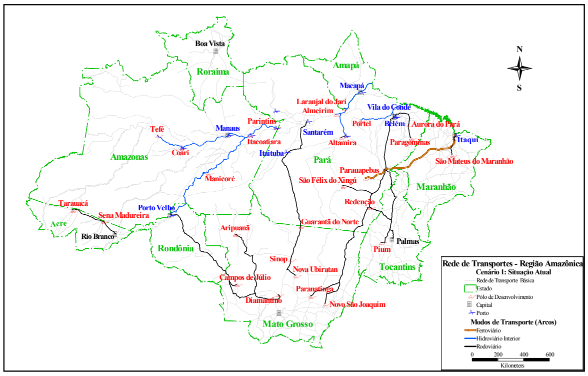
- Scenario 2 – investment in transport infrastructure through the Brazilian Growth Acceleration Plan (PAC): changes in the transport infrastructure of the Amazon Region represent this scenario. These changes were result of the PAC, a program devised by Brazilian government which allocated investments in transport infrastructure;
- Scenario 3 - strategic: this scenario acknowledges both PAC investments and an action strategy for the Amazon Region, which is an estimation of the total navigability of the Araguaia and Tocantins rivers. This would allow the whole Amazon Region to be connected, by waterways, to Brazil's central region.

Therefore, considering the basic network established in Stage 6, minimum operating transportation cost routes were set between the O/D pairs for the three scenarios described above. A set of routes was obtained, which established the final structures of the three networks. Routes were established using operating costs calculated in Step 7.2 and GIS software, which provides the Dijkstra algorithm (used to determine the shortest path routes).

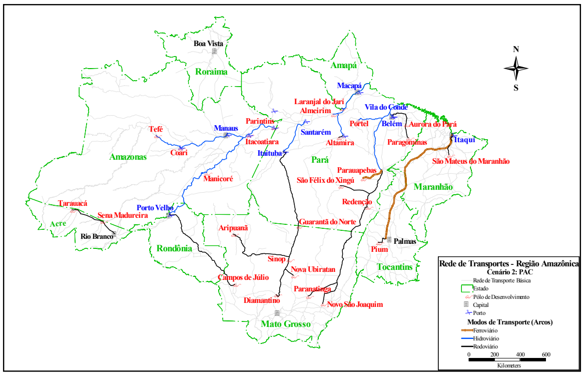
Step 7.5: Graphic representation of the multimodal freight transportation network

Three freight transportation networks were designed. Each network was composed of the minimum cost routes, which were identified for each growth pole (centroid node). Because more than one possible destination (port) was considered for each origin (i.e., growth pole), different routes and different operating costs for such routes were found. At last, the routes that make up each network were identified, which are those with the lowest operating costs of transportation. The networks established for each of the three scenarios are shown in figures 4 (a), (b) and (c).

(a)



(b)



(c)

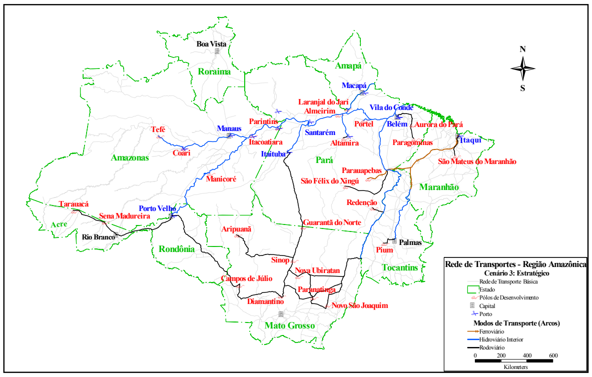


Fig. 4. Multimodal freight transportation network in Amazon Region: (a) scenario 1; (b) scenario 2; (c) scenario 3.

Stage 8: Assessing the multimodal freight transportation networks

The network assessment performed at this stage considers the total cost of each network, thus enabling the identification of the cheapest network in terms of total operating cost of transportation. Accordingly, a GIS software was used to calculate the total costs of each network, which were found to be the following:

- Scenario 1: the total cost of the multimodal cargo transportation network is was *Ctr* = 1,915.02 R$/ton;
- Scenario 2: the total cost of the multimodal cargo transportation network is *Ctr* = 1,548.38 R$/ton;
- Scenario 3: the total cost of the multimodal cargo transportation network is *Ctr* = 1,662.10 R$/ton.

Note that scenario 1 has the highest cost, followed by scenario 3, and, at last, scenario 2. These values indicate that investments in infrastructure reduce operating costs of cargo transportation. It is worth pointing out that the network designed for scenario 3 acknowledges the inland waterway subsystem as the most important transport mode in its structure. Even though the network in scenario 3 had the largest number of arcs representing rivers, its total cost is greater than the total cost of transportation in network 2. This occurred because the network of scenario 3 encompassed eleven routes in order to connect the sub networks that emerged, which caused the total cost of transportation in the network to change, going from 1,415.65 R$/ton to 1,662.10 R$/ton.

6. Conclusions

There are few studies in Brazil dealing with relationship between transportation and economic development, especially regarding the Amazon region, where most studies were conducted in the 70s. Note there is an increasing need for carrying out studies and alternative projects to provide better understanding of the role transportation plays in supporting regional economic growth and development. In this study, four factors were prioritized: transportation, economic development, spatial analysis and the area under study. These elements were incorporated in the proposed guidelines. Therefore, assessing how these elements were dealt with in the Amazon region is a form of assessing how significant this research is. Thus, this proposal is important because the guidelines are feasible.

Over the years, policymakers have made the mistake of disregarding the Amazon's economic potential and its vast natural resources as vital elements that should be acknowledged when designing a network. Most plans and economic projects aimed at Amazon overlook the relationship between transportation and development. The study of the relationship between transportation and development enabled us to design a transportation network for the Amazon based on a combination of Perroux's Theory of Growth and Development Poles, and Graph Theory.

In the end of the study it was possible to reach some results, which must be highlighted: the study put forth in this paper acknowledges theories that aim at achieving regional economic growth and development by means of transportation infrastructure; using spatial analysis in the proposal enables us to manipulate several pieces of information, which supports decision making; this study favors and makes full use of the available natural resources and infrastructure; moreover, key bottlenecks in the network can be identified by means of applying the proposed guidelines. In addition, proposals for developing growth poles can be tested.

However, a few limitations were found, namely, it is difficulty to gather data that mirror the region's socioeconomic and infrastructure features because it is a developing area. Furthermore, affordable tools that support manipulation of large amounts of data are unavailable. Some recommendations can guide future studies on the topic, for instance, devising a multimodal freight transport network that accounts for the future demand and dynamic changes in the spatial structure and implementing such proposal. Another recommendation is proposing sensitivity analysis of the cost of transportation as well as the capacity and vulnerability of the transportation network.

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