DEVISING A MULTIMODAL CARGO TRANSPORTATION NETWORK IN THE AMAZON REGION UNDER A REGIONAL ECONOMIC GROWTH APPROACH

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ABSTRACT

The relationship between transport and economic development has been studied for years. In Brazil, especially in the Amazon Region, such matter began in the 70s with the creation of several economic development plans and projects. However, due to many factors, such as the incompatibility between the proposed models of transport planning and territorial planning, the expected results were not achieved. In that perspective, this paper aims at designing a multimodal cargo transportation network that enables goods to be efficiently carried in a region. This network was developed using the available natural resources and it stimulates regional economic growth and development based on the Growth Pole and Development Pole Theory, and Graph Theory, which are widely used in network transportation studies. Consequently, three networks, related to three different scenarios – status quo, investment in transportation infrastructure, and the strategic scenario – have been devised and analyzed considering the operating costs of transportation and their spatial configuration.

Keywords: transportation network, economic development, growth pole theory, graph theory.

1. INTRODUCTION

Large countries like 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 mirrored by inefficiency in regional planning, mainly in its two principal branches: transportation and territorial planning

(Vasconcelos, 2000). 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 (Richardson, 1969). In turn, inefficient planning may be responsible for scattering economic activities geographically and, consequently, causing improper land use.

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

Designing a multimodal transportation network that enables goods to be transported efficiently and accelerates economic growth in regions such as the Amazon is supported by two theoretical assumptions: Perroux’s Growth Poles and Development Poles Theory; and Graph Theory, which is widely used in network creation techniques.

This paper sets out to design a multimodal cargo transportation network that allows goods to be transported efficiently, making use of the available natural resources (e.g., rivers and local production) and infrastructure (e.g., ports, airports, roads, railways etc). The network presented in this paper was developed for the Amazon region, where the main centers of economic growth (integral elements of the transportation network) were identified. Then, information regarding transportation infrastructure was collected and analyzed. Such information is important for determining the edges of the network. It must be noted that the region’s huge hydrographic basin brings enormous benefits when integrated to the network.

2. THEORETICAL ASSUMPTIONS

Two main theoretical assumptions have been established to develop this study. The first one concerns regional economic development and the development poles theory, and the second relates to transportation networks and graph theory. The following sections present a few considerations about these theories.

2.1. Theories and Models of Regional Economic Development: A Geoeconomic Approach – Space seen as a Dynamic Unit

It is common practice for economic analyses within the field of regional development to acknowledge disaggregation trends of the variables at hand. However, this breakdown must aim to encompass all variables to ensure that the analyses achieve high accuracy levels. Space was a variable that has recently begun to be considered in disaggregation analyses

(Lopes, 2001; Santos, 2003), given that, in the field of regional economics, most analyses explain the facts without acknowledging the spatial locations in which they occur.

Models and theories that account for the spatial factor in regional economic growth analyses were developed by means of acknowledging that there are spatial interactions taking place between the activities and the stakeholders in the regional sphere. Here, they are referred to as geoeconomic studies. Perroux's Growth Poles and Development Poles Theory serve as a theoretical basis for this paper.

2.1.1. 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 (Haddad et. al., 1972; 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 (Haddad et. al., 1972). The homogeneous aggregate, which is well known to geoeconomists, 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).

Note the importance given by geographers to the urban core as a polarizing agent, while the transportation network is considered an expansion factor, which expands the city's polarization influence. Thus, this mechanism creates regional and polarization centers. Perroux's (1964) concept of region has been widely accepted and used by economists, geographers and sociologists in attempting to apply his theory to regional planning.

2.1.2. 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 the 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).

Even though Perroux developed his theory around the industry because modern economy is led by industrial economic activity and also because he conducted his studies in industrialized countries, he extends the propulsive function to primary activities such as mining, forestry and farming. 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. Regional development is always linked its pole's development trends.

2.2. Transportation Network

Networks stemmed from the need for the delivery of basic services such as sanitation, electricity, water and transport. Back then, most networks were cross-linked, and, in the beginning, they were classified as technical urban networks because they only catered for the proper distribution of such services in urban environments, where there was greater population concentration. Therefore, they were analyzed by means of material flows (Dupuy, 1998).

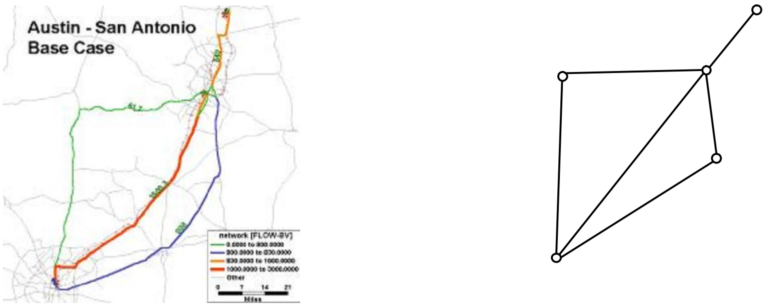
Due to population growth, and, consequently, increases in demand for these services, analyses needed to be conducted in broader fields, which encouraged the creation of what scholars consider to be the modern concept of network. In this perspective, a transmission system is a physical structure that comprises a set of elements from a transportation system as well as abstract elements such as desires, actions, and the links between transportation infrastructure and the environment where it is in. The degree of connection between these elements determines the intensity in which spatial changes occur in the environment where the network is located.

2.2.1. Graph Theory in Transportation Network Study

Graph theory terms used in the field of transportation are linked to real geographic objects, in which nodes and arcs may represent specific features of such objects. In addition, graph theory stands out as a support tool for solving problems found in the field of transport, such as a road's capacity and the shortest path route (Almeida et al., 2003).

2.2.2. Graphic Representation of a Transportation Network

The representation of a given transportation system in graph theory perspective is associated with the usual concept of a transport network. In this case, a transportation network is comprised of nodes and arcs, where nodes are important points in space and arcs represent the physical connections between these points. Figure 1(a) represents highways and their flows, which are graphically represented in Figure 1(b) as a transportation network.



(a) (b)

Figure 1 – Actual transportation flow on highways (a), and its graphic representation (b)

2.2.3. Costs in a Transportation 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. Reference levels regarding the price of hired carriers will be found when working with the direct costs of handling cargo so as to determine the routes, which are represented by the arches. This approach allows for assessing the different routes so as to find the cheapest one, taken that all routes deliver similar quality in the services they offer.

2.2.3.1. Costs of Transportation in an Arc

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 cargo. In addition, the operating cost of transporting cargo 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), considering the model used by most cargo carriers in Brazil.

$$cl_i = cfl_i + cvl_i \tag{1}$$

Where cl_i: Cost of transportation in arc l_i;

cfl_i: Fixed cost in arc l_i per day;

cvl_i: Variable cost per kilometer in arc l_i.

As seen in equation (2), the usual separation scheme between variable and fixed costs was adopted, given that that model is popular among most carriers (Filho & Gameiro, 2001). In this case, fixed and variable costs in the arc (l_i) can be mathematically represented by equations (2) and (3), respectively.

$$cfl_i = \frac{cfv}{Vm \cdot htd} \cdot D_i, \tag{2}$$

$$cvl_i = cvv \cdot D_i \tag{3}$$

Where cfl_i: Fixed cost of transportation in arc l_i (R$);

cfv: Fixed cost of the vehicle per day (R$);

D_i: Length of arc l_i (km);

Vm: Average vehicle speed in arc l_i (km/h);

htd: Number hours worked per day (h);

cvl_i: Variable cost per kilometer in arc l_i (R$);

cvv: Fixed cost of the vehicle (R$).

By replacing equations (2) in (3) equation (1), we get the following (4).

$$cl_i = \frac{cfv}{Vm \cdot htd} \cdot D_i + cvv \cdot D_i \tag{4}$$

By dividing the cost of transportation in a given arc by the vehicle's load capacity (P), there is equation (5), which is expressed in terms of total operating cost per ton carried through the network's arcs.

$$cl_i = \frac{\left(\frac{cfv}{Vm \cdot htd} \cdot D_i\right) + \left(cvv \cdot D_i\right)}{P}, \text{ or } \quad cl_i = \frac{\left(\frac{cfv}{Vm \cdot htd} + cvv\right)}{P} \cdot D_i \tag{5}$$

3. METHODOLOGY FOR DESIGNING A MULTIMODAL CARGO TRANSPORTATION NETWORK

The methodology to design a multimodal transportation network encompasses eight stages, as shown in Figure 2.

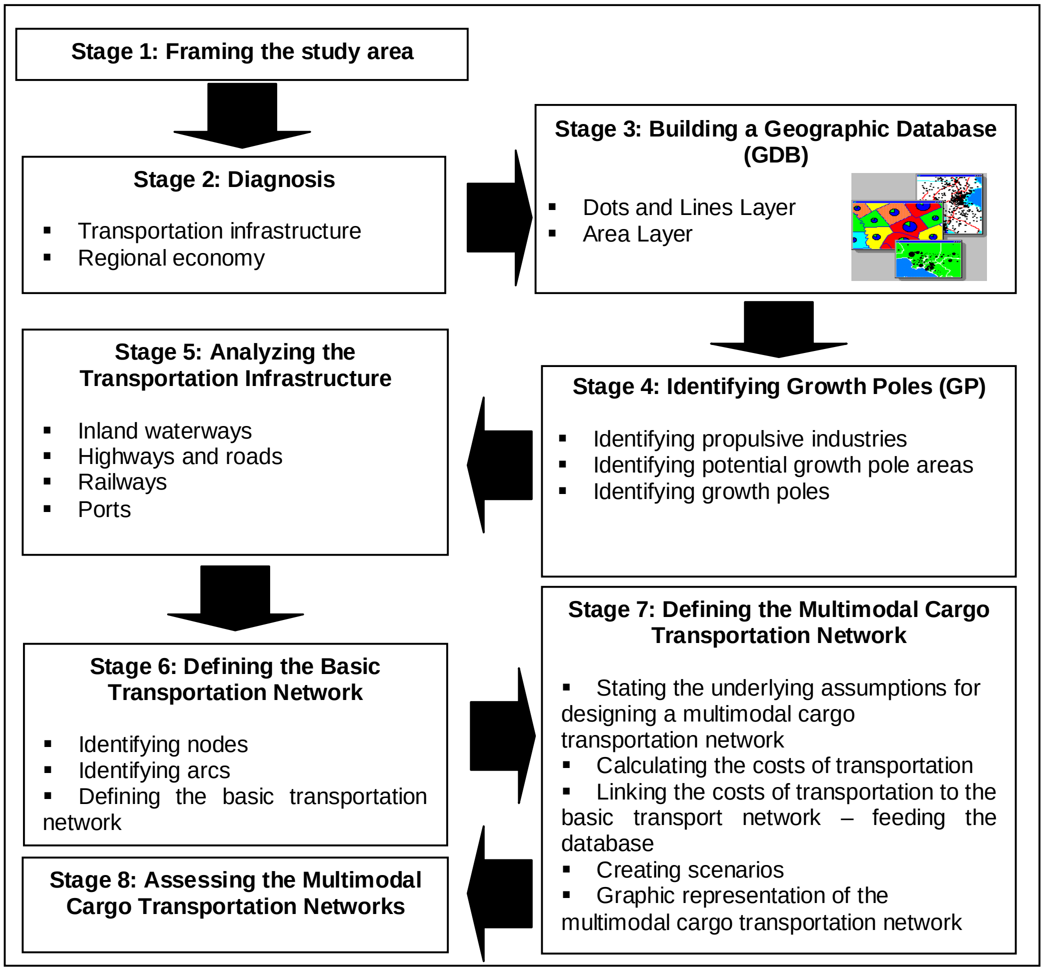


Figure 2 – Methodology used for designing the multimodal cargo transportation network

4. DESIGNING A MULTIMODAL CARGO TRANSPORTATION NETWORK

This section presents the steps taken in the process of designing a multimodal cargo transportation network for the 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 (the State of Maranhão) (ADA, 2007). Figure 3 shows the geographical extent of the Amazon Region being considered in this study, which comprises nine states (792 municipalities).

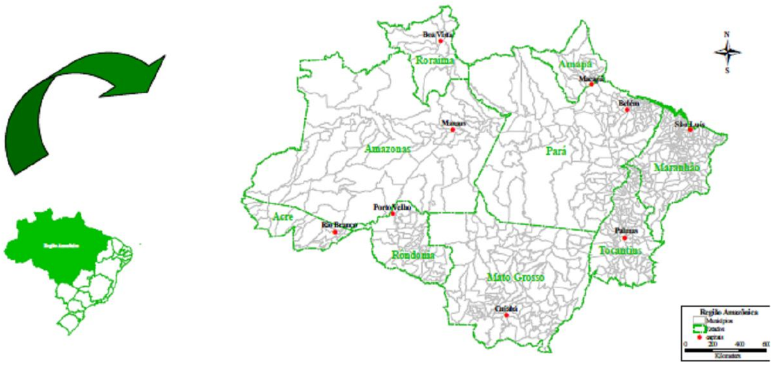


Figure 3 – Geographic boundaries of the Brazilian Amazon Region

Stage 2: Diagnosis

In order to develop a multimodal cargo transportation network, a diagnosis needs to be conducted regarding the existing transportation infrastructure and the regional economy.

Step 2.1: Analyzing the Regional 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.

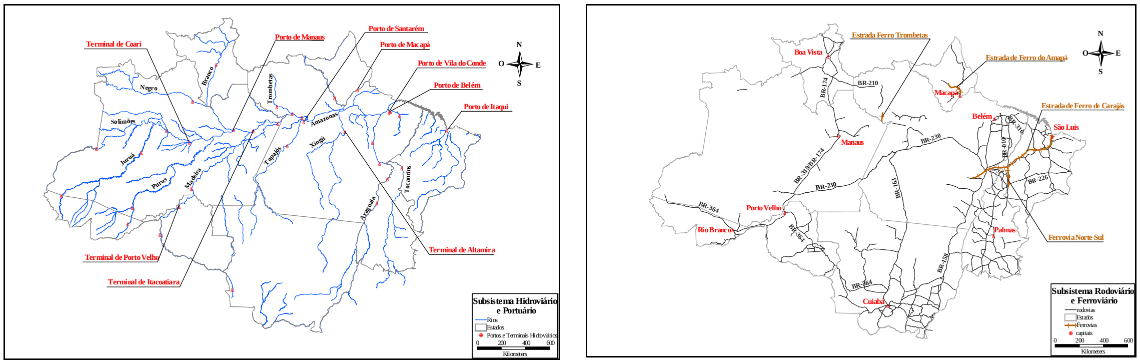
1. **Inland waterways:** from the hydrographic perspective, the Amazon has the largest drainage basin in the world, which accounts for approximately one-fifth of the world's total river flow (INPA, 2003). Rivers are supported by rainy periods and they are, with a few exceptions, the only means of transport available to most local communities. There are over 20,000 km of navigable rivers linking distant communities. Another equally important drainage basin located in the same region is Tocantins River basin. Figure 4 shows the Amazon region and the main rivers of the Amazon and Tocantins basins.

2. **Ports:** the vast Amazon river network is served by a port subsystem that, currently, fairly meets the existing flows. According to the set of technical features that determine cargo handling and the conveyance of passengers, there are two

categories of port facilities: sea ports and waterway terminals (Almeida et. al., 2004). Figure 4(a) shows the seaports and waterway terminals in the Amazon Region.

3. **Highways and roads:** the road subsystem in the Amazon was designed to serve as a complement to the inland waterways; it aims at ensuring that feeder roads be built. Note that there are few roads, mainly due to the geological conditions of the local soil, which are considered unsuitable for highways (Almeida et. al. 2004). Figure 4(b) shows the existing highways and railroads in the Amazon Region.

4. **Railways:** the railroads in the Amazon Region serve the purpose of meeting the demand for distribution of large amounts of ore, conveying them from the mines to the exporting ports. The railway subsystem in the Amazon region has four operating railways, namely: Amapá Railroad (EFA); Jarí Railroad (EFJ); Trombetas Railroad (EFT), Carajás Railroad (EFC); North-South Railway (FNS) (ANTT, 1997).



(a) (b)

Figure 4 - (a) port subsystem and main rivers in the Amazon Region and (b) highway and railway subsystems in the Amazon Region

Step 2.2: Analyzing the Regional Economy

The 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 main products that sustain this economy, which can be classified in the following groups of activities:

1. **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 and oil are the most important products;

2. **Forestry:** these activities are characterized by the extraction and/or processing wood and latex, mainly;

3. **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 using data gathered during the diagnosis stage. Three types of layers were manipulated, namely:

1. **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. Additionally, this layer presents the amount of the main types of cargo handled in 2000;

2. **A Line Layer,** representing the rivers in the Amazon and Tocantins basin, as well as their main features, such as name, periods of high and low waters, length, width and depth. Other line layers referring to highways and railways are also created;

3. **An area Layer,** representing the 792 municipalities of the Amazon Region 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 municipality 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: identifying propulsive industries, framing potential growth pole areas; and, finally, defining 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: Identifying propulsive industries

In this stage, propulsive industries were identified. 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, consequently, 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 Curve made it possible to find the most economically important products. Table 1 presents a list of the twenty products tested, according to their production values in (R$). The highlighted lines show the most important products (Class A and B) in terms of production value, as demonstrated by the ABC Curve (Figure 5). According to the classification guidelines, there is:

1. Class A = 4.20% of products account for 54.33% of the total production value in the Amazon Region. These products deserve special attention;

2. Class B = 6.30% of products account for 13.23% of the total production value in the Amazon Region. These products deserve some attention;

3. Class C = 10.50% of products account for 32.44% of the total production value in the Amazon Region. These products deserve little attention.

Table 1 – ABC Curve: Production value of goods in the Amazon Region

Produtos	Valor de Produção (R$)	Valor de Produção Acumulado	% Sobre o Valor Total Acumulado	Classificação Ordenada
Soja	2.283.324.000,00	2.898.288.980,00	27,22883062	1
Ferro	1.351.064.014,00	4.249.352.994,00	39,92	2
Arroz	797.524.000,00	5.046.876.994,00	47,41	3
Petróleo	735.902.790,00	5.782.779.784,00	54,3280302	4
Mandioca	714.826.000,00	6.497.605.784,00	61,04367388	5
Madeira	693.594.000,00	7.191.199.784,00	67,55984728	6
Algodão	607.811.000,00	7.799.010.784,00	73,27010698	7
Milho	497.470.000,00	8.296.480.784,00	77,94373561	8
Banana	483.161.000,00	8.779.641.784,00	82,48293413	9
Alumínio	436.997.218,00	9.216.639.002,00	86,58843337	10
Caulim	306.290.482,00	9.522.929.484,00	89,46596964	11
Café	305.857.000,00	9.828.786.484,00	92,33943343	12
Gás Natural	289.828.980,00	10.118.615.464,00	95,06231727	13
Pimenta-do-Reino	140.897.000,00	10.259.512.464,00	96,38601569	14
Feijão	106.804.000,00	10.366.316.464,00	97,38941737	15
Estanho	101.772.424,00	10.468.088.888,00	98,34554842	16
Bauxita	67.782.073,00	10.535.870.961,00	98,98234709	17
Calcário	52.005.590,00	10.587.876.551,00	99,47092895	18
Latex	35.149.000,00	10.623.025.551,00	99,8011466	19
Cromo	21.166.338,00	10.644.191.889,00	100	20

The ABC Curve 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.

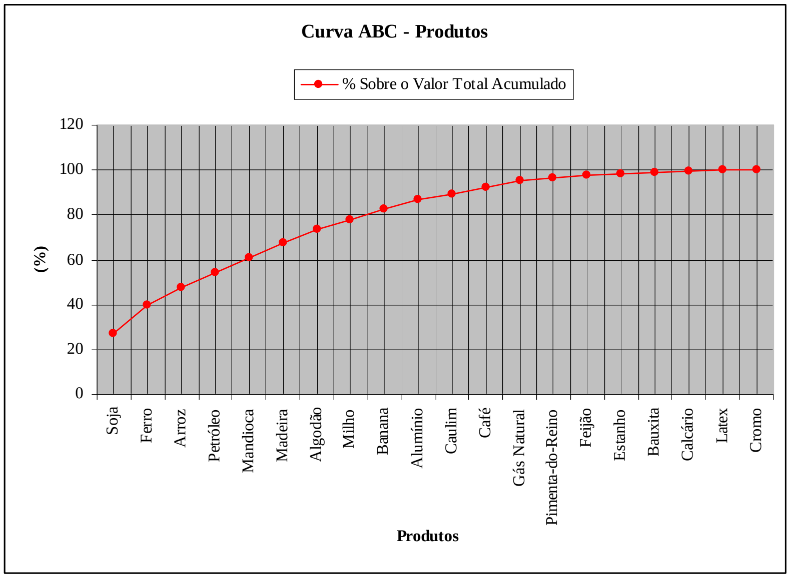


Figure 5 - ABC Curve of the production value of goods in the Amazon Region (year 2000)

Step 4.2: Identifying Potential Growth Pole Areas

At this stage, potential growth pole areas for timber were identified. Here, potential areas are portions of space within the Amazon Region, represented by the municipalities 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 6) was created. Analyses of spatial distribution were conducted on that map to identify geographic areas encompassing sets of municipalities that have the highest production values.

In Figure 6, 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.

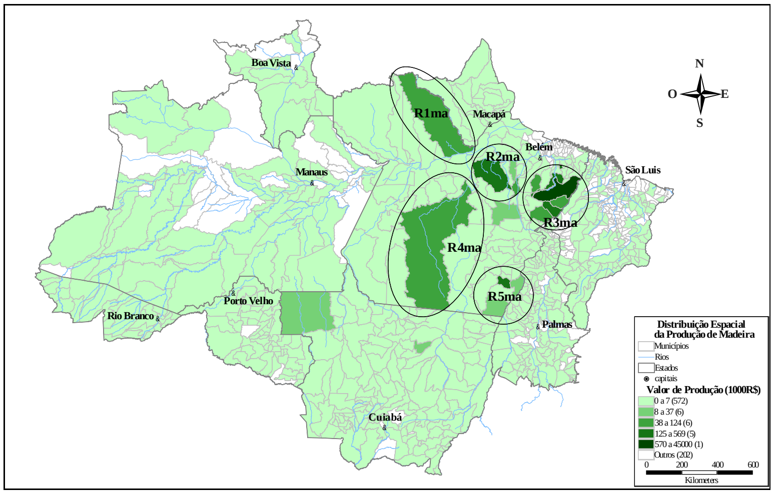


Figure 6 – Spatial allocation of the production value of timber in the Amazon Region (year 2000)

Step 4.3: Identifying 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 7. The Box Map shows that is a well-defined cluster of areas with the same aggregation patterns. Aggregate areas shown in a darker color, which are most strongly related (high-high) due to the attributes' values, overlap the areas previously identified as potential growth poles

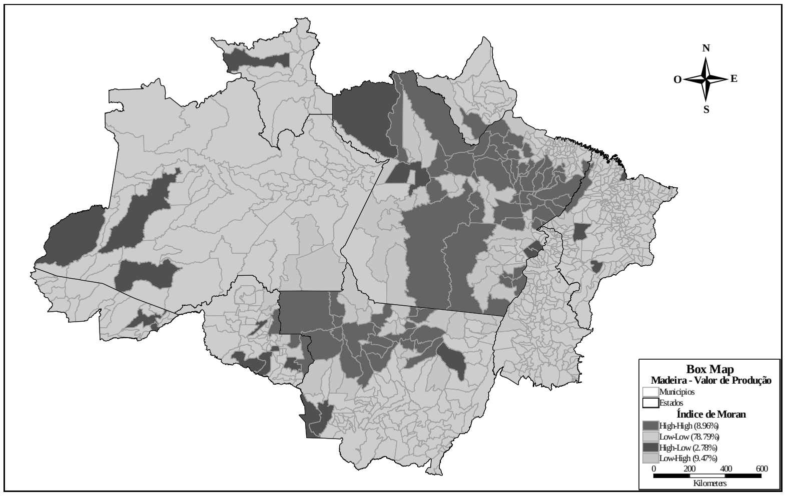


Figure 7 - Box Map of the production value of timber in the Amazon Region (year 2000)

Areas that are significant at 95% certainty are shown by the Moran Map (Figure 8). The dark 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 8 overlap the areas initially identified as possible growth poles (Figure 6). We conclude 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

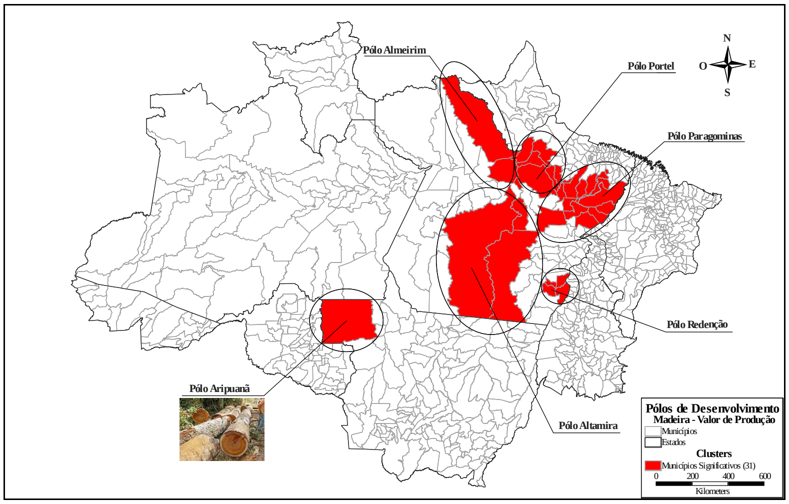


Figure 8 - Moran Map of the production value of timber in the Amazon Region (year 2000)

The municipality of Aripuanã is identified in Figure 8 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 city has a high positive autocorrelation pattern (High-High). The Moran

Map in Figure 8 statistically confirmed that the municipality of Aripuanã is a growth pole. In addition, Figure 8 presents some clusters composed of municipalities that are significant in the production of timber. These clusters are growth poles in the Amazon Region in the perspective of timber producers, which are represented by the following municipalities: Paragominas; Redenção; Portel; Almeirim; Altamira; and Aripuanã. Then, growth poles for each product were determined according to the following criteria:

1. Moran Maps were created for the selected products, as these maps show the statistically significant groups of municipalities. Groups of municipalities (clusters) that constituted the growth pole were identified on each product's map;
2. a municipality was chosen to represent the growth pole in each cluster;
3. municipalities that represent each growth pole were chosen regarding their production value and the existing transportation infrastructure.

Stage 5: Analyzing the Transportation Infrastructure

According to the Theory of Growth and Development Poles, transportation infrastructure can be understood as the 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, transportation infrastructure can be translated as a set of arcs and nodes, which make up a transportation network.

The analyses regarding the Amazon Region's transportation infrastructure were needed to identify the desired lines for defining the arcs of the basic transportation network. Moreover, such analyses enabled us to identify the main bottlenecks and/or impedance locations that could affect vehicle flow and, consequently, the conveyance of cargo.

Since each transport mode has its own features, separate analyses were performed for each transportation subsystem. The tests considered factors such as: the rivers' navigability (i.e., inland waterways), the use of highways for conveying cargo and the cargo handling intensity in ports and railways.

Stage 6: Defining the Basic Transportation Network

This stage encompassed three activities: defining the nodes, defining the arcs; and designing the basic transportation network.

Step 6.1: Defining the Nodes

First, two sets of nodes were defined: vertexes and edges.

1. **Nodes:** for each cluster, which is a growth pole, the municipality with the highest production value is identified and defined as the vertex of its cluster. Vertexes Were

determined for all the growth poles, totaling twenty-six nodes, namely: Almeirim, Altamira, Aripuanã, Aurora do Pará, Campos de Júlio, Coari, Diamantino, Guarantã do Norte, Itacoatiara, Laranjal do Jarí, Manicoré, Nova Ubiratã, Novo São Joaquim, Paragominas Paranatinga, Parauapebas Parintins, Portel, Pium, Redenção, São Félix do Xingú, São Mateus do Maranhão, Sena Madureira, Sinop, Tarauacá, e Tefé;

2. **Edges (links):** 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 (links) along with the arcs.

Step 6.2: Defining the Arcs

Arcs comprised by the basic transportation network were defined using the transportation 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 and unique geographical structure was created. This platform consisted of arcs (navigable rivers, highways in operation and railways) and edges (connection nodes).

Step 6.3: Defining the basic transportation network

In the final step of Stage (6), a basic transportation network was created. The output of this activity was a thematic map of arcs and nodes. The network was created by means of overlapping two different thematic maps: one showing vertexes and the other, arcs and edges (links). Figure 9 presents the geographic configuration of the basic transportation network designed for the Amazon Region.

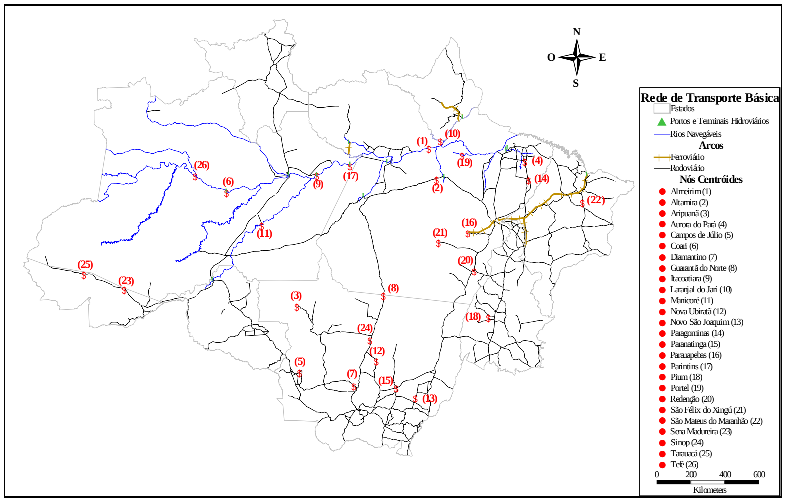


Figure 9 – Spatial Configuration of the basic transportation network in the Amazon Region

Stage 7: Defining the Multimodal Cargo Transportation Network

This step of the methodology is based on Graph Theory so as to design the transportation network. Some activities were conducted to design the three multimodal cargo transportation networks, namely: defining basic assumptions to develop the multimodal cargo transportation network; defining the transportation costs; calculating the cost of transportation for the basic network - feeding the database; composing possible scenarios, and the graphically representing the transportation networks.

Step 7.1: Stating the Assumptions for Designing a Multimodal Cargo Transport Network

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

1. Each possible network is represented by a direct graph;
2. Vertexes (nodes) correspond to locations where trips are generated;
3. A minimum cost route was set for each growth pole. All arcs in the basic transportation network were acknowledged in determining the shortest paths;
4. For nodes representing the growth poles of the cassava propulsive industry, state capitals were considered as destinations in the analysis of the transportation cost. This alternative was chosen because most of the cassava production is consumed locally, and, because the population is concentrated in the capital, capitals could represent destinations of trips generated by those vertexes;
5. 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 vertexes representing growth poles;
6. Three scenarios were created to represent different situations (i.e., status quo, investments in transportation infrastructure, and strategic) that are central for designing the three networks;
7. Operating costs in the arcs and nodes (transhipment) were acknowledged so as to determine the shortest path routes;
8. A few cargo vehicles were considered for calculating the operating cost of transportation. Along with such vehicles, some of their features were identified, namely: fixed costs (cfv) variable costs (cvv) of vehicles; load capacity (P); average speed (Vm); and the road's length (D_i) ;
9. The cargo vehicles used in the cost analysis, as well as their unique features, were defined in terms of the roads' physical characteristics;

10. The cost analysis for the road transport mode considered a truck type with a load capacity of 30 tons. The average speeds developed by the truck type between two nodes were considered to be 60km/h on paved stretches and 30km/h on unpaved stretches of highways;

11. The cost analysis for the inland waterway mode considered a type of barge with a 2,200 ton load capacity and was defined in terms of navigability restrictions of the rivers. The average speed (Vm) developed by the barge system between two nodes was considered to be 11.10km/h (6 knots);

12. The cost analysis for the railway mode considered a type of railway convoy system with a 6,480 ton load capacity and it develops an average speed (Vm) of 45.00km/h.

Step 7.2: Calculating the Costs of Transportation

This step is central for analyzing the minimum cost routes, which allow for establishing the transportation routes in the Amazon Region. To that end, two types of costs were considered: costs of transportation and transhipment costs. Both of them were calculated using equation (6), as follows.

$$C'_{rota} = \sum_{i=1}^{I} coa_i + \sum_{j=1}^{J} cn_j \qquad (6)$$

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 (5) was used for calculating the operating cost of transportation in the arcs. Because the basic network consists of arcs that represent roads, rivers and railways, a commercial vehicle was defined for each mode of transport. Then, figures for fixed and variable costs were gathered for each type of vehicle. These figures, regarding the assumed vehicles, were collected from carriers that operate in the Amazon Region. By means of replacing the data provided by carriers in equation (5), the following reduced equations were found for each transport mode:

1. For a truck traveling at an average speed of $Vm = 60km/h \Rightarrow coa_i = 0{,}085 R\$/T.km \cdot D_i$. Here, the arc represents a given stretch of a paved highway;

2. For a truck traveling at an average speed of $Vm = 30km/h \Rightarrow coa_i = 0{,}117 R\$/T.km \cdot D_i$. Here, the arc represents a given stretch of an unpaved road;

3. For a barge traveling at an average speed of $Vm = 11{,}10km/h \Rightarrow coa_i = 0{,}016 R\$/T.km \cdot D_i$. Here, the arc represents a given stretch of a navigable river;

4. For a railway convoy system carrying grains (soybean and rice): $coa_i = 0{,}038 R\$ / T.km \cdot D_i$;

5. For a railway convoy system carrying iron ore: $coa_i = 0{,}043 R\$ / T.km \cdot D_i$.

In addition to the operating costs for the three modes of transportation (i.e., road, rail and waterway) 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 (7). 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.

$$cn_j = T_{1j} + T_{2j} + Op_j \tag{7}$$

Where: cn_j: cost of transportation in node n_j;
T_{1j}: 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).

As for cargo handling (*Op*) costs, we adopted 3 R$/ton for all ports and products considered in the analysis due to two basic reasons. First, it is difficult to obtain data regarding cargo handling in each port and for each product because in Brazil this service is provided by private operators, who do not make these values available. Second, in face of the difficulty in obtaining such data, we chose to use the mean of cargo handling costs provided by Antaq's Technical Report (2006), which considers all goods handled in ports and waterway terminals in the Amazon Region. In the case of a transshipment terminal other than a port or inland waterway, the transfer cost corresponds to the cargo handling (*Op*) portion of the total cost.

Step 7.3: Linking the Costs of Transportation to the Basic Transport Network – Feeding the Database

As seen in the previous step, 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 (D_i). Thus, both the expressions for specific transport modes and the values calculated for each port were used to feed the database, linking them through GIS-based tools (TransCAD software). 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 transhipment takes place.

Step 7.4: Creating Scenarios

After all operating costs are calculated and defined, the next step is to create possible scenarios. In this study, three scenarios were created, and, consequently, three multimodal cargo transportation networks were designed: one for each scenario. The aspect that differentiated the three scenarios concerns changes in the transportation infrastructure in the Amazon Region, which resulted in changes in the spatial structure of the networks in the following way:

1. **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;

2. **Scenario 2 – investment in transportation infrastructure through the Brazilian Growth Acceleration Plan (PAC):** changes in the transportation infrastructure of the Amazon Region were acknowledged in this scenario. These changes were a result of the Brazilian Growth Acceleration Plan (PAC), a program devised by the Brazilian government which allocated investments in infrastructure for all transportation modes;

3. **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 Step 6, minimum operating transportation cost routes were set between the O/D pairs for the three scenarios described above. A set of routes was then obtained, which established the final structures of the three multimodal cargo transportation networks. Routes were established using the operating costs calculated in step 7.2 and TransCAD (GIS software), which provides an operating tool called Dijkstra algorithm (used to determine the shortest path routes between the O/D pairs).

Step 7.5: Graphic Representation of the Multimodal Cargo Transportation Network

Finally, three multimodal cargo transportation networks were designed (i.e., status quo, PAC, and strategic). Each network was composed of the minimum cost routes, which were previously identified for each growth pole (represented by vertex). 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 10, 11 and 12.

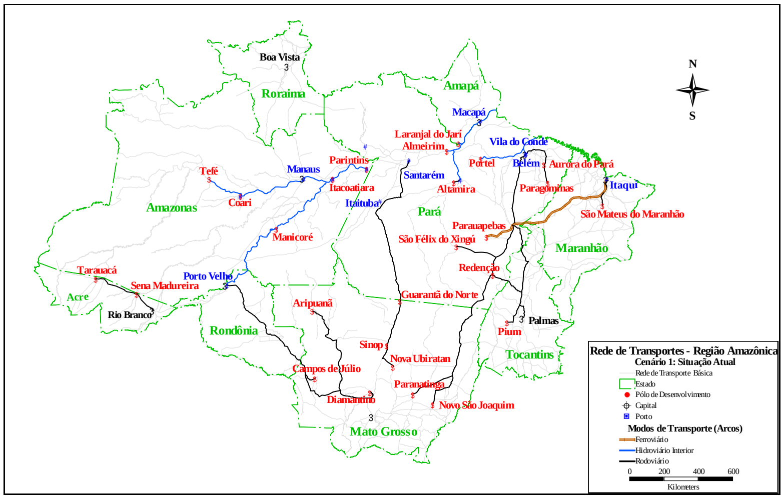


Figure 10 - Multimodal Cargo Transportation Network in the Amazon Region – scenario 1

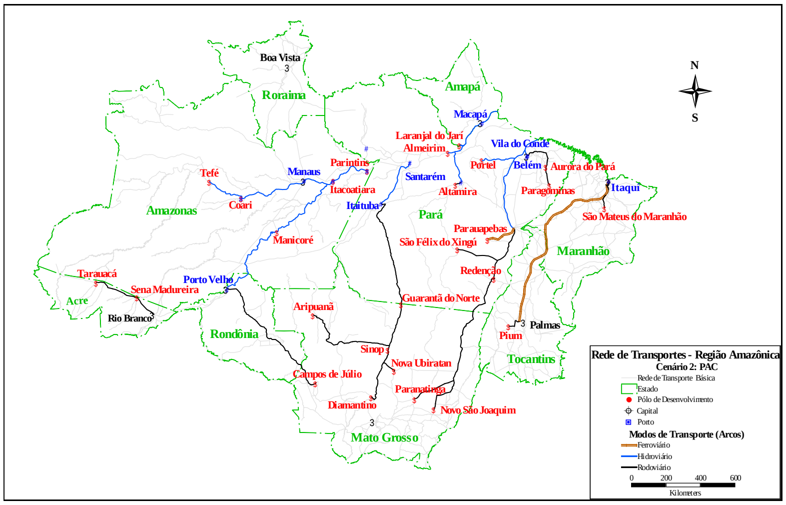


Figure 11 - Multimodal Cargo Transportation Network in the Amazon Region – scenario 2

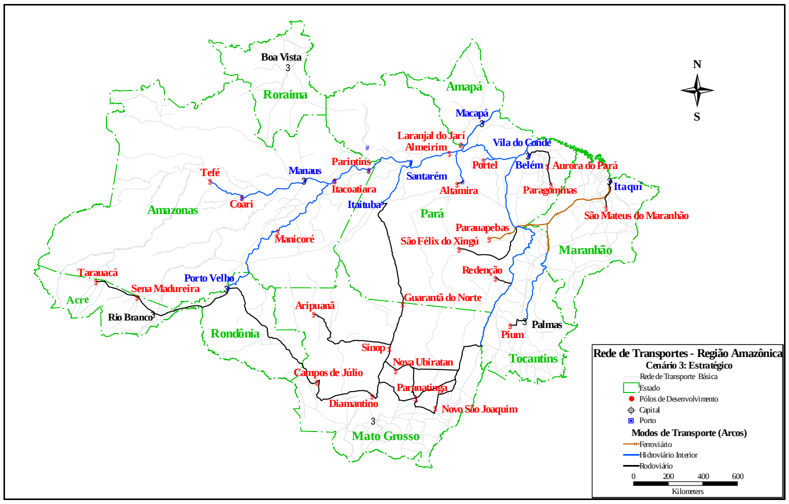


Figure 12 - Multimodal Cargo Transportation Network in the Amazon Region – scenario 3

Stage 8: Assessing the Multimodal Cargo 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, TransCAD was used to calculate the total costs of each network, which were found to be the following:

1. **Scenario 1 – status quo:** the total cost of the multimodal cargo transportation network for scenario 1 was Ctr = 1,915.02 R$/ton;

2. **Scenario 2 – investment in infrastructure:** the total cost of the multimodal cargo transportation network for scenario 2 was Ctr = 1,548.38 R$/ton;

3. **Scenario 3 – strategic:** the total cost of the multimodal cargo transportation network for scenario 3 was 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.

5. CONCLUSIONS

There are few studies in Brazil dealing with the relationship between transportation and economic development, especially regarding the Amazon region, where most studies were conducted in the 70s. Note that 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 and consolidated in the proposed methodology. Therefore, assessing how these elements were dealt with in the Amazon region is a form of assessing how significant this methodology is. Accordingly, this proposal is important because the methodology is feasible.

Thus, designing a transportation network that boosts economic development is of utmost importance because it is the first attempt to deal with the matters of reducing socioeconomic inequality levels between the Amazon and the rest of Brazil using that approach. Over the years, policymakers have repeatedly made the mistake of disregarding the Amazon's economic potential and its vast natural resources as vital elements that should be acknowledged when designing such a network. Most plans and economic development projects aimed at Amazon overlook the relationship between transportation and growth/development.

The study of the relationship between transportation and growth/development enabled us to design a transportation network for the Amazon region, based on a combination of Perroux's Theory of Growth and Development Poles, and Graph Theory. The following results must be highlighted:

1. The study put forth in this paper acknowledges theories that aim at achieving regional economic growth and development by means of transportation infrastructure;
2. 2. Using spatial analysis in the proposal enables us to manipulate several pieces of information, which supports decision making;
3. This study favors and makes full use of the available natural resources and infrastructure;
4. Key bottlenecks in the network can be identified by means of applying the proposed methodology. In addition, proposals for developing growth poles can be tested.

However, a few limitations were found, namely:

1. It is difficulty to gather data that mirror the region's socioeconomic and infrastructure features because it is a developing area;
2. Affordable tools that support the manipulation of large amounts of data are unavailable.

The following recommendations can guide future studies on the topic:

1. Sensitivity analysis of the cost of transportation cost as well as the capacity and vulnerability of the transportation network;
2. Devising a multimodal cargo transport network that accounts for the future demand and, consequently, dynamic changes in the spatial structure; and implementing such proposal.

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