IMPERIAL

OPTIMISING BIOECONOMY LOGISTICS FOR THE AMAZON REGION

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Group 6

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Abstract

The Amazon region is an essential source of bio-economic products. However, due to the unique climate and topography, as well as the perishable nature of bioeconomy products, there are certain challenges in logistics. Our project takes the Brazilian Amazon as the study area and selects three bioeconomy products: acai berries, Brazil nuts, and pirarucu. By analysing their sources and production as well as the Brazilian transport network, we develop 6 main transport strategies based on network optimisation and sequential optimisation models in Python. In addition, we take energy efficiency, digital access, construction and maintenance costs, potential volume growth, job creation, environmental impact, sensitivity to climate events, and safety and security as criteria to develop the assessment model of transport strategies. The results show that the system optimisation strategy that aims to minimise time performs best. We visualise the strategy by creating an interactive map and propose a seven-phase roadmap. Our findings propose a comprehensive logistical framework that promotes sustainable development in the Amazon and recommends a balanced transportation strategy that meets social, economic, and environmental goals.

1. Introduction

1.1 Background

The Amazon region is critical to the world's ecosystem but is at huge risk because of deforestation, biodiversity loss, and climate change. Bioeconomy can be a way forward in achieving sustainable development despite these challenges. By exploiting the rich biodiversity of this region, Açai, Brazil nuts, and Pirarucu offer economic opportunities aligning with environmental conservation needs. The Amazon is also home to over 28 million people, most of whom live in urban areas. This intricate balance between natural and human systems presents unique challenges and opportunities for sustainable development.

The concept of bioeconomy provides an encouraging way to economic activities that utilise biological resources sustainably. Key bioeconomy products from the Amazon, such as Açaí, Brazil nuts, and Pirarucu, have shown significant potential in providing economic benefits while promoting environmental conservation. Açaí, for instance, is harvested from native palm trees and contributes minimally to deforestation. Similarly, the harvesting of Brazil nuts encourages forest conservation, and Pirarucu fish farming supports aquatic biodiversity. Açaí, primarily harvested in the western Amazon, has a short shelf life, requiring immediate refrigeration or processing into more stable forms like frozen pulp or powder. Brazil nuts, found across the Amazon, provide economic incentives for forest conservation but face transport challenges due to their remote locations and the risk of contamination. Pirarucu, a large freshwater fish, supports local economies through both wild harvesting and aquaculture, but efficient transport is needed to reduce costs, improve market access, and face its perishability. Nevertheless, the development of these bioeconomy sectors is restricted by logistical challenges, including inadequate transportation infrastructures, limited digital connectivity, and seasonal waterway fluctuations.

1.2 Our Objectives

The objective of our project is to optimise the logistics of bioeconomy products in the Amazon region, focusing on transportation strategies that enhance economic opportunities without contributing to deforestation. We aim to analyse and elaborate transport strategies for Açaí, Brazil nuts, and Pirarucu, and assess their potential on energy efficiency, digital access, construction and maintenance cost, the potential for volume growth, job creation, environmental impact, and sensitivity to climate events, among other things.

To do so, we aim to analyse the current transportation network in the Amazon forest and to evaluate the situation of the region regarding different criteria. In the meantime, thanks to several modelling methods, data collection and processing, our objective is to set up precise supply chains and logistics for Açaí, Brazil nuts and Pirarucu. We will then compare the different strategies by creating a framework to assess different criteria to judge their benefits and costs.

To achieve these goals, our project will deliver the following:

a. An outline of the key stakeholders impacted by and/or interested in improving the transport of the selected bioeconomy product, including an assessment of their interest and influence.
b. Identification of potential conflicts between stakeholders related to the transport infrastructure of the specific bioeconomy product.
c. A list of transport and broader challenges tied to current transport infrastructure for the selected bioeconomy product.
d. A list of potential transportation strategies for the selected bioeconomy product.
e. A comprehensive list of criteria to compare various transport strategies based on a literature review, including but not limited to energy efficiency, digital access, construction and maintenance cost, potential for volume growth, job creation, environmental impact, and sensitivity to climate events.
f. A methodology to quantify the impact and weigh the developed criteria.
g. An assessment of various transport strategies' benefits, costs, and impacts, with a recommended preferred option based on the developed methodology.
h. An estimate of the number of people that could benefit from the preferred option.
i. Visualisation of critical elements of the recommended solution.
j. A roadmap for delivering the recommended solution.

By realising these deliverables, we aim to create a comprehensive logistical framework that supports sustainable development in the Amazon and produce one final transport strategy that will be the optimal regarding our holistic analysis.

1.3 Region’s Analysis and key issues

1.3.1 Key Stakeholders

For each product, we identified eight potential stakeholders impacted or interested in improving the transport of bio-economy products.

For açai, the indigenous people and local communities, such as the local açai producers from the Bailique Archipelago, are interested in maintaining sustainable harvesting and benefiting economically without compromising local ecosystems. They have limited influence on policies but a considerable influence on sustainable practices and local consumer trust. The Local Authorities, such as the municipal government in Amapá state, are interested in fostering local economic development, regulating local businesses, and ensuring environmental compliance, leading to moderate influence on enforcing local regulations and supporting infrastructure developments. Also, Local Associations like AmazonBai, a cooperative of açaí producers, aim to enhance product quality and logistics to boost profitability and efficiency in transport, with an influence on local supply chains and a significant role in setting standards and negotiating terms with transporters. For instance, they implemented the construction of an ice factory to prevent fruit loss and maintain its quality during transportation. On the National Government side, the Brazilian Ministry of Agriculture facilitates agricultural development and is interested in export growth and sustainable practices across the nation. They have major influence through regulatory frameworks and national policies on agriculture and exports. Besides, private companies invest in specialised transport solutions to enhance efficiency and product quality, aiming to reduce costs and increase market reach. Through their high influence, they control the transport infrastructure and capabilities. For instance, large producers are investing in initiatives such as the one of Bertolini da Amazônia. The company, based in Manaus, has built an 80m x 18m vessel in which it transports an açaí processing unit, including refrigeration, water treatment, and pasteurisation, among other things, where it intends to benefit açaí in the producing regions. In addition, banks such as Banco da Amazônia provide grants for infrastructural improvements and logistic ventures and are interested in profitable investments in sustainable practices. Banks' moderate influence is crucial for funding but dependent on project viability assessments. Customers, both domestic and international consumers of açaí, are interested in high-quality and sustainably sourced products. They moderately influence transport logistics by driving demand for better preservation methods and affect market trends and quality standards through purchasing choices. As well as Environmental NGOs such as the Sustainable Amazon Foundation guarantee sustainable harvesting, biodiversity conservation, and reduce impacts of deforestation. They highly influence public opinion and policymaking, and funding can be through advocacy, research, and international networks.

For Brazil nuts, the Indigenous People and Local Communities, such as harvesters and families involved in Brazil nut collection, are interested in reliable and efficient transport to reduce loss and contamination. Although they moderately influence sustainable harvesting practices, their influence is limited in broader logistics decisions. The Local Authorities, such as the local government entities in harvesting areas, ensure economic stability and compliance with environmental regulations. While they moderately influence infrastructure support, they have a limited influence on broader national policies. Also, Local Associations, like Cooperativa Mista Extrativista Vegetal dos Agricultores do Laranjal do Jari (Comaja), are interested in maximising product quality and minimising losses during transport, driving innovation like biomass energy from nut waste. They have a major influence in organising and directing logistics and storage solutions. Besides, The National Government, such as the Ministry of Science, Technology, and Innovation, foster technological advancements and innovation in transport and storage, aiming to support economic growth and sustainability. They highly influence funding controls and national policy direction that can facilitate or hinder logistics improvements. The Private Companies, similar to companies specialising in the storage and transport of perishable goods, aim to reduce costs and spoilage through innovative logistics solutions and are interested in expanding market access for Brazil nuts. They highly influence the design and implementation of logistics chains that ensure product integrity. Moreover, Banks, e.g., Local, and national financial institutions, provide capital for infrastructure improvements and technological advancements in logistics. Their moderate influence is essential for financing but selective in project backing based on profitability assessments. Customers, who are the global consumers of Brazil nuts, have high expectations for product quality influencing transport methods to ensure minimal contamination and maximum freshness. They highly influence driving demand for stringent logistics solutions to meet quality standards. In addition, Environmental NGOs, such as the Observatório da Castanha-da-Amazônia, ensure the Amazon's biodiversity is preserved and protected through sustainable harvesting practices and promote conservation efforts to maintain the forest ecosystems. They highly influence policymaking through advocacy, research, and public campaigns. They also raise awareness of good practices on harvesting and transport that are eco-friendly.

For Pirarucu, the Indigenous People and Local Communities, such as the Fishermen from Sustainable Fishing on the Amazon Coast project, are directly impacted by transport logistics and are interested in maintaining sustainable practices and improving livelihood. They have a moderate influence on local practices but limited influence on broader policy decisions. The Local Authorities, such as the State government of Amazonas, oversee fisheries compliance and are interested in economic and environmental sustainability within the region. Their moderate influence led to their capability of implementing state-level regulations and supporting infrastructure projects. Local Associations, like Fundação Amazônia Sustentável (FAS), improve fishing practices and logistics. They are interested in the economic well-being of communities and sustainable fishing, with high influence involved in infrastructure development and community engagement. On the National Government side, the Ministry of Environment is interested in conservation and sustainable economic practices across the Amazon region. They have a high influence through conservation policies and national sustainability initiatives. Besides, private companies, such as local logistics firms specialising in refrigerated transport, seek to expand services and improve profitability through efficient logistics solutions for the specific needs of Pirarucu transport. Their medium influence is dependent on regional demand and cooperative agreements with fisheries. In addition, Banks such as BNDES (Brazilian Development Bank) fund sustainable development projects and are interested in backing economically viable and environmentally sustainable initiatives. Banks have a high influence in financing large-scale projects and infrastructure improvements. Customers, like restaurants and markets requiring fresh fish, require ambitious standards of product freshness, driving demand for effective and fast transport solutions to maintain Pirarucu quality. They have a high influence through direct impact on logistics requirements and standards for delivery. Furthermore, Environmental NGOs such as Instituto De Desenvolvimento Sustentável Mamirauá (IDSM) protect aquatic biodiversity and sustainable fishing practices, and it is essential to preserve healthy ecosystems in the Amazon by promoting conservation efforts. Their considerable influence can impact local and national stakeholders through awareness, policies via research, and support for sustainable fishery practices.

In conclusion, a wide range of stakeholders, each with distinct interests and various levels of influence, are involved in the transportation of bio-economy products, including Açaí, Brazil nuts, and Pirarucu. Different stakeholders are crucial to ensure sustainable practices, economic viability, and effective logistics, including Indigenous Communities, Local Authorities, Local Associations, National Government, Private Companies, Financial Institutions, Customers, and Environmental NGOs. Hence, strategies that consider the perspectives and interactions of different stakeholders are essential to improve sustainability and optimise the supply chain for these valuable products.

1.3.2 Conflict matrix

All stakeholder conflicts are presented in Table 1, 2 and 3. Details are discussed below.

Table 1.1 Conflict matrix for Açai Fruit

Stakeholders	Indigenous People and Local Communities	Local Authorities	Local Organisations/ Associations/ Cooperatives	National Government	Private Companies (Transport & Logistics)	Banks	Customers	Environmental NGOs
Indigenous People and Local Communities		1.a		1.b	1.c			
Local Authorities				1.d				
Local Organisations/ Associations/ Cooperatives					1.e			
National Government						1.f		1.g
Private Companies (Transport & Logistics)							1.h	1.i
Banks								
Customers								
Environmental NGOs								

Table 1.2 Conflict matrix for Brazil Nuts

Stakeholders	Indigenous People and Local Communities	Local Authorities	Local Organisations/Associations/Cooperatives	National Government	Private Companies (Transport & Logistics)	Banks	Customers	Environmental NGOs
Indigenous People and Local Communities				2.a				
Local Authorities								
Local Organisations/Associations/Cooperatives				2.b	2.c			
National Government								
Private Companies (Transport & Logistics)						2.d	2.e	2.f
Banks								
Customers								
Environmental NGOs								

Table 1.3 Conflict matrix for Pirarucu

Stakeholders	Indigenous People and Local Communities	Local Authorities	Local Organisations/Associations/Cooperatives	National Government	Private Companies (Transport & Logistics)	Banks	Customers	Environmental NGOs
Indigenous People and Local Communities				3.a	3.b			
Local Authorities			3.c		3.d			
Local Organisations/Associations/ Cooperatives							3.e	
National Government								
Private Companies (Transport & Logistics)							3.f	
Banks								
Customers								
Environmental NGOs								

1) Açai Fruit

a. Local authorities might implement regulations that do not align with traditional practices of indigenous communities.
b. Conflict arises when important decisions are made without asking local communities, those who live there can feel like they are not important. There should be a fair distribution of profits and members of this community must take part in any decision-making process.
c. Private companies may prioritise efficiency and cost-reduction, possibly compromising sustainable practices important to local communities.
d. Local authorities may have different priorities or regulations compared to national standards, leading to policy conflicts.
e. Disagreements over logistics operations and profit sharing; companies may push for more control over the supply chain. Private companies may prioritise profit and efficiency, potentially leading to disagreements over fair pricing and sustainable practices.
f. International Organisations and Donors vs Local and Regional Governments conflict arises from imposing rigorous environmental and social safeguards versus local governments' development goals. To resolve this conflict, a balance between short term economic needs and long-term sustainability is needed by means of participatory planning and flexible funding arrangements.
g. There might be disagreements between NGOs against projects that lead to deforestation or land degradation as they advocate conservation or restoration, while governments prioritise economic development. The conflict might be resolved by the utilisation of green infrastructure means, environmental impact assessments together with incorporating the objectives of conservation into plans.
h. Customers demand high-quality, sustainably sourced products, while companies seek to minimise costs, potentially compromising product quality.
i. In the ongoing conflict between the private sector which prioritises cost-effective, rapid infrastructure development and the NGOs that focus on conserving goals. To make sure business activities are eco-friendly, CSR, green certifications implantation and public-private partnerships should be promoted by firms.

2) Brazil Nuts

a. Local communities may have traditional methods and needs that conflict with broader national policies or innovation initiatives.
b. The national government may impose policies that conflict with the operational strategies and autonomy of local cooperatives.

c. Conflicts over the control of logistics and storage technologies, with companies potentially pushing for practices that locals do not support.
d. Financial institutions may be reluctant to invest in necessary infrastructure improvements, conflicting with the needs of companies and local groups.
e. Customers require nuts to be transported under conditions that prevent fungal contamination, which may conflict with companies' logistical approaches or cost-cutting measures.
f. Environmental NGOs may oppose the methods used by private companies if they are deemed harmful to the environment.

3) Pirarucu

a. Local communities may have traditional methods and needs that conflict with broader national policies or innovation initiatives. The national government may introduce fishing regulations that are not aligned with traditional fishing practices, leading to disputes.
b. Communities may resist changes that threaten traditional practices or sustainability, while companies focus on profitability and efficiency.
c. Local governance may impose regulations that restrict the operational flexibility of local organisations, affecting their ability to manage resources efficiently.
d. Conflicts may arise over compliance with environmental regulations versus the companies' logistical and operational needs.
e. Customers demanding stringent quality and sustainability standards may conflict with the capabilities or resources of local organisations.
f. Customers might demand sustainable practices, putting pressure on transport companies to adopt environmentally friendly methods, which could increase operational costs.

1.3.3 Transport challenges

The Amazon, located in the northern part of South America, is an essential source of bioeconomy products. It has a flat topography and is dotted with vast rivers, wetlands and flood plains, including the Amazon, the world's highest-flow river. Its climate is dominated by a tropical rainforest climate, with high temperatures and humidity throughout the year and annual rainfall of more than 2,000 mm. This terrain and climate facilitate the growth of bioeconomy products but also pose certain challenges for their transport. On the one hand, there is a high density of rivers, but some of them have a very low capacity and cannot be utilised, while at the same time dense waterways affect the construction of roads and railways. On the other hand, excessive temperature and humidity increase the difficulty and uncertainty of storing and transporting these perishable products. Challenges are broadly based in construction, utilisation and operation, as well as in laws and regulations (Table 1.4). More details are provided below.

Table 1.4 Transport Challenges

<table>
<tr><th colspan="2">Challenges</th><th>Road</th><th>Rail</th><th>Water</th><th>Air</th></tr>
<tr><td colspan="2" rowspan="4">Construction</td><td colspan="2">Difficulties in construction and maintenance</td><td></td><td></td></tr>
<tr><td colspan="2">High construction costs due to little infrastructure</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Lock and dyke construction</td><td></td></tr>
<tr><td></td><td></td><td>Dredging and widening of river channels</td><td></td></tr>
<tr><td rowspan="12">Utilisation and Operation</td><td rowspan="5">Mode</td><td colspan="2">Cost and effectiveness of the specialised design</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Climate challenges</td></tr>
<tr><td></td><td>Current low network density affects transport efficiency</td><td></td><td></td></tr>
<tr><td></td><td>Balance between frequency and operating costs</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Limited capacity and functionality</td><td></td></tr>
<tr><td rowspan="2">Facility</td><td></td><td colspan="3">Lack of handling equipment and storage facilities at train stations</td></tr>
<tr><td></td><td></td><td>Port adaption and resilience</td><td></td></tr>
<tr><td rowspan="3">Technology</td><td>Lack of real-time information</td><td></td><td></td><td></td></tr>
<tr><td>Low map accuracy and precision</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Insufficient navigation equipment</td><td></td></tr>
<tr><td rowspan="2">Personnel</td><td>Inexperienced drivers</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Engagement of indigenous people</td><td></td></tr>
</table>

Laws and Regulations	**Intra-region**	Strict environment conservation requirements			
		Avoiding the destruction of Aboriginal communities			
				Security risks and regulations	
	Inter-region			Long customs clearance process deteriorates the quality of products	

1) Construction

a. Difficulties in construction and maintenance:

There are many rivers and wetlands in the Amazon, making road construction technically difficult. And the climate is humid and rainy, with frequent floods and mudslides, and roads require special design and maintenance.

Such difficulties are similar to roads and motorways, but worth noting the role of soil. Very high rainfall in the Amazon region leads to soil instability, which is a major test for railway infrastructure. And complex terrain and water networks add to the difficulty of route planning, with the need to avoid rivers, wetlands and forest reserves.

b. High construction costs due to little infrastructure:

It is difficult to transport construction materials and equipment in areas where there is a lack of infrastructure, which makes construction more challenging and costly.

c. Lock and dyke construction:

In order to overcome challenges such as changes in water levels and river flows; locks and dikes may need to be constructed to improve the safety and efficiency of ship movement.

d. Dredging and widening of river channels:

Sufficient depth and width of river channels are required to accommodate the passage of vessels and may therefore require river dredging and widening projects. If they are difficult to implement, as in the case of channels in the forest, it is likely to result in low transport capacity.

2) Utilisation and operation

a. Cost and effectiveness of the specialised design (e.g., refrigeration and dehumidification):

These bioeconomy products usually have high requirements for the transport environment, such as low temperature and dryness, without which their quality cannot be ensured during transport. Equipment and technology require a significant investment of money, and sometimes the effectiveness is not guaranteed.

For trains, in addition to the need to design rolling stock that can be adapted to different types of products (e.g., refrigeration), specialised loading and unloading equipment and infrastructure are required to handle cargo efficiently and safely.

b. Climate challenges:

Water levels in the Amazon basin can vary significantly from season to season, as well as climatic extremes such as floods and droughts, which can affect the capacity and safety of waterway transport, and measures need to be taken to address these climate challenges. Such challenges are similar to air transport. There is frequent rainfall, thunderstorms and other inclement weather in the Amazon, which may affect the normal take-off and landing of aircraft, resulting in flight delays or cancellations.

c. Current low railway density affects transport efficiency:

   In the Brazilian Amazon, for example, current railway density is low (Fig 1), with inadequate connectivity and coverage. Transport by rail would face inefficiencies or high construction costs.

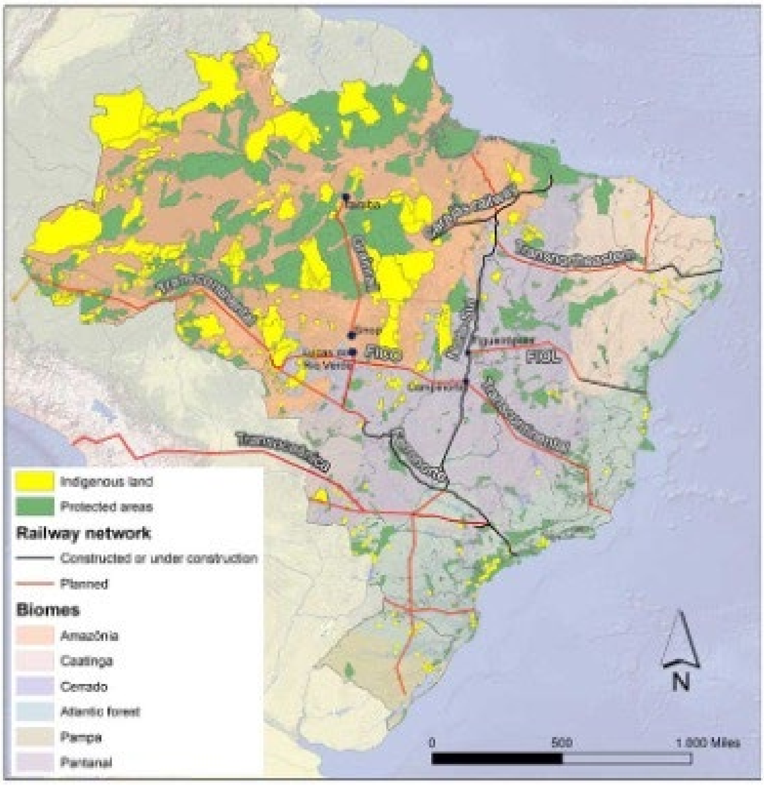

Fig 1.1 A map of major proposed and existing Brazilian railways

d. Balance between frequency and operating costs:

   Bioeconomy products often require high-frequency transport and efficient scheduling to ensure freshness and market availability. But this can lead to increased operating costs.

e. Limited capacity and functionality:

   In some regions, due to waterway conditions and economic levels, only primitive boats can be used (Fig 1.2), which does not guarantee transport efficiency and product quality.

Fig 1.2 Açai berry collection canoes

f. Lack of handling equipment and storage facilities:
Due to the characteristics of bioeconomy products, these products require specialised handling equipment and temporary storage facilities at the train station, ports and airports, such as refrigerated warehouses, heavy duty cranes, etc.

g. Port adaption and resilience:
Hydrographic conditions in the Amazon region are complex and variable, and ports may face problems such as changes in water levels and siltation, affecting the access of vessels and the loading and unloading of products.

h. Lack of real-time information:
The lack of stable mobile communication networks in many remote areas makes it difficult for navigation equipment to obtain real-time data updates, affecting the accuracy and reliability of navigation. Moreover, the monitoring of fleet location and product condition is impractical in this case, increasing the difficulty of management

i. Low map accuracy and precision:
Inaccurate or incomplete map data for many remote areas due to geographical and socio-economic reasons (e.g., excessive vegetation cover).

j. Insufficient navigation equipment:
The environment in the Amazon basin is complex and varied, but some vessels are not equipped with advanced navigation and communication equipment. As well, navigational facilities such as navigational signs, beacons and channel buoys in the waterways may be insufficient or inadequate. As a result, the safety of vessel navigation cannot be ensured.

k. Inexperienced drivers:
Driving in complex terrain and road conditions requires highly specialised skills. Many drivers may lack the necessary training.

l. Engagement of indigenous people:

Part of the collection the bioeconomic products is done by indigenous people, due to their unique growing conditions, and then are transported to the local markets by water. Therefore, the training and management of locals and the protection of their rights and interests have become a challenge.

3) Laws and regulations

a. Strict environment conservation requirements:

The Amazon Basin has large areas of primary forest and ecosystems with strict regulations and policies for environmental protection. Transport activities may be restricted and require compliance with environmental regulations. In addition, large-scale construction projects in the Amazon require an exhaustive Environmental Impact Assessment (EIA) to ensure that the project does not cause irreversible damage to the local ecosystem. This is often a time-consuming and expensive process.

b. Avoiding the destruction of Aboriginal communities:

The land rights and cultural traditions of the indigenous people need to be respected and protected, and the impacts of transport activities need to be fully assessed and negotiated.

c. Security risks and regulations:

Vessel operations in the Amazon carry certain security risks (e.g., smuggling and drug trade) that require effective security management regulations to safeguard crews and cargo.

d. Long customs clearance process deteriorates the quality of products:

If cross-border transport is involved, there is a need to comply with international trade regulations and customs rules, including laws and regulations on import and export procedures, duties and taxes. Sometimes the customs clearance process takes a long time.

2. Methodology

2.1 Analysis tools

Microsoft Excel, QGIS and Jupyter Notebook are the primary analysis tools used in our project. Excel is a spreadsheet software developed by Microsoft with powerful features for data processing, analysis and visualisation. In our project, Microsoft Excel is mainly employed for production forecasting and criteria quantification. In addition, most inputs and outputs to the code used for transport strategy modelling are in .xlsx format files.

The formulation and evaluation of transport strategies for bioeconomy products in the Amazon region is highly spatially relevant. QGIS is an open-source Geographic Information System (GIS) software for viewing, editing, and analysing geospatial data. In our project, Brazilian waterways, roads and highways and railways are imported into QGIS in .shp file format for spatial analysis and OD matrix generation. Data visualisation relies on QGIS as well, such as visualisation for predicted production and the preferred transport strategy.

In the modelling section, the codes are compiled based on Python and run using Jupyter Notebook. Jupyter Notebook is an open-source web-based application for creating and sharing documents containing code, equations, visualisations and narrative text. And PuLP is a Python library designed to solve linear programming problems, which we use to develop transport strategies efficiently. This is explained in more detail in a later section.

2.2 Data collection and processing methods

2.2.1 Source of Data

The data required for the project consists of the following: firstly, the production and origin of the three products. Secondly, information on road, waterway and railway connections between towns and cities, which OD-Matrix needs to be mapped against, and lastly, ports or airports that can be used for export, where the coordinates of potential ports and airports need to be known, as well as the types of goods they mainly handle.

1) Production Data

Based on the report of Bioeconomy Products in the Amazon Region from World Bank, Data were collected from Brazilian government websites such as IBAMA, IBGE and other official NGO websites. Many studies and literature can also pinpoint these data sources more precisely.

Production data for Açai Fruit and Brazil Nuts is available directly from the IBGE website and contains production origin and value data from 2000 to 2016, and the year of 2020 to 2022.

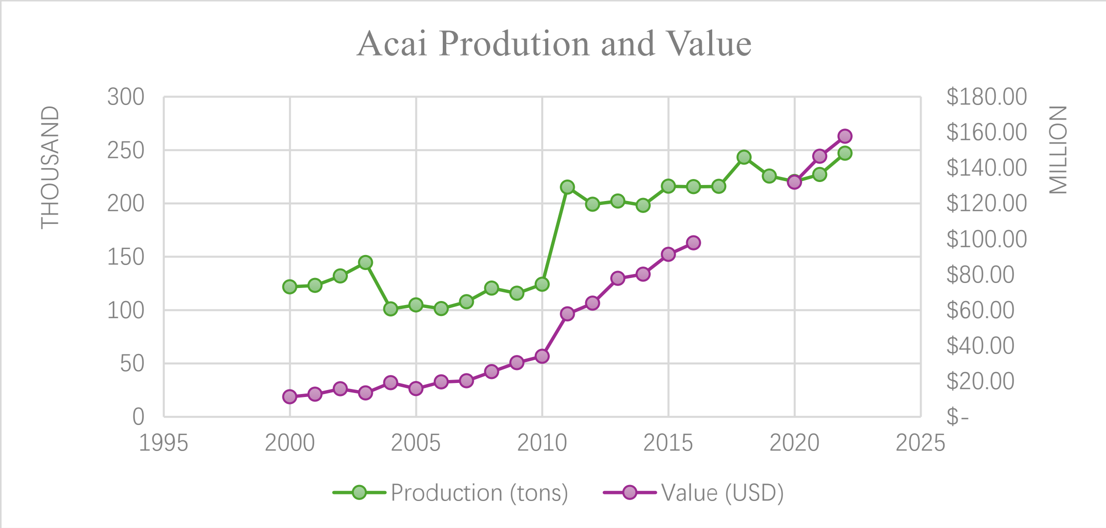

Fig 2.1 Açai Production and Value

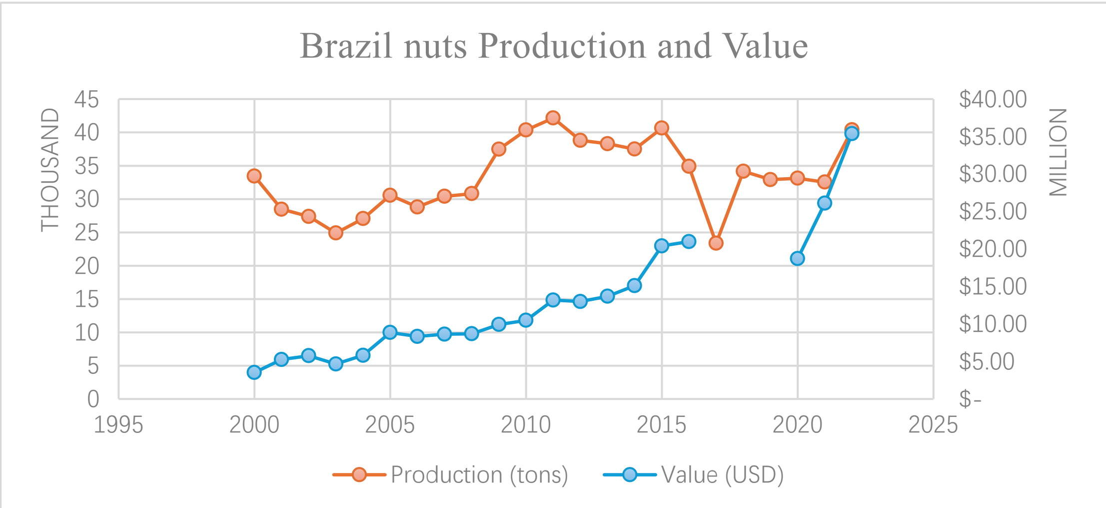

Fig 2.2 Brazil Nuts Production and Value

Fig 2.1 represents the production and market value trends for Açai over the same period, from 2000 to 2022. For production trend, represented by the green line, shows an overall increasing trend. Starting from 2000, there is a steady rise in production until the mid-2000s, followed by a slight decline. Around 2010, there is a significant increase in production, which then stabilises with minor fluctuations, maintaining a prominent level through to 2022.

The value of Açai, depicted by the blue line, follows a similar upward trajectory. From 2000, the value remains relatively stable with a gradual increase, aligning with the production trends. Post-2010, there is a sharp increase in value, indicating a positive market response to the increased production. The value continues to rise, showing minor fluctuations but maintaining an upward trend through to 2023.

The Fig 2.2 illustrates the trends in Brazil nuts production and their corresponding market value over a span of approximately 20 years, from 2000 to 2023. The production of Brazil nut is represented by the orange line. Starting from 2000, there is a noticeable decline in production until around the early 2000s. From the mid-2000s, production shows some fluctuations but maintains a relatively stable trend until a significant drop around 2020. Post-2020, there is a marked increase in production, peaking towards 2022. The value of Brazil nuts, measured in USD, is depicted by the yellow line. Initially, there is a gradual increase in value from 1995, which remains relatively stable until the mid-2000s. From around 2005, the value exhibits a steady upward trend with some fluctuations, aligning with the changes in production. Notably, after 2020, there is a sharp increase in value, reaching its highest point towards 2025, indicating a strong market response to the changes in production volumes.

At the same time, specific production data were obtained for each town, labelled with the town's latitude and longitude coordinates, as well as the percentage of production value, which facilitated the subsequent processing of the data.

The data related to pirarucu was considered one of the main challenges in the process of data collection, with fewer relevant studies and data. Using Conab's report, the relevant production data was found on IBAMA's website, and production data was collected over a 10-year period from 2011 to 2021.

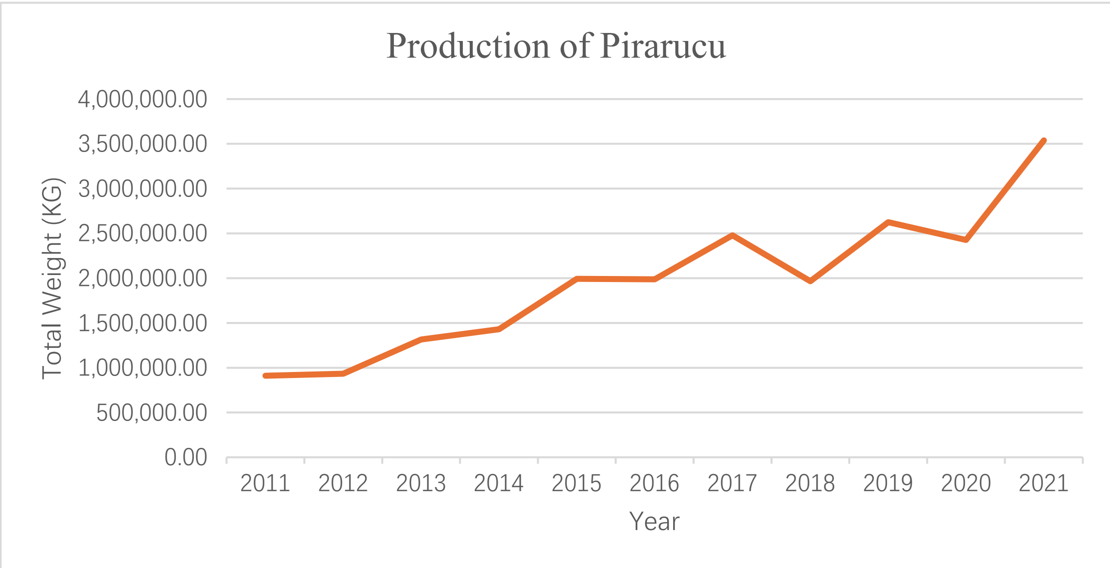

Fig 2.3 Pirarucu Production

For information on the production site, the local organisation COLETIVO DO PIRARUCU has given the appropriate information, with 17 towns, several nature reserves and local communities labelled as places of origin.

Fig 2.4 Production site of pirarucu

Once enough information on yields and origins has been obtained, it is essential to standardise the data so that subsequent analyses and modelling require the use of the same year of data, and to ensure that the range of data is consistent. Specific data cleaning and processing methods will be introduced in 2.2.2.

2) Network Data

Road network information is required for the establishment of supply chain networks, and for the construction of the OD-Matrix between towns and cities, motorway network data from the Brazilian government website for the year 2014 were used. Visualisation of the road network is possible with QGIS.

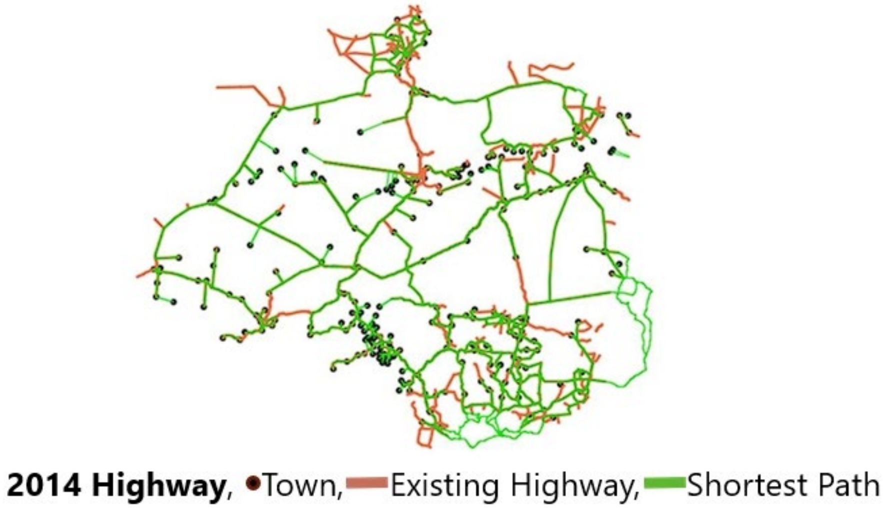

Fig 2.5 Highway map

The OD-Matrix of the waterway network is realised by QGIS combined with high-precision maps.

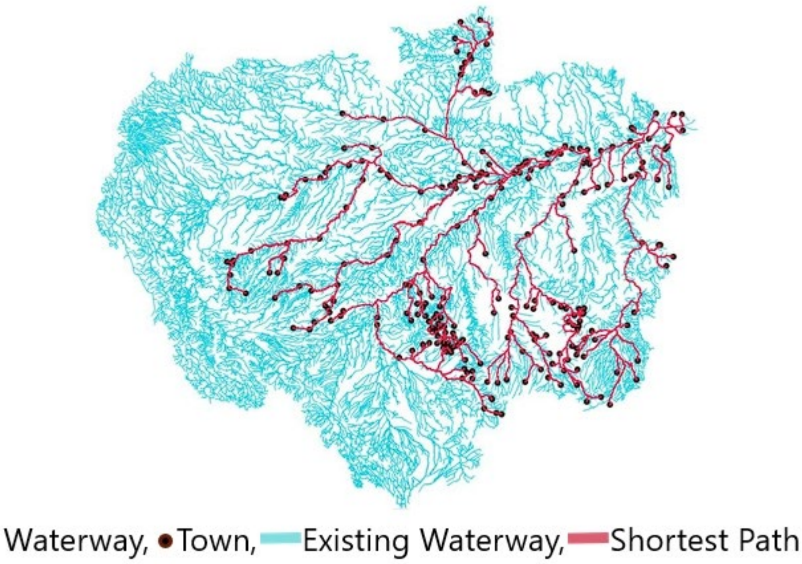

Fig 2.6 Waterway map

3) Ports and Airports Data

Ports and airports are important transit points for exports, so it is important to select the appropriate node as the final node of the supply chain based on the main products handled by the ports and airports. Information on Brazil's major airports and ports is collected, including latitude and longitude coordinates, product type and capacity.

Table2.1 Ports and Airports information

Type	Name	Latitude	Longitude	Product Type
Port	Porto de Santos	-23.97	-46.30	bulk cargo (grain and sugar)
	Porto de Paranaguá	-25.52	-48.51	grain, sugar and coffee
	Porto de Rio Grande	-32.11	-52.10	grain and meat
	Porto de Itaqui	-2.56	-44.37	grain
	Porto de Suape	-8.39	-34.98	liquid and solid bulk
	Porto de Vitória	-20.32	-40.34	grain, sugar and coffee
	Porto de Aratu	-12.78	-38.52	liquid bulk (biofuels and fertilisers)
	Porto de Manaus	-3.14	-60.02	products from the Amazon
	Porto de Itapoá	-26.12	-48.61	bulk agricultural products
	Porto de São Francisco do Sul	-26.24	-48.63	grain and timber
	Porto de São Luís	-2.56	-44.37	grain
	Porto de Itaguaí	-22.93	-43.82	grain and biofuels
Airport	BRGIG - Internacional de Galeao	-22.81	-43.25	
	Santarem	-2.42	-54.79	
	Monte Dourado Airport	-0.89	-52.60	
	Val De Cans Intl (Belém)	-1.38	-48.48	
	Cachimbo	-9.33	-54.97	
	Internacional de Campinas/Viracopos	-23.01	-47.14	
	Internacional de Sao Paulo - Guarulhos	-23.43	-46.48	
	Internacional Eduardo Gomes	-3.03	-60.05	
	Altamira	-3.25	-52.25	
	Pinto Martins – Fortaleza International Airport	-3.78	-38.53	Fruit and Fish

The bolded ports and airports are potential candidates because they handle agricultural products.

2.2.2 Data Processing Method

1) Forecasting of Production

Due to the variability of the yield information obtained during the data collection phase, it is essential to pre-process the data and use the same years of data. Considering also that yields in the coming years will be considered when evaluating the potential development of the strategy, future projections based on historical yields will be made in this section.

To have insights about the future production of bioeconomy goods, we have investigated the data of IBGE website. This source only provided data of production between years 2000 to 2022 (as explained in 2.2.1 Source of Data). We decided to use the Holt-Winter's seasonal method (referred to our Freight and Logistics Transport's Master course) for the Açaí production and the Brazil nuts production. We have made a forecast from 2023 to 2050 based on the 2000 to 2022 data.

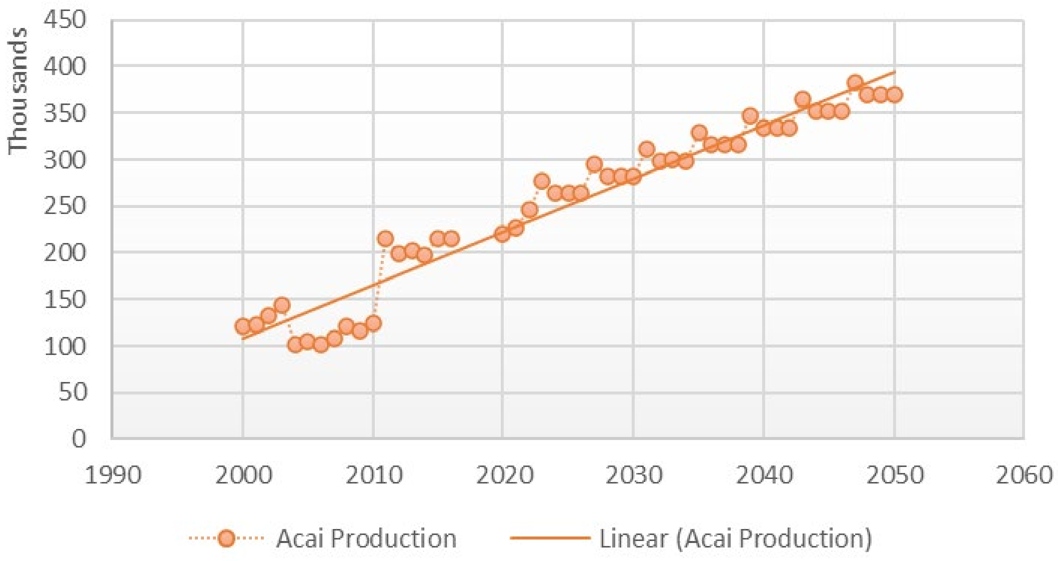

Fig 2.7 Açai forecast production with Holt-Winter's seasonal method

We decided to use a seasonal factor of 4 for both products. The output gave us that the Açai production will grow from around 250 thousand tons in 2022 to nearly 350 thousand tons in 2050. Also, the production of Brazil nuts will increase from more than 40 thousand tons in 2022 to more than 80 thousand tons in 2050. So, for both products, this forecast expects that the production of goods will double in almost thirty years.

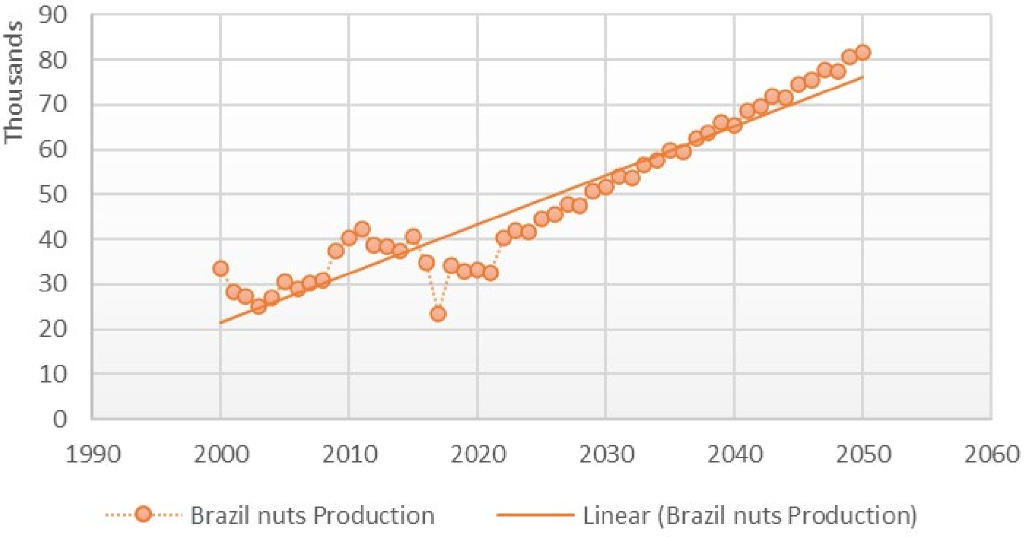

Fig 2.8 Brazil nuts forecast production with Holt-Winter's seasonal method

For Pirarucu, because of the different source of data (2.2.1) we decided to use a different method of forecasting.

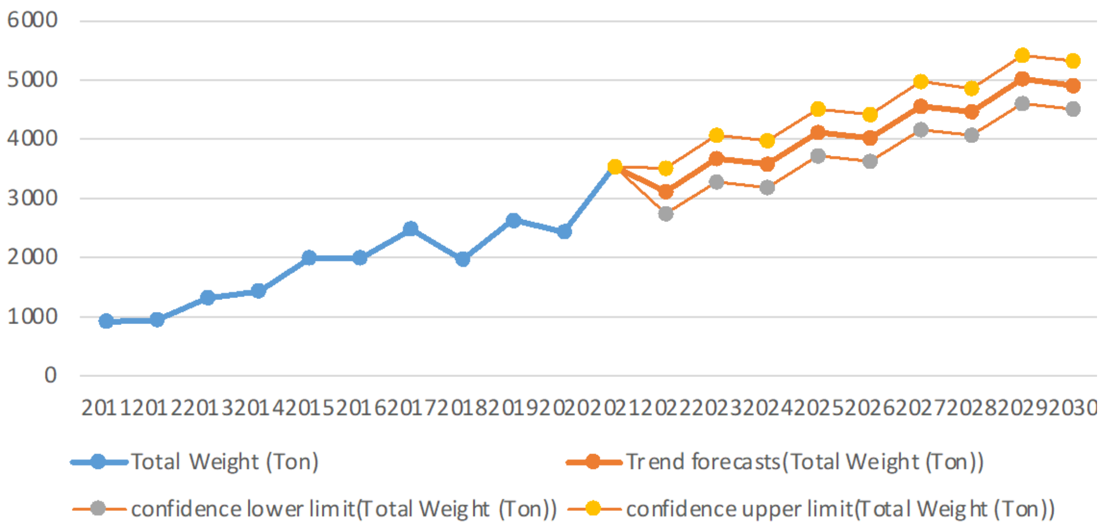

Fig 2.9 Pirarucu forecast production with Excel methods

The chart is an Excel-generated forecast of Pirarucu production, showing historical data from 2011 to 2020 and projected data from 2021 to 2030. Here is a breakdown of its components and results:

The Blue Line represents the historical and actual production data from 2011 to 2020. Shows a generally increasing trend with some fluctuations. Trend Forecasts (Orange Line) indicates the predicted production values from 2021 to 2030 based on historical trends. Continues the increasing trend observed in the historical data. The production is expected to continue growing, reaching between approximately 4500 and 6000 tons by 2030. The forecasted trend line suggests steady growth, though the confidence intervals widen over time, indicating increasing uncertainty further into the future.

2) QGIS and QNEAT3

The geographical data could be found in various formats, the Shapefile stand out for the storage of the spatial data type. Quantum Geographic Information System or QGIS software is a free geographical analysis software that allows for Shapefiles processing. The QGIS Network Analysis Toolbox 3 or QNEAT3 plugin allows QGIS to process the shortest distance between nodes along the route network producing the output in the form of the origin and destination (OD) matrix. The plugin's ellipsoidal calculation greatly improves the distance calculation accuracy, especially for large regions like the Amazon rainforest. However, multisource data tends to have a mismatch in map projections resulting in inaccurate alignment and distance calculation. We ensured all data layers were projected to EPSG:4326 – WGS 84 standard. Lastly, the distance calculated using the QNEAT3 between each node is a sum of the network/route distance and the shortest distance from the node to access the route. Since the proportion of access distance to the network distance is generally much smaller, the model will assume the total distance to be the distance between nodes without any mode change or geographical restrictions.

3) Mapping

Visualisation of the production distribution on a map could be a great asset in transport strategic planning. Using folium and branca.colormap libraries in Python, we could plot the location of the production sites with the colour coded according to production quantity on the world map. The input data required are latitude, longitude, and production amount for each town. The latitude and longitude data could be extracted from just the town name and state using Python's Geocoder library. With this approach, we could plot the map for the Acai fruit production sites for both past and future years. Allowing for a better understanding of the growth of the Acai supply in the region.

Acai production in Year 2050 (Tonnes)

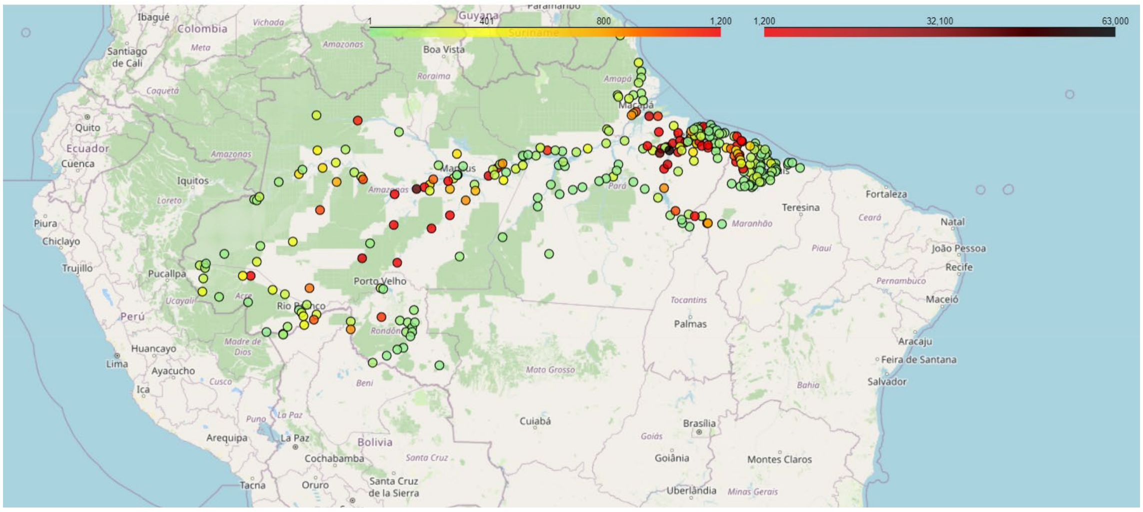

Fig 2.10 Acai production in year 2050 (Tonnes)

2.3 Transport strategies

The transport strategy comprises the strategic plan, infrastructure requirements, and governance for the project. The main challenges in strategy development are implementation feasibility and conflict with stakeholders. The methodology we employ is the convergent thinking idea revised by (Gabora, 2018) where we narrow down options toward the main goal. Initially, 5 main extreme goals were chosen: Minimised Cost, Minimised Transit Time, Minimised Environmental Impact, Minimised Initial Implementation Time, and Maximised Local Benefits. Each of these aims stemmed from various aspects of the project goal.

Minimised cost aims to provide the region with a complete supply chain with minimal requirements for funding. Minimised Transit Time aims to tackle the high perishability of bioeconomy products by reducing transportation time. Minimised Environmental Impact directly related to the project's critical requirement of zero deforestation. Minimised Initial Implementation Time aims to establish the logistic chain as fast as possible to generate economic benefit sooner. Lastly, Maximised Local Benefits aims to increase the involvement of the indigenous and residents in the supply chain, providing economic benefits directly to the locals.

Each of the strategies was then populated with 10 consideration characteristics which could be categorised into infrastructure, operation, and governance. Each category describes the suitable choice to achieve the main goal within each echelon. Mode type and transport infrastructures consider the type of vehicle and route respectively for both existing and potential choices. Inter-modal considers the type of transit port (wet port, dry port) which will correspond to the loading process selection with the options of lift on/off or roll on/off. The operational aspect is captured in the operational structure and containment type component where frequency, size, and container type of shipments are decided. The warehouse placement component determines the placement strategy between localised or centralised. The governance aspect is captured in the organisation structure and infrastructure ownership consideration which determine the level of managing power between private and government as well as the investor for infrastructure construction. Lastly the energy distribution considerations would explore the type, potential sources, and source location for the required type of energy and its distribution.

From the 5 main strategies, components that contradict the critical goals are removed while similar aspects are combined for a more holistic strategy. The sustainable alternative modes and infrastructure from the minimised environmental impact are moved to be the future goal while the multi-purpose vehicle utilisation from the maximise local benefit strategy is kept as potential vehicle utilisation during the bioeconomy low season. The idea of only utilising existing waterways, roads, and railways from the minimised initial implementation time is kept as it is in line with the critical goal. Therefore the 2 main strategies moving forward would be to minimise cost and minimise transit time with the consideration of the beneficial aspect of the other 3 strategies. Further optimisation is done by considering the combined time and cost savings which would be implemented later in the modelling stage.

2.4 Research methodology

This section reviews the literature on criteria used in assessing transportation strategies of bio-economy products, such as energy efficiency, digital access, construction and maintenance cost, potential for volume growth, job creation, environmental impact, sensitivity to climate events, and safety & security. Each of these factors is essential to guarantee that transportation methods are not only efficient and cost-effective but also adaptable to the specific challenges faced in Amazon's diverse and frequently extreme environments and environmentally sustainable. The quantification of this criteria will follow in the next section.

2.4.1 Energy efficiency

Energy efficiency is the total energy required to transport a bioeconomy product over a given distance, and its importance in achieving sustainable transport in the Amazon cannot be exaggerated. If electrified modes of transport are applied, the carbon emissions will decrease compared to the traditional fossil fuel-powered forms, e.g., a motor canoe powered by renewable energy sources. Furthermore, renewable energy sources such as solar or biofuel can help maintain the environment and promote sustainability. In urban habitats worldwide, there is a call for renewable power sources to counteract global warming, as demonstrated by Grimm et al., 2008. Thus, the principle applies even in the Amazonian bioeconomy by examining the use of solar power or biofuels for urban areas, which minimises the negative impacts of transportation logistics. Therefore, improving energy efficiency reduces greenhouse gas emissions and fuel consumption, aiming to attain sustainable development objectives. Accordingly, our goal is to evaluate different strategies necessitating the calculation of a total energy efficiency score for each approach based on three factors:

a. Energy Efficiency (kWh per ton-km): measures the energy needed to transport one ton of goods over one km.
b. Fuel efficiency (L per ton-km): measures the fuel required to transport one ton of goods over one km.
c. Carbon emissions (kg of CO2 per ton-km): measure the quantity of CO2 emitted to transport one ton of product over one km.

Hence, for each type of transportation mode, we got the values for each factor and calculated a total energy efficiency based on a weighting of 30% for energy consumption, 30% for fuel efficiency, and 40% for carbon emissions. We assign carbon efficiency a slightly higher weight than energy consumption and fuel efficiency because lowering carbon emissions is essential to mitigate climate change, which is an urgent threat to human health and world ecosystems. So, reducing carbon emissions is essential to attain sustainable development because it also addresses air pollution and conforms to stringent environmental laws. Based on our models, for each strategy, we got the total number for each vehicle types required to transport the products, and we know the energy efficiency of each vehicle type. Hence, the total energy efficiency score can be calculated for each strategy by multiplying the total number of vehicle type by its corresponding energy efficiency and summing over all the vehicle types and we divide by the total number of vehicles to get a score over 100.

2.4.2 Digital Access

Digital infrastructure is vital in optimising logistics. The low connectivity levels prevailing at Amazon impede real-time tracking and data accuracy. One possible manner entails improving digital access, such as expanding network coverage to remote areas, thus allowing real-time monitoring of transport conditions and fleet management. It has been shown that improving digital connections boosts logistical efficiency and lowers operating expenses. For instance, integrating blockchain with IoT might enhance supply chain capabilities, increase automation, and enhance decision-making, contributing to increased sustainability and performance (McKinsey, 2023).

Digital access is the extent and quality of digital connection required for efficient coordination, monitoring and optimisation of transport operations in logistics supply chain management. Improved digital access helps in enhancing logistical efficiency, reduces operational costs, and supports economic growth. We assumed that digital access improvement would be more valuable when a factory is built in an unconnected town compared to an urban-connected one. Based on our models for each strategy, we know the factory locations, and with an interactive map shown in Fig 2.11, we get the coverage in each town. The improvement is assessed incrementally with a factor of 0.2. If the facility is built in an area without coverage the factor will be 1, going down to 0 if the area has 5G coverage. For each strategy, we calculate the average digital access improvement over all the town to conclude the best one based on digital access.

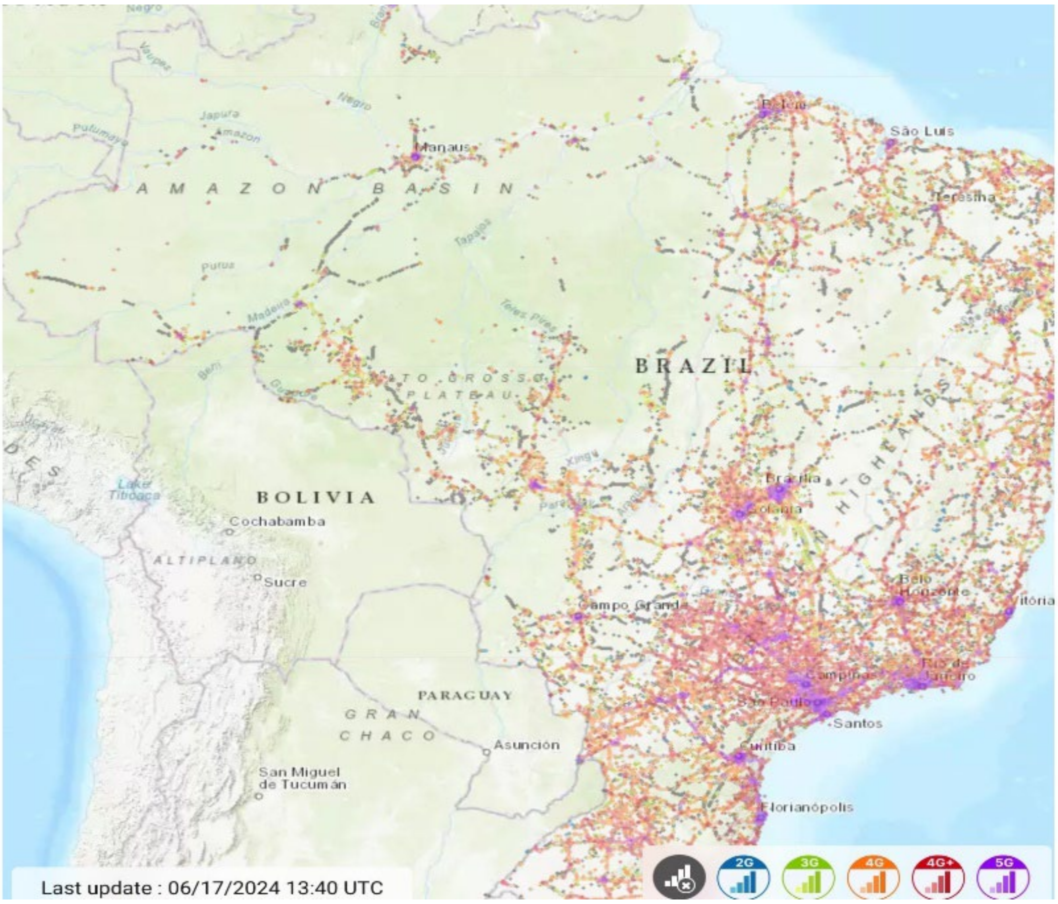

Fig 2.11 Network Coverage in the Amazon

2.4.3 Construction and Maintenance Cost

Infrastructure development in the Amazon is expensive because of the challenging terrain and weather conditions (Fearnside, 2005). For instance, constructing roads or railways needs significant resources to counteract soil instability and recurrent floods. Ways which are cheaper, such as using rivers that already exist for better waterway transportation have been proven to require less money while ensuring that the products are transported efficiently. Maintenance costs must also account for the durability of infrastructure against climate-induced damage.

To measure the cost of building and maintaining equipment, NPV (Net present value) is used more visually in the calculation of this indicator, the main step being to count all those future cash flows to the present day, and then add them together. Due to the current lack of clarity on future project revenues, all investment cash flows were converted to positive values to compare the cash flows of the various scenarios more visually.

Table 2.2 Example Cash Flow Calculations and Results

Year	0	1	2	3	…	10
Cash flow	4,745,000.00	45,000.00	45,000.00	45,000.00	...	45,000.00
Discounted cash flow	4,745,000.00	42,857.14	40,816.33	38,872.69	…	27,626.10
Total discounted cash flow	9,490,000.00	85,714.29	81,632.65	77,745.38	…	55,252.19
Total	9,490,000.00	9,575,714.29	9,657,346.94	9,735,092.32		10,184,956.14

The table above shows an example of the present value of the total investment required over a 10-year period for the 2 facilities. The specific calculation formula and input parameters are as follows:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{2.1}$$

Where C_t is the cash flow in year t, r is the discount rate, and n is the range of project. Knowing the investment required for the construction of the warehouse, the annual maintenance costs, and the number of warehouses in the program, the corresponding NPV can be calculated.

2.4.4 Potential Volume Growth

To support the expanding bioeconomy, the transport infrastructure must be scalable. Waterways should have a substantial demand for an increase in their volume, and this can be done by improving capacity and reliability through investments that increase locks, dikes, and dredging. Products like açai and pirarucu should be transported with high frequency, so the system should be scalable enough to meet market demand without reducing the quality (Merry et al., 2009).

To assess the scalability of a strategy, it is necessary to compare the projected value of production with the total capacity of the number of warehouses selected for the current strategy, and to check whether it will be able to cope with growth over the next few years. Assuming the project's growth potential needs to be assessed between now and 2030, the forecast yields of the three bio-economy products for the corresponding years can be obtained in 2.2.2.

Table 2.3 Forecasted value of production for 3 products – Year 2030

	Year	Yearly Production	Daily Production
Forecast Value for Açai Fruit	2030	281482.00	771.18
Forecast Value for Brazil Nuts	2030	51640.00	141.48
Forecast Value for Pirarucu	2030	4912.00	13.46

The average daily handling capacity of a single warehouse is known to be 150 units. It is therefore possible to calculate the difference between the predicted average daily value of production and the average daily value handled in the warehouse. For example:

Table 2.4 Example result of potential growth for strategy 1 – minimise time

Strategy 1 - Minimise time	
Factory Number	17
Daily process capacity	2550
Gap with 2030	1623.88

Table 2.5 Example result of potential growth for strategy 1 – minimise cost

Strategy 1 - Minimise Cost	
Factory Number	2
Daily process capacity	300
Gap with 2030	-626.12

After this the potential growth value of different strategies can be assigned a score based on the gap values of all strategies

2.4.5 Job Creation

Transportation infrastructure development can lead to many job opportunities, especially for local communities. For instance, waterway logistics improvement creates direct and indirect job openings. This reflects on the bioeconomy sector in terms of more people employed in harvesting, processing, and logistic support for such products as açai and Brazil nuts, hence improving the lives of the indigenous and local populations. According to the WRI article, employing a zero-deforestation strategy can create 312,000 additional jobs and substantially enhance the GDP of Brazil; this backs the idea that such projects might lead to significant job increases (WRI, 2023).

The number of direct jobs is calculated based on the number of factories and vehicles each strategy requires. We assume each factory employs 130 workers (SuperFrio, 2019) and for each vehicle type, we consider 3 workers per vehicle to account for drivers and maintenance staff.

We use an input-output economic multiplier related to changes to the economy in the Amazonian region to calculate the indirect and induced jobs created. Demski states that using the type of SAM (Social Accounting matrix) multiplier, we can account for direct, indirect, and induced effects using data representative of how households and government institutions spend their earnings in the economy after taxes, personal savings, and so on.

Based on similar studies in the Amazonian region, we consider a Multiplier of 1.5 to 2.5. we can then calculate indirect and induced jobs, (Farmers in the Amazon could earn 9 times more and prevent ecosystem collapse 2021) (Latam, 2023)

2.4.6 Environmental Impact

There is a focus on reducing the effects on the environment in the Amazon basin. The protection of biodiversity and the prevention of deforestation should be given importance by sustainable transport approaches (Moutinho et says 2016). Pollution is significantly reduced using electric modes of transportation which are driven by renewable energy sources. The Amazon's gentle ecosystems can especially benefit from minimal ecosystemic disruption using waterways for transport. Safety of regional biodiversity entails implementing tight environmental laws, as well as carrying out comprehensive EIAs.

We based our environmental criteria on the amount of direct CO2 emissions per load produced by the strategy, focusing on the factories and vehicle emissions.

Table 2.6 CO2 emission factors

Factories						
No of Factories	2	18	10	3	30	3
CO2 Emissions						
Ferry with Freezer	60g CO2/ton-km (Global Container Shipping Trade Lane emissions 2020)					
Mid-Size ferry	18g CO2/ton-km (Environmental performance: Comparison of CO2 emissions by different modes 2022)					
Large ferry	15g CO2/ton-km (Specific CO2 emissions per ton-km and mode of transport in Europe 2017)					
River Barges	30g CO2/ton-km (ECSA 2020)					
Refrigerator truck	100g CO2/ ton-km (ECSA 2020)					
Normal Truck	80 g CO2/ton -km (ECSA 2020)					

2.4.7 Sensitivity to climate change

The climate of the Amazon makes it difficult to move around. As a result, moving goods in the area is tough. For example, floods, droughts, and other weather events may interfere with the movement of goods in this area and will disrupt logistics operations. Consistent transport conditions are essential, particularly for perishable products such as açai and pirarucu, to ensure that the quality is maintained even with climate changes (Arima et al., 2005).

We based our study on an IBGE research and map (IBGE, 2014). The study considers the rainy season, dry season, annual precipitation, and concentration index over the states of the Amazon. According to these factors, different classes are set up and the Amazon region is entirely defined by each class. In figure 2.12 we can see a part of the map.

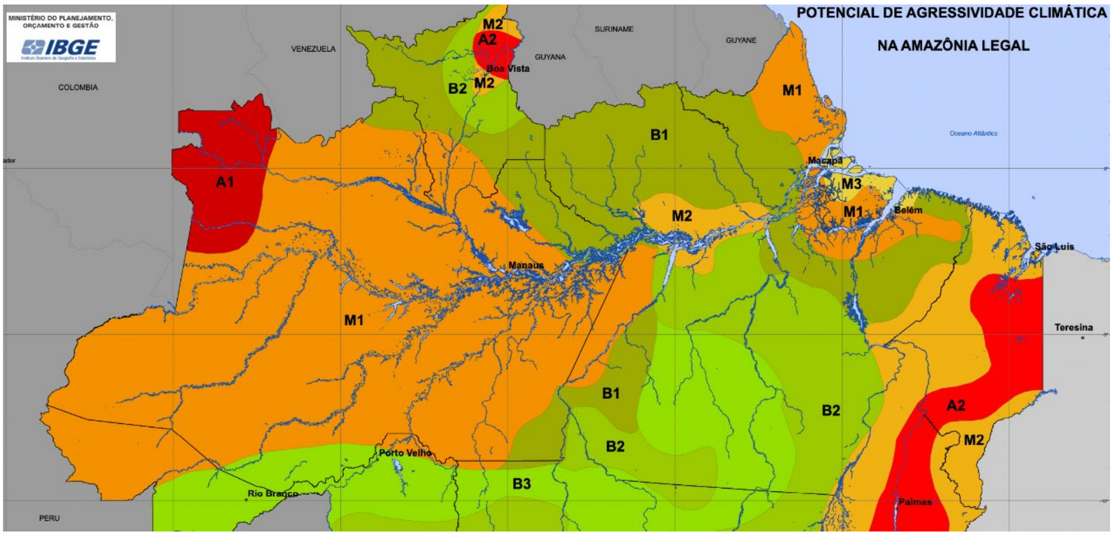

Fig 2.12 The potential for climate aggression in Amazonian law

Then, we have made a translation of the IBGE table:

Table 2.7 Translation of the IBGE map legend

CLASSES	FACTOR	CONCENTRATION INDEX (%)	RAINY MONTHS	DRY MONTHS	ANNUAL AVERAGE PRECIPITATION (mm)
HIGH (H)	1	< 35	12	0	> 3000
	2	> 55	5 to 6	5 to 6	1000 to 2750
MEDIUM (M)	1	< 35 and 35 to 45	9 to 12	0 to 2	2250 to 3000
	2	> 55 and 45 to 55	5 to 6	4 to 5	1250 to 2000

	3	45 to 55	7 to 8	3	> 3000
LOW (L)	1	35 to 45 and 45 to 55	8	2 to 3	1750 to 2500
	2	45 to 55	7	2 to 3	1500 to 2250
	3	45 to 55	7	3 to 4	1750 to 2250

In our methodology, if a location is in class High 1 (Alta 1 in Portuguese), we assume that this zone is the most sensitive to climate change due to the high climate aggressiveness. Indeed, a high climate aggressiveness means that the zone is subject to high yearly precipitation and drought (dry months factor) that can lead to disruptions of the transport routes or even disruptions at the production site. So, a high climate aggressiveness means a high climate danger resulting to a high sensitivity to climate events. That is why we have set up a Climate Sensitivity Score (CSS), that highlights the sensitivity of climate events. A high CSS score indicates that the region is less sensitive to climate events. We consider that no sensitivity to climate events reflects a high resilience which is a positive aspect to ensure the transport logistics of goods (Boulton, C.A., Lenton, T.M. & Boers, N. 2022)

To do so, we have set up a climate danger score. We have considered the legal Amazon states, and we measured the percentage of each class within each state. Then, to get the climate danger score, we have considered that a high class has more impact than a low class. Given the percentage of classes within a state, we got a weighting average for this state. With a factor of 9 for class High 1, factor of 8 for class High 2, factor of 7 for class Medium 3, going decremental to factor of 2 for class Low 3 (No factor equals 1). This weighting average is the climate danger score. More aggressiveness leads to more sensitivity, the CSS of a state equals to 100 minus climate danger score of the state. All the results are summarised in table 2.8.

Table 2.8 Calculation for Climate Sensitivity Score

State	Code	H1	H2	M1	M2	M3	L1	L2	L3	Climate danger	CSS
Acre	AC			60%					40%	11.4	**88.6**
Amazonas	AM	10%		70%			10%		10%	14.5	**85.5**
Amapá	AP			50%			50%			12.5	**87.5**
Maranhão	MA		40%		60%					15.5	**84.5**
Mato Grosso	MT		20%		30%			20%	30%	10.5	**89.5**
Pará	PA			10%	10%	5%	40%	20%	15%	9.2	**90.8**
Rondônia	RO			5%	10%			45%	40%	7.0	**93.0**

Roraima	RR	5%	20%	5%		60%	10%		10.9	**89.1**
Tocantins	TO	50%		50%					15.9	**84.1**

To summarise, a high score for a state indicates less sensitivity for climate events.

Then, to assess a transport strategy the methodology for this criterion will use all the routes within the strategy, their origin, destination, and the time spend on the route. Some indicators and variables to assess a transport strategy for sensitivity to climate events are as follows.

$$CSS\_AVG = AVERAGE\ (CSS\_origin, CSS\_destination) \tag{2.2}$$

$$TIME\_Index\ =\ (TIME\_SPEND\_ON\_THE\_ROUTE\ -\ MIN\_x)\ /\ (MAX\_x\ -\ MIN\_x) \tag{2.3}$$

$$CSS\_Index\ =\ 1\ -\ TIME\_Index \tag{2.4}$$

$$CSS\_SCORE\ =\ CSS\_AVG\ \times\ TIME\_Index \tag{2.5}$$

$$CSS\_Strategy\ =\ AVERAGE(CSS\_SCORE) \tag{2.6}$$

The score (e.g., CSS_origin) for origin and destination of a facility (production site, warehouse, or final port/airport) will be the score of the state the facility is located in. So, if a destination is in Amazonas, its score $CSS\_destination$ will be the score of Amazonas state. Then, we consider the time spent on the route, and we index it to a value from 0 to 1. We also consider that the more time spent on the route, the more chance there is of disruption happening. That is why we got the CSS_Index, which is the opposite of the $TIME\_Index$. We get a score for the route by multiplying the origin/destination average score by the CSS_Index time. After this, to get one final score for the strategy, we make an average of all the scores of the routes.

Finally, we end up with one final score (over 100) for one strategy.

2.4.8 Safety and Security

To avoid theft, spoilage, or breakage, products in the bioeconomy should be safely moved from place to place. One way of safeguarding valuable cargo is through robust security measures such as GPS tracking, secure packaging, and surveillance. Additionally, many studies have emphasised the need for procedural security measures to ensure the security of goods through the transportation process (Rodrigue, Comtois, & Slack, 2016). Also, to protect transportation infrastructure from vandalism, disasters, and other threats, we should ensure the longevity and reliability of the logistics network. It is, therefore, necessary to implement strategies such as surveillance systems, maintenance protocols, and disaster preparedness plans. In addition, rapid growth in digitisation rates within this industry has exposed it to all manner of risks, making it vulnerable to cyberattacks and necessitating robust cybersecurity measures (Chan et al., 2021). Moreover, the safety of workers and passengers involved in transportation is essential. We should ensure that safe working conditions prevail, providing instruction concerning procedures for using tools or materials, understanding the terrain, and setting safety protocols to prevent accidents and injuries. Hence, strict safety regulations and extensive safety training can significantly lower workplace hazards, improving the general safety of transportation operations (Tseng & Pilcher, 2017).

We based our methodology on a data analysis from Brazilian Ministry of Justice and Public Security (National Public Security Data) and more precisely on the legal Amazon region. In our models, all the factories are the same type. So, the working conditions will be the same everywhere. That is why for this criterion we only focus on criminality and crime cases.

From data of 2015 to 2024, we have chosen to focus on the biggest year in terms of Cargo theft, which is 2022 with 615 cases of cargo theft. From this year, we registered the data of Cargo theft, Apprehension for Cocaine, Apprehension for Marijuana, Cases of drug traffic, cases of firearms, cases of vehicle theft with violence ‘Roubo’ and cases of vehicle theft without violence ‘Futro’ given their state.

Table 2.9 Cases of crimes in 2022 in Amazon states

2022	Code	**Cargo theft**	Apprehension Cocain	Apprehension Marijuana	Drug Traffic	**Total drug**	**Firearm**	Roubo Vehiculo	Futro Vehiculo	**Total vehicule theft**	Occurrence	**Normalised**
Acre	AC	**0**	748	405	886	**755**	**579**	522	665	**1187**	492	**4.27%**
Amazonas	AM	**19**	5229	21569	1816	**6620**	**1582**	645	526	**1171**	2406	**20.90%**
Amapa	AP	**0**	47	131	819	**488**	**405**	344	450	**794**	326	**2.83%**
Maranhao	MA	**145**	236	1397	1627	**1233**	**2292**	482	665	**1147**	944	**8.20%**
Mato Grosso	MT	**283**	23255	8086	4289	**9790**	**2196**	565	767	**1332**	3579	**31.08%**
Para	PA	**162**	1454	1964	4894	**3448**	**3619**	303	487	**790**	1760	**15.29%**
Rondonia	RO	**0**	7742	831	1343	**2840**	**1935**	663	1040	**1703**	1398	**12.14%**
Roraima	RR	**6**	42	413	470	**351**	**283**	671	327	**998**	300	**2.61%**
Tocantins	TO	**0**	0	0	681	**375**	**570**	324	418	**742**	309	**2.68%**
	Total	**615**	**38752**	**34794**	**16825**	**25901**	**13461**	**4519**	**5345**	**9864**	11515	**100.00%**
		40%				**30%**	**15%**			**15%**		

Then, we got a generalised section for drug crimes with weight of 55% for drug traffic crimes, 25% for cocaine apprehension and 20% for marijuana apprehension (Vox, German Lopez, 2015). We also combine 'Roubo' vehicle theft and 'Futro' vehicle theft.

We have obtained a generalised crime occurrence with a weight of 40% for Cargo theft, 30% for total drug crimes, 15% for firearm cases and 15% for total vehicle theft. We then normalised this occurrence. This number is what we call the danger score. By assuming that danger score is the opposite of security score, we got the security score (SS) for each of the state of the legal Amazon.

Table 2.10 Security score of each state

State	Code	Security score
Acre	AC	95.7
Amazonas	AM	79.1
Amapá	AP	97.2
Maranhão	MA	91.8
Mato Grosso	MT	68.9
Pará	PA	84.7
Rondônia	RO	87.9
Roraima	RR	97.4
Tocantins	TO	97.3

To summarise, a high score means a high state security.

Then, to assess a transport strategy the methodology for this criterion will use all the routes within the strategy, their origin, destination, and the time spent on the route. The following process is the same as the Sensitivity to climate events criterion. Some indicators and variables to assess a transport strategy for security are as follows.

$$SS\_AVG = AVERAGE\ (S\_origin, S\_destination) \tag{2.7}$$

$$TIME\_Index = (TIME\_SPEND\_ON\_THE\_ROUTE - MIN\_x)\ /\ (MAX\_x - MIN\_x) \tag{2.8}$$

$$SS\_Index = 1 - TIME\_Index \tag{2.9}$$

$$SS\_SCORE = SS\_AVG * TIME\_Index \tag{2.10}$$

$$SS\_Strategy = AVERAGE(SS\_SCORE) \tag{2.11}$$

The score (e.g., S_origin) for origin and destination of a facility (production site, warehouse, or final port/airport) will be the score of the state the facility is located in. So, if a destination is in Amazonas, its score $S\_destination$ will be the score of Amazonas state for example. Then, we consider the time spent on the route, and we index it to a value from 0 to 1. We also consider that the more time spent on the route, the more chance there is of disruption happening. That is why we got the SS_Index, which is the opposite of the $TIME\_Index$. We get a score for the route by multiplying the origin/destination average score by the SS_Index time. After this, to get one final score for the strategy, we make an average of all the scores of the routes.

Finally, we end up with one final score (over 100) for one strategy.

2.4.9 Criteria weight and importance

To assess a transport strategy, our framework gives us a score out of 100 for each of our eight criteria. Our aim is to have an overall score for a holistic analysis to then compare different transport strategies and pick-up the best option for our study.

To do so, we need to allocate importance to each of the criteria. Not all the criteria weigh the same importance. We based our methodology on existing analysis (Elita Amrina et al. and Procedia Manufacturing 43 (2020) 674–681) that provides us with a calculated weight for each criterion. We combine some of our criteria and delete some of the existing analysis to keep only our eight criteria. We then normalise each criterion to get a total on 100%.

Table 2.11 Importance of each criterion

Aspects	Indicators	Calculated	Weight
Economic	Construction and Maintenance cost	0.237	15.45%
	Digital access	0.126	8.21%
	Potential volume growth	0.050	3.26%
Social	Safety and security	0.409	26.66%
	Job creation	0.167	10.89%
Environmental	Environmental Impact	0.234	15.25%
	Energy efficiency	0.124	8.08%
	Sensitivity to climate change	0.187	12.19%
Total		1.534	100.00%

We have made sure that our analysis about criteria weighting is in accordance with our project's objectives and values. Indeed, safety and security is the most critical criterion in optimizing the transportation logistics for bioeconomy products in the Amazon. Given the remote and often challenging conditions of the region, ensuring the safety and security of transportation routes is central. This includes safeguarding against illegal activities such as drug trafficking and ensuring the protection of both goods and personnel. High safety and security standards prevent losses and damage that could threaten the entire supply chain, making it the highest priority. Construction and maintenance costs are significant in determining the feasibility of transportation infrastructure projects. Given the Amazon's challenging terrain and environmental sensitivity, constructing and maintaining infrastructure is both complex and expensive. Prioritizing cost-effective solutions ensures that the project remains financially viable while enabling sustainable development. High construction and maintenance costs can hold back a project, hence their substantial weight. Minimizing environmental impact is crucial for a region as ecologically sensitive as the Amazon. The bioeconomy aims to use the region's resources sustainably, and any transportation strategy must align with this goal. Infrastructure projects must avoid contributing to deforestation, biodiversity loss, or other forms of environmental degradation. Ensuring that transportation strategies are environmentally friendly helps preserve the Amazon's unique ecosystems and contributes to global climate goals. The Amazon is highly vulnerable to the impacts of climate change, including extreme weather events and alterations in river levels. Transportation infrastructure must be resilient to these changes to ensure long-term viability. Strategies that account for climate sensitivity help mitigate potential disruptions and maintain consistent supply chains, thus supporting sustainable economic activities in the region. Job creation is a critical social benefit of optimizing transportation logistics. Improving transportation infrastructure can generate numerous employment opportunities, from construction and maintenance to logistics and distribution. Prioritizing job creation helps enhance the well-being of local communities, supports economic development, and aligns with the social objectives of the bioeconomy. Enhancing digital access is essential for modernizing the supply chain and improving market connectivity. Better digital infrastructure facilitates real-time monitoring, efficient communication, and access to broader markets. While it is less immediately impactful than safety or environmental considerations, it is still crucial for long-term operational efficiency and integration into the global economy. Energy efficiency is important for reducing the overall carbon footprint of transportation activities. Given the remote nature of the Amazon, energy-efficient solutions can lower operational costs and contribute to environmental sustainability. Prioritizing energy efficiency supports the broader goals of the bioeconomy by promoting sustainable practices. Potential volume growth, while important, is given the least weight because it is more of a long-term consideration. The ability to scale operations is crucial for future growth and profitability, but initial efforts must focus on establishing a reliable and sustainable transportation network. Ensuring that the infrastructure can handle increased volumes in the future is important, but immediate priorities such as safety, cost, and environmental impact take precedence. By prioritizing these criteria, the project aims to develop a transportation strategy that balances economic, social, and environmental goals, ensuring the sustainable development of the Amazon's bioeconomy.

Given one transport strategy, we can now assess each criterion, and then give to this score its weight and we can get one final holistic score to the transport strategy. This framework will allow us to compare different strategies with the same criteria and same factors. The preferred strategy will be the strategy with the highest score.

Our methodology is now ready to choose one transport strategy among others.

3. Analysis and results

3.1 Modelling process

Development of a transport strategy can be regarded as an optimisation problem, i.e., finding the solution that best satisfies the objective among all feasible solutions under certain constraints. In response to our project, the objective is usually time minimisation or cost minimisation, and the constraints usually relate to the capacity of the factory. By setting decision variables and solving optimisation problems, plant locations and transport mode choices can be obtained to develop a range of strategies. Two commonly used modelling approaches are network optimisation and sequential optimisation, which are explained in detail in the following sections.

3.1.1 Parameters and assumptions

Prior to developing a mathematical model, the relevant parameters should first be determined. These parameters include production volumes, construction costs and capacities of factories, transport costs and capacities of various modes of transport, distances between towns and cities in Brazil under different modes.

1) Production

Our aim is to develop a unified mathematical model for transport strategies for all bioeconomy products, and therefore adopt a weighted gross production. The weights for each product are determined by its unit value, and the sum of the weights equal to 1 (Table 3.1). Weighted production is calculated by the sum of the products of the weights and actual production of the three products. Actual production is referenced to the data processing section and daily production in 2022 is selected. In the end, we obtained 340 sources and the corresponding weighted production per day, and total daily production is 259.5t.

Table 3.1 Unit value and weight of each product

Product	Unit Value ($)	Weight

Açaí Fruit	1.13	0.31
Brazil Nut	1.53	0.42
Pirarucu	0.97	0.27

2) Factory

All the three bioeconomy products have temperature and humidity requirements for processing and storage environments. SuperFrio is a renowned cold chain logistics company in Brazil dedicated to providing high quality cold chain solutions and warehousing services. It has established itself as a leading provider of cold chain services in South America, particularly in the Brazilian market. SuperFrio's cold storage facility is therefore considered a standard factory for modelling. Considering the maximum capacity of the SuperFrio cold facility and the fact that it also serves a wide range of products besides the açaí berry, Brazil nut and pirarucu, the standard factory was set up to handle 150t of products a day. An assumption is that there is a maximum of one factory in a town. The top 30 production sites are chosen as the potential factory location due to the realities and complexity of modelling solutions (Table 3.2).

Table 3.2 Top 30 sources and corresponding production

No.	Town	Production (ton per day)
1	Limoeiro do Ajuru	34.20
2	Codajás	25.56
3	Oeiras do Pará	23.28
4	Afuá	8.06
5	Mocajuba	7.62
6	Lábrea	6.64
7	Humaitá	6.57
8	Inhangapi	6.30
9	Muaná	6.20
10	Coari	5.32
11	Itacoatiara	5.25
12	Ponta de Pedras	5.23
13	São Sebastião da Boa Vista	5.05
14	Igarapé-Miri	4.01
15	São Miguel do Guamá	3.71
16	São Domingos do Capim	3.33
17	Magalhães Barata	3.32
18	Manicoré	3.03
19	Óbidos	2.64

20	Oriximiná	2.46
21	Sena Madureira	2.41
22	Nova Olinda do Maranhão	2.35
23	Beruri	2.30
24	Marapanim	1.88
25	Brasiléia	1.79
26	Rio Branco	1.77
27	Luís Domingues	1.75
28	Novo Aripuanã	1.74
29	Boca do Acre	1.73
30	Porto Velho	1.70

Moreover, it assumed that all products from a certain source are transported to a single factory and all products in a certain factory are transported to a single export port in our model.

3) Mode

Existing and commonly used modes of transport for transporting bio-economic products in Brazil include waterways, landways and railways. As mentioned above, logistics of our project can be categorised into two echelons. Due to geographic and socio-economic factors, different modes are available for different echelons. For instance, the first echelon, i.e., from collection or harvest sites to factories, is usually in the Amazon rainforest, where rivers are narrow and road facilities are inadequate. It results in some heavy cargo ships or lorries not being able to participate in the transport of these products. For the second echelon, however, the terrain is more open and economically developed, and railways are even available. Moreover, considering the requirements of temperature for transporting perishable products, vehicles, ships, and trains are categorised into two types: normal and refrigerated. Information on all modes of transport, including capacity, cost and speed is presented in Table 3.3 and 3.4.

Table 3.3 Capacity, cost, and speed of modes for Echelon 1

Category	Category	Capacity (t)	Initial Cost ($/veh)	Shipment Cost ($/t/km)	Speed (km/h)
Ferry with freezer	Water	125	600,000.00	0.125	20
Mid-size ferry	Water	150	2,000,000.00	0.0435	21
Refrigerator truck	Road	18	150,000.00	3.00	80
Normal truck	Road	22.5	100,000.00	1.75	80

Table 3.4 Capacity, cost, and speed of modes for Echelon 2

Category	Category	Capacity (t)	Initial Cost	Shipment Cost	Speed

			($/veh)	($/t/km)	(km/h)
Ferry with freezer	Water	125	600,000.00	0.125	20
Mid-size ferry	Water	150	2,000,000.00	0.0435	21
Large ferry	Water	900	4,000,000.00	0.0435	21
River Barges	Water	3500	1,250,000.00	0.0300	12
Refrigerator truck	Road	18	150,000.00	3.00	80
Normal truck	Road	22.5	100,000.00	1.75	80
Standard cargo train	Rail	7000	2,000,000.00	0.0200	60
Refrigerated cargo	Rail	7000	5,000,000.00	0.0350	60

In addition, our model assumes that only one mode is used in each echelon and that the movement of vehicles, ships and trains does not stop.

4) Export port

Thanks to its well-developed water system, most of Brazil's products are exported through its ports, where Porto de Manaus, Porto de Itaqui and Porto de São Luís play a key role in exporting bioeconomy products. As they are located in Manaus or São Luís, the two cities are set as export sites in modelling, i.e., all products are transported there after leaving factories. Considering the large size of the three ports and the limited production of these products, our model assumes that infinite capacity at each export site.

5) Distance and time

It has already been described in the previous section how the OD matrix is obtained. It is worth noting that even for the same pair of towns, the distance between them varies when various categories of modes are used, as the route and accessibility of each mode varies. In our model, distance between towns depends on which category of modes is chosen to transport these bioeconomy products. And transport time is obtained by dividing the distance by the speed of the specific mode (because it is assumed that there is no standstill in the transport process).

3.1.2 Network Optimisation

Network optimisation modelling is to find globally optimal solutions on the first and second echelons, including factory locations and allocations as well as mode choices for each echelon. It is solved using PuLP library in Python in our project, and the code is shown in Appendix I. A detailed description of the decision variables, parameters, objective function, and constraints follows.

1) Decision variables

Decision variables should cover the variables in the transport strategy, and for network optimisation, two echelons should be considered simultaneously. In our model, there are three decision variables representing the factory location, the factory allocation and mode choices for sources in the first echelon, and port allocation and mode choices for factories in the second echelon, separately (Table 3.5). All decision variables are Boolean variables.

Table 3.5 Decision variables for network optimisation

Decision Variable	Description
x_{ij}	Whether type factory j opened at town i
y_{kij}^{m}	Whether products collected from source k transported to type j factory to town i by mode m
z_{ijl}^{n}	Whether products from type j factory at town i to port l by mode n

2) Parameters

All parameters have been described in the previous section and are defined in this section. In the network optimisation model, the parameters consist of four categories: production, capacity, cost, and distance and time (Table 3.6).

Table 3.6 Parameters for network optimisation

Parameters	Description	Unit
q_k	Weighted quantity of products at source k	t/day
c_{fj}	Capacity of factory j	t/day
c_m	Capacity of mode m	t
c_n	Capacity of mode n	t
a_{fj}	Cost of construction and operation factory j	$
a_{m0}	Initial cost for purchasing vehicle of mode m	$/veh
a'_{m0}	Initial cost of mode m (converted to per ton of products)	$/t
a_m	Cost of shipping by mode m	$/t/km
a_{n0}	Initial cost for purchasing vehicle of mode n	$/veh
a'_{n0}	Initial cost of mode n (converted to per ton of products)	$/t
a_n	Cost of shipping by mode n	$/t/km
d_{kij}^{m}	Distance from source k to type j factory at town i by mode m	m

d_{ijl}^{n}	Distance from type j factory at town i to port l by mode n	m
v_m	Speed of mode m	km/h
v_n	Speed of mode n	km/h
t_{kij}^{m}	Time from source k to type j factory at town i by mode m	hr
t_{ijl}^{n}	Time from type j factory at town i to port l by mode n	hr

3) Objective function

We have three options regarding the objective function, which are time minimisation, cost minimisation and time and cost mix minimisation. In the network optimisation model, total time is the sum of time in the two phases of transport. And considering the computational complexity, cost is defined as the cost of building and operating all the factories plus the total cost of transporting one ton of goods across two echelons, in which case the model is a linear optimisation model and if there is a solution it must be optimal. Objective functions are defined as follows.

Option 1: time minimisation:

$$min \sum_{kijm} y_{kij}^{m} \times t_{kij}^{m} + \sum_{ijln} z_{ijl}^{n} \times t_{ijl}^{n} \tag{3.1}$$

Option 2: cost minimisation:

$$\begin{aligned} min \sum_{ij} x_{ij} \times a_{fj} + \sum_{m} [(\sum_{kij} y_{kij}^{m} \times d_{kij}^{m}/1{,}000) \times a_m + a'_{m0}] \\ + \sum_{n} [(\sum_{ijl} z_{ijl}^{n} \times d_{ijl}^{n}/1{,}000) \times a_n + a'_{n0}] \end{aligned} \tag{3.2}$$

Option 3: time and cost minimisation:

$$\begin{aligned} min \sum_{kijm} y_{kij}^{m} \times t_{kij}^{m} + \sum_{ijln} z_{ijl}^{n} \times t_{ijl}^{n} + \{ \sum_{ij} x_{ij} \times a_{fj} \\ + \sum_{m} [(\sum_{kij} y_{kij}^{m} \times d_{kij}^{m}/1{,}000) \times a_m + a'_{m0}] \\ + \sum_{n} [(\sum_{ijl} z_{ijl}^{n} \times d_{ijl}^{n}/1{,}000) \times a_n \\ + a'_{n0}]\}/100{,}000 \end{aligned} \tag{3.3}$$

Note that there is a scale parameter $100{,}000$ in the last objective function. It is because total time and total cost are of different scales in the result.

4) Constraints

All constraints stem from our assumptions mentioned in the previous section. All the constraints are as follows.

$$\sum_j x_{ij} \leq 1 \quad \forall i \tag{3.4}$$

$$\sum_k \sum_m y_{kij}^m \leq x_{ij} \quad \forall i, j \tag{3.5}$$

$$\sum_m \sum_{ij} y_{kij}^m = 1 \quad \forall k \tag{3.6}$$

$$\sum_l \sum_n z_{ijl}^n \leq x_{ij} \quad \forall i, j \tag{3.7}$$

$$\sum_n \sum_l z_{ijl}^n = 1 \times x_{ij} \quad \forall i, j \tag{3.8}$$

$$\sum_k \sum_m y_{kij}^m \times q_k \leq x_{ij} \times c_{fj} \quad \forall i, j \tag{3.9}$$

Constraint (3.4) ensures that each town has at most one factory. Constraint (3.6) and (3.8) are there to guarantee the assumptions that all products from a given source are delivered to a single factory using a single mode and all products from a given factory are delivered to a single port using a single mode hold. As the two assumptions are only valid when a specific factory is open, constraint (3.5) and (3.7) are in place. Constraint (3.9) is the factory capacity constraint.

After running the code, we get the results of the three transport strategies. Table 3.7 lists some critical elements in the output. In the table, total time is defined by,

$$Total\ Time = \sum Number\ of\ Vehicles \ \times Time\ on\ one\ Vehicle \tag{3.10}$$

and total cost is defined by,

$$Total\ Transport\ Cost\ (each\ echlon) = \sum Initial\ Cost + Shipment\ Cost \tag{3.11}$$

$$\begin{aligned} Total\ Cost = {} & Factory\ Construction\ Cost \\ & + \sum_{Echelon1, Echelon2} (Initial\ Cost + Shipment\ Cost) \end{aligned} \tag{3.12}$$

Table 3.7 Network optimisation results

Strategy		Min Time	Min Cost	Min Time and Cost
Number of Factories		18	2	10
Echelon 1	Most Used Mode	Refrigerator truck	Mid-size ferry	Normal Truck
	Total Time (h)	3,013	15,798	3,337
	Total Transport Cost ($)	182,160,091	673,311,370	168,262,559
Echelon 2	Most Used Mode	Refrigerator truck	River Barges	Normal Truck
	Total Time (h)	596	87	428
	Total Transport Cost ($)	22,133,974	2,503,896	16,812,451

Total Time (h)	3,609	15,885	3,765
Total Cost ($)	289,704,065	685,305,267	232,525,010

3.1.3 Sequential Optimisation

The sequential optimisation modelling approach aims to optimise each echelon separately. The first model "Facility location" selects the suitable facility location and routes to them from all towns. The second model "Port Routing" performs a capacitated routing optimisation between the factories and the selected international ports. This would allow the selected supply chain strategy to be more resilient to demand fluctuation due to more market trends or changes in the import-to-export ratio.

1) Decision variables

Similar to the network optimisation algorithm, the decision variables are the output for the optimisation algorithm. The same decision variables are utilised in both model with only y_j term which apply only to facility location algorithm. The model is simplified by allowing only one type of factory.

Table 3.8 Decision variables for facility location and port routing

Decision Variable	Description
x_{ij}^m	Number of products collected from source/factory i transported to the factory/port in town j by mode m (Continuous)
y_j	Whether factory opened at town i (Boolean) (Only for facility location model)
z_{ij}^m	Whether products collected from source/factory i transported to the factory/port in town j by mode m (Boolean)

2) Parameters

The parameters used for both models concern the production quantity and mode characteristics. The distance is not only dependent on origin/destination but also on mode type allowing multiple routes to be used per origin/destination pair. The total cost for the mode is a sum of the mode's purchase cost and variable which is dependent on the route distance and quantity transferred. The facility location algorithm has 2 extra parameters capturing the factory characteristics.

Table 3.9 Parameters for facility location and port routing

Parameters	Description	Unit	Use in model
P_j	Factory j capacity	tons	Facility location
c_j	Cost of facility j	$	Facility location
Q_i/QF_i	Production quantity from source/Factory i	tons	Facility location & Port routing
d_{ij}^m	Distance from source i to factory j using mode m	km	Facility location & Port routing
m_m	Capacity of mode m	tons	Facility location & Port routing
mc_{ij}^m	Total cost for mode m when used on route i,j for one day	$	Facility location & Port routing
s_m	Speed of mode m	km/h	Facility location & Port routing
n_{min}, n_{max}	Minimum and maximum number of factories to be build		Facility location

3) Objective function

Similar to network optimisation, each of the sequential optimisation algorithm has three options which are time minimisation, cost minimisation, and time and cost minimisation. With the separated model, the absolute cost could be calculated for each of the model. The objective functions are defined as follows.

Option 1: cost minimisation:

$$min \sum_{ijm} x_{ij}^m \times mc_{ij}^m + \sum_j c_j \times y_j \tag{3.13}$$

Option 2: time minimisation:

$$min \sum_{ijm} \frac{d_{ij}^m}{s_m} \times x_{ij}^m \tag{3.14}$$

Option 3: time and cost minimisation:

$$min \sum_{ijm} \frac{mc_{ij}^m}{5000} \times x_{ij}^m + \sum_j c_j \times y_j + \sum_{ijm} \frac{d_{ij}^m}{s_m} \times x_{ij}^m \tag{3.15}$$

The 5,000 division in time and cost minimisation is the cost scale factor to allows the cost and time to have similar weighting in the optimisation.

4) Constraints

The constraints are similar to the network optimisation with some additional constraints to limit some mode travel time and linking decision variables together. The constraints for facility location model and port routing model are identical with some additional constraints regarding factories operation for the facility location model.

$$\sum_{m}\sum_{j} x_{ij}^{m} = Q_i \quad \forall i \text{ or } \sum_{m}\sum_{j} x_{ij}^{m} = QF_i \quad \forall i \tag{3.16}$$

$$\sum_{m} z_{ij}^{m} \leq y_j \quad \forall\, i,j\ (Only\ facility\ location) \tag{3.17}$$

$$if \sum d_{ij}^{m} = 0 \quad \forall\, i,j,m\ where\ i \neq j, z_{ij}^{m} = 0 \tag{3.18}$$

$$\sum_{m}\sum_{i} x_{ij}^{m} \leq P_j y_j \quad \forall\, j\ (Only\ facility\ location) \tag{3.19}$$

$$n_{min} \leq \sum y_j \leq n_{max} \quad \forall\, j\ (Only\ facility\ location) \tag{3.20}$$

$$\sum_{m} z_{ij}^{m} \leq 1 \quad \forall\, i,j \tag{3.21}$$

$$\sum_{m}\sum_{j} z_{ij}^{m} \quad \forall i \tag{3.22}$$

$$x_{ij}^{m} \leq Q_i \times z_{ij}^{m}\ and\ z_{ij}^{m} \leq y_j\ \forall i,j,k \tag{3.23}$$

$$\text{If m not in refrigerated mode, } \frac{d_{ij}^{m}}{s_m} \times z_{ij}^{m} \leq 24 \quad \forall i,j,k \tag{3.24}$$

The constraint (3.16) defines the quantity of product delivered from each town. Constrain (3.17), (3.19), (3.20) ensure route create only if there is factory, factory capacity must not be exceeded, and number of factories are within the defined range respectively. The constraint (3.18) prevent zero distance trip between town since infeasible routes are valued as zero in the origin and destination matrix. The constraint (3.21) limit one mode type per route while the constraint (3.22) limit one factory as destination for each town. The constraint (3.23) links the definition of X and Z. The constraint (3.24) limits the mode type without refrigeration to have maximum travel time of 24 hours.

5) Result

The top 3 results after weighted ranking using network cost, time, and future resilience are 1. Minimise Cost then Minimise Cost&Time, 2. Minimise Cost then Minimise Time, 3. Minimise Time then Minimise Cost with the detail result in the table below.

Table 3.10 Comparison of Strategies

Strategy		Min Cost then Min Cost and Time	Min Cost then Min Time	Min Time then Min Cost
Number of Factories		3	3	30
Echelon 1	Most Used Mode	Normal truck	Normal truck	Refrigerated Truck

	Total Time (h)	9,762	9,762	2,659
	Total Transport Cost ($)	91,652,639	91,652,639	272,263,748
Echelon 2	Most Used Mode	Normal truck	Ferry with Freezer	Normal Truck
	Total Time (h)	217	262	607
	Total Transport Cost ($)	3,021,489	9,843,184	5,837,443
Total Time (h)		9,979	10,024	3,265
Total Cost ($)		94,674,128	101,495,823	278,101,191

3.2 Criteria quantification

In this section, our aim is to quantify the criteria to compare different strategies.

3.2.1 Energy efficiency

Based on the three factors, the energy efficiency for each transportation mode is calculated using the equation below and the results are shown in the table below.

$$\begin{aligned} &Energy\ Efficiency \\ &\quad = 0.3 \times Enery\ Consumption + 0.3 \times Fuel\ Efficiency \\ &\quad + 0.4 \times Carbon\ Emission \end{aligned} \tag{3.25}$$

Table 3.11 Energy efficiency for each type of transportation mode

Mode	**Type**	**Energy Consumption**	**Fuel Efficiency**	**Carbon Emission**	**Energy Efficiency**
Water	Freezer Boat	0.10	0.03	0.00	0.039
	Ferry with Freezer	0.15	0.05	0.11	0.103
	Mid-Size ferry	0.12	0.04	0.11	0.091
	Large ferry	0.09	0.03	0.11	0.079
	River Barges	0.08	0.03	0.11	0.075
	Voadeiras	0.05	0.02	0.08	0.052
Road	Refrigerator truck	0.80	0.24	0.07	0.340
	Pickup Truck	1.50	0.45	0.22	0.671
	Vans	1.20	0.36	0.11	0.511
	Normal Truck	0.60	0.18	0.05	0.253
Air	Medium Propeller	1.50	0.45	0.45	0.764

	Planes				
	Large Cargo Planes	3.20	0.96	0.38	1.399
	Helicopters	5.00	1.50	4.20	3.630
Train	Standard Cargo Train	0.50	0.15	0.26	0.299
	Refrigerated Cargo	0.70	0.21	0.30	0.393

We will now assess the six different strategies based on the number and type of vehicles required using the formula below:

$$\begin{aligned} &Energy\ Efficeincy\ Score \\ &\qquad = Energy\ Efficiency \times Total\ Numbre\ of\ Vehicles \end{aligned} \tag{3.26}$$

For the strategy Method 1: Minimise Time

Table 3.12 Energy efficiency score for time minimisation strategy

Method 1: Minimise Time						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	8		8	0.82
	Mid-Size Ferry	0.091	71	164	235	21.39
Road	**Refrigerator Truck**	0.340	178	176	354	120.36
	Normal Truck	0.253	83		83	21.00
Sum			340	340	680	163.6
Normalised energy efficiency score			$163.6/680 \times 100\% = 24.1\%$			
Higher Score = Higher Efficiency			75.9%			

For the strategy Method 1: Minimise Cost

Table 3.13 Energy efficiency score for cost minimisation strategy

Method 1: Minimise Cost						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	2		2	0.21
	Mid-Size Ferry	0.091	337		337	30.67

	River Barges	0.075		340	340	25.50
Road	**Normal Truck**	0.253	1		1	0.25
Sum			340	340	680	56.6
Normalised energy efficiency score			$56.6/680 \times 100\% = 8.3\%$			
Higher Score = Higher Efficiency			91.7%			

For the strategy Method 1: Minimise Time & Cost

Table 3.14 Energy efficiency score for time and cost minimisation strategy

Method 1: Minimise Time & Cost						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	5		5	0.52
	Mid-Size Ferry	0.091	69	150	219	19.93
	Large Ferry	0.079		13	13	1.03
Road	**Refrigerator Truck**	0.340	7		7	2.38
	Normal Truck	0.253	259	177	436	110.31
Sum			340	340	680	134.2
Normalised energy efficiency score			$134.2/680 \times 100\% = 19.7\%$			
Higher Score = Higher Efficiency			80.3%			

For the strategy Method 2: Minimise Cost then Cost & Time

Table 3.15 Energy efficiency score for Minimising cost then cost & time strategy

Method 2: Minimise Cost then Cost & Time						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	80	210	290	29.93
Road	**Refrigerator truck**	0.340	64		64	21.79
	Normal Truck	0.253	195	129	324	81.91
Sum			339	339	678	133.6

Normalised energy efficiency score	$133.6/678 \times 100\% = 19.7\%$
Higher Score = Higher Efficiency	80.3%

For strategy Method 2: Minimise Cost then Time

Table 3.16 Energy efficiency score for minimising cost then time strategy

Method 2: Minimise Cost then Time						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	80		80	8.26
	Mid-Size Ferry	0.091		5	5	0.46
Road	**Refrigerator truck**	0.340	64	334	398	135.48
	Normal Truck	0.253	195		195	49.30
Sum			339	339	678	193.5
Normalised energy efficiency score			$193.5/678 \times 100\% = 28.5\%$			
Higher Score = Higher Efficiency			71.5%			

For the strategy Method 2: Minimise Time then Cost

Table 3.17 Energy efficiency score for minimising time then cost strategy

Method 2: Minimise Time then Cost						
Mode	**Type**	**Energy Efficiency**	**Echelon 1: Nb of Veh**	**Echelon 2: Nb of Veh**	**Total Nb of Veh**	**Energy Efficiency Score**
Water	**Ferry with Freezer**	0.103	14	28	42	4.33
	Mid-Size Ferry	0.091	41		41	3.74
Road	**Refrigerator truck**	0.340	284		284	96.67
	Normal Truck	0.253		311	311	78.62
Sum			339	339	678	183.4

Normalised energy efficiency score	$183.4/678 \times 100\% = 27.0\%$
Higher Score = Higher Efficiency	73.0%

The table below shows the Energy efficiency score for each strategy.

Table 3.18 Energy efficiency score for the different strategies

Strategy	Energy Efficiency Score
M1: Minimise time	24.1%
M1: Minimise cost	8.3%
M1: Minimise time & cost	19.7%
M2: Minimise Cost then Cost & Time	19.7%
M2: Minimise Cost then Time	28.5%
M2: Minimise Time then Cost	27.0%

3.2.2 Digital Access

Based on the factories locations, the digital access is assessed, and the results are shown the tables below.

For the strategy Method 1: Minimise Time

Table 3.19 Digital Access score for time minimisation strategy

Factory Location	Factor for M1: Min Time	Factory Location	Factor for M1: Min Time
Afuá	0.4	Nova Olinda do Maranhão	0.2
Beruri	0.8	Óbidos	0.2
Coari	0.2	Oeiras do Pará	1
Humaitá	0.2	Ponta de Pedras	0.4
Itacoatiara	0.2	Porto Velho	0
Limoeiro do Ajuru	0.4	Rio Branco	0
Luís Domingues	0.8	São Domingos do Capim	1

Marapanim	0.4	São Miguel do Guamá	0.2
Mocajuba	0.2	Sena Madureira	0.4

For the strategy Method 1: Minimise Cost

Table 3.20 Digital Access score for cost minimisation strategy

Factory Location	Factor for M1: Min Cost
Afuá	0.4
Itacoatiara	0.2

For the strategy Method 1: Minimise Time & Cost

Table 3.21 Digital Access score for time and cost minimisation strategy

Factory Location	Factor for M1: Min Time & Cost
Afuá	0.4
Coari	0.2
Itacoatiara	0.2
Nova Olinda do Maranhão	0.2
Óbidos	0.2
Ponta de Pedras	0.4
Porto Velho	0
Rio Branco	0
São Miguel do Guamá	0.2
Sena Madureira	0.4

For the strategy Method 2: Minimise Cost then Cost & Time

Table 3.22 Digital Access score for minimising cost then cost & time strategy

Factory Location	Factor for M2: Min Cost then Cost & Time
Coari	0.2
Ponta de Pedras	0.4
São Sebastião da Boa Vista	0.2

For strategy Method 2: Minimise Cost then Time

Table 3.23 Digital Access score for minimising cost then time strategy

Factory Location	Factor for M2: Min Cost then Time
Coari	0.2
Ponta de Pedras	0.4
São Sebastião da Boa Vista	0.2

For the strategy Method 2: Minimise Time then Cost

Table 3.24 Digital Access score for minimising time then cost strategy

Factory Location	Factor for M2: Min Time then Cost	Factory Location	Factor for M2: Min Time then Cost	Factory Location	Factor for M2: Min Time then Cost
Afuá	0.4	Lábrea	0.2	Óbidos	0.2
Beruri	0.8	Limoeiro do Ajuru	0.4	Oeiras do Pará	1
Boca do Acre	0.4	Luís Domingues	0.8	Oriximiná	0.4
Brasiléia	0.4	Magalhães Barata	0.4	Ponta de Pedras	0.4
Coari	0.2	Manicoré	0.2	Porto Velho	0
Codajás	0.2	Marapanim	0.4	Rio Branco	0
Humaitá	0.2	Mocajuba	0.2	São Domingos do Capim	1
Igarapé-Miri	0.2	Muaná	0.4	São Sebastião da Boa Vista	0.2
Inhangapi	1	Nova Olinda do Maranhão	0.2	São Miguel do Guamá	0.2
Itacoatiara	0.2	Novo Aripuanã	0.2	Sena Madureira	0.4

The table below shows the average improvement in digital access for each strategy.

Table 3.25 Digital Access improvement for the different strategies

Strategy	Average Improvement in Digital Access	% Improvement in Digital Access

M1: Minimise time	0.39	39
M1: Minimise cost	0.30	30
M1: Minimise time & cost	0.22	22
M2: Minimise Cost then Cost & Time	0.27	27
M2: Minimise Cost then Time	0.27	27
M2: Minimise Time then Cost	0.37	37

3.2.3 Construction and Maintenance Cost

Assigning scores to different strategies based on the number of warehouses selected for the strategy, the construction costs and the annual maintenance costs, which are converted to current cash flows by the NPV method.

The formula for calculating the specific score is:

$$Number\ of\ Facilities\ Score = 100 - \frac{(Value - Min) \times 100\%}{Max - Min} \quad (3.27)$$

Table 3.26 Construction and Maintenance Cost for different strategies

Strategy	M1: Min Time	M1: Min Cost	M1: Min Time & Cost	M2: Min Cost then Min time	M2: Min Time then Min Cost	M2: Min Cost then Min Time & Cost
Number of Facilities	2	17	12	3	30	2
Score	100.00	64.29	46.43	96.43	0.00	100.00

3.2.4 Potential Volume Growth

In this section, the difference between the forecasted gross value of the three products in 2030 and the maximum capacity of the chosen strategic facilities is used to calculate the scores, which are calculated as follows:

$$Potential\ Volume\ Growth\ Score = 100 - \frac{(Value - Min) \times 100\%}{Max - Min} \quad (3.28)$$

Table 3.26 Potential Volume Growth for different strategies

Strategy	M1: Min Time	M1: Min Cost	M1: Min Time & Cost	M2: Min Cost then Min time	M2: Min Time then Min Cost	M2: Min Cost then Min Time & Cost
Number of Facilities	2	17	12	3	30	2
Gap with 2030	-626.12	1623.88	873.88	-476.12	3573.88	-626.12
Score	0.00	38.66	20.81	111.34	100.00	0.00

3.2.5 Job Creation

Job creation is evaluated based on the number of direct and indirect jobs created.

$$Induced\ and\ Indirect\ Jobs = (Economic\ Multiplier - 1)\ \times Direct\ Jobs \tag{3.29}$$

Table 3.27 Job Creation for different strategies

Strategy	M1: Min Time	M1: Min Cost	M1: Min Time & Cost	M2: Min Cost then Min time	M2: Min Time then Min Cost	M2: Min Cost then Min Time & Cost
Number of Factories * Workers	2340	260	1300	390	3900	390
Number of Vehicles * Workers	2040	2040	2040	1095	1122	1047
Total direct Jobs	4380	2300	3340	1485	5022	1437
Indirect Jobs Created	2190	1150	1670	742.5	2511	718.5
Total Job Creation	6570	3450	5010	2227.5	7533	2155.5

Prioritising Direct jobs over indirect Jobs, the score sore each strategy is calculated,

$$Job\ Creation\ Score = \frac{(0.25\ \times indirect\ Jobs + 0.75\ \times direct\ jobs)}{\sum(0.25\ \times indirect\ Jobs + 0.75\ \times direct\ jobs)} \times 100\% \tag{3.30}$$

Table 3.28 Job Creation for different strategies

Strategy	M1: Min Time	M1: Min Cost	M1: Min Time & Cost	M2: Min Cost then Min Time	M2: Min Time then Min Cost	M2: Min Cost then Min Time & Cost
Score	43.7	23	33.3	18.7	63.2	18.1

3.2.6 Environmental Impact

Environmental impact is assessed on the amount of CO2 emissions per load for each strategy. Below is a table outlining the emission calculations for each strategy.

Table 3.29 Environmental Impact for different strategies

Strategy	M1: Min Cost	M1: Min Time	M1: Min Time&Cost	M2: Min Cost then Min Time	M2: Min Time then Min Cost	M2: Min cost then Min Time&Cost
Vehicles						
Ferry with Freezer	2	8	5	80	42	290
Mid-Size ferry	337	235	219	5	41	
Large ferry			13			
River Barges	340					
Refrigerator truck		354	7	398	284	64
Normal Truck	1	83	436	195	311	324
Total CO2 emissions in millions (g CO2)	5553968	7802544	7086278	29732	10562	17907

The score is calculated by,

$$Environmental\ Impact\ Score = \frac{Total\ CO2\ emissions}{\sum Total\ CO2\ emission} \times 100\% \qquad (3.31)$$

Table 3.30 Environmental Impact for different strategies

Strategy	M1: Min Time	M1: Min Cost	M1: Min time & Cost	M2: Min Cost then Min Time	M2: Min time then Min Cost	M2: Min cost then Min Time & Cost

Score	61.8	72.8	65.3	48.9	81.9	69.2

3.2.7 Sensitivity to climate change

We assess six different strategies. We use the method explained in paragraph 2.4.7. In these tables, we can see the first rows for each of the strategies.

Tables 3.31 Example of the Climate Sensitivity Score calculations (M1: Min Time)

	Origin	**Destination**	**Average**	**TimeOnRoute**	**TimeIndex**	**CSS_Index**	**CSS_Score**
Echelon 1	90.80	90.80	90.80	16.38	0.15	0.85	77.49
	90.80	90.80	90.80	1.58	0.01	0.99	89.70
Echelon 2	90.80	91.80	91.30	39.24	0.37	0.63	57.40709
	85.45	79.10	82.28	13.67	0.11	0.89	73.16788

We can see the value of each of the parameters such as origin score, destination score, average score, $TimeOnRoad$, $TimeIndex$, $CSS\ Index$ and the score for every route in different echelons. As stated in 2.4.7, we then make an average for every route given one strategy.

Table 3.32 Summary of the different score for Sensitivity to Climate events

Strategy	**M1: Min Time**	**M1: Min Cost**	**M1: Min Time&Cost**	**M2: Min Cost then Cost & Time**	**M2: Min Cost then Time**	**M2: Min Time then Cost**
Score	80.5	62.8	80.2	69.8	69.7	76.2

3.2.8 Safety and Security

We assess six different strategies. We use the method explained in paragraph 2.4.8. In these tables, we can see the first rows for each of the strategies

Tables 3.33 Example of the Safety and Security Score calculations (M1: Min Time)

	Origin	**Destination**	**Average**	**TimeOnRoute**	**TimeIndex**	**SS_Index**	**SS_Score**
Echelon 1	84.71	84.71	84.7	16.4	0.147	0.853	72.299
	84.71	84.71	84.7	1.6	0.012	0.988	83.686

Echelon 2	84.71	91.80	88.26	39.24	0.37	0.63	55.49
	79.10	79.10	79.10	13.67	0.11	0.89	70.34

We can see the value of each of the parameters such as origin score, destination score, average score, TimeOnRoad, TimeIndex, SS Index and the score for every route in different echelons. As stated in 2.4.8, we then make an average for every route given one strategy.

Table 3.34 Summary of the different score for Safety and Security

Strategy	**M1: Min Time**	**M1: Min Cost**	**M1: Min Time&Cost**	**M2: Min Cost then Cost&Time**	**M2: Min Cost then Time**	**M2: Min Time then Cost**
Score	78.9	59.8	78.8	66.2	66.1	74.8

3.2.9 Assessment

After assessing all our eight criteria, in this section we summarise the different scores on a table (Table 3.35). Then we need to multiply each of the criterion by the weight of this criterion, so that each score can contribute to the overall grade given its importance. That is why we finally set up the final following table with the weight of every criterion for each of the strategies (Table 3.36) able 3.35 Final Score

Aspects	Indicators	M1: Min Time	M1: Min Cost	M1: Min Time&Cost	M2: Min Cost then Cost&Time	M2: Min Cost then Time	M2: Min Time then Cost
Economic	Construction and Maintenance cost	46.4	100.0	64.3	96.4	96.4	0.0
	Digital access	38.9	30.0	22.0	27.0	27.0	37.3
	Potential volume growth	38.7	0.0	20.8	0.0	100.0	11.3
Social	Safety and security	78.9	59.8	78.8	66.2	66.1	74.8
	Job Creation	43.7	23.0	33.3	18.1	18.7	63.2
Environmental	Environmental Impact	61.8	72.8	65.3	69.2	48.9	81.9
	Energy efficiency	24.1	8.3	19.7	19.7	28.5	27.0
	Sensitivity to climate change	80.5	62.8	80.2	69.8	69.7	76.2

Table 3.36 Final scores given weight for each criterion and for each strategy

Aspects	Indicators	Calculated	Weight	M1: Min Time	M1: Min Cost	M1: Min Time&Cost	M2: Min Cost then Cost&Time	M2: Min Cost then Time	M2: Min Time then Cost
Economic	Construction and Maintenance cost	0.237	15.45%	7.2	15.4	9.9	14.9	14.9	0.0
	Digital access	0.126	8.21%	3.2	2.5	1.8	2.2	2.2	3.1
	Potential volume growth	0.05	3.26%	1.3	0.0	0.7	0.0	3.3	0.4
Social	Safety and security	0.409	26.66%	21.0	15.9	21.0	17.7	17.6	19.9
	Job Creation	0.167	10.89%	4.8	2.5	3.6	2.0	2.0	6.9
Environmental	Environmental Impact	0.234	15.25%	9.4	11.1	10.0	10.6	7.5	12.5
	Energy efficiency	0.124	8.08%	1.9	0.7	1.6	1.6	2.3	2.2
	Sensitivity to climate change	0.187	12.19%	9.8	7.7	9.8	8.5	8.5	9.3
Total		1.534	100.00%	58.6	55.8	58.4	57.4	58.3	54.2

This table summarises the holistic analysis of the strategies according to our criteria and methodology. As defined in our methodology (2.4.9) the preferred option is the strategy with the highest score. In our analysis, the preferred option is the strategy ‘Minimise Time’ from the Network Optimisation method.

This strategy that presents eighteen factories is indeed the best strategy for Digital Access, Safety and security and Sensitivity to climate change. It is also the second-best strategy for Potential volume growth and Job creation. This strategy is last in no criteria.

Our framework gives us the best strategy in a holistic vision. In conclusion, the ‘Min Time’ option is preferred because it effectively addresses the urgent logistical needs of the bioeconomy sector in the Amazon, supports economic and social objectives, and ensures environmental considerations are met directly.

3.3 Interpretation of results

1) Financial Benefit Analysis

The Brazilian government has estimated the production and valuation for the selected bioeconomy of the Amazon Forest region in 2022 shown in the table below.

Table 3.37 Production and Value of Bioeconomic Products

Bioeconomic products	Açai berry	Brazil nut	Pirarucu
Production (tons)	247,034	40,365	3,355
Value per Weight ($/kg)	1.13	1.53	0.97

(Instituto Brasileiro de Geografia e Estatística, 2022)

The hot and humid climate of the Amazon rainforest caused losses of around 30% to 40% of bioeconomic products harvested. (Rosenfeld, 2024) The introduction of refrigerated vehicles by our strategy would potentially eliminate this loss. With an assumption that the production amount reported was collected after all losses, the net value of all products could be calculated as shown in the table below.

Table 3.38 Lost Prevention and Value of Bioeconomic Products

Bioeconomic products	Açai berry	Brazil nut	Pirarucu
Amount of lost prevention (tons)	164,689	26,910	2,236

Value of lost prevention ($)	0.2 billion	41.2 million	2.2 million

From the estimation, over 229 million US Dollars of revenue loss could be prevented.

The long-term financial impact of the strategy would be the potential growth. With the investment in 18 factories each with 150 tons of production capacity per day, the total production capacity per day would be 2,700 tons per day. This is over 5 times greater than the total average daily production for all 3 products in 2022 combined. Using the average value per weight of 1.21 USD/kg, the potential increase in production value per day is found to be over 3 million USD which amounts to 1.1 billion USD yearly.

2) Estimating beneficiaries

The level of benefits from the chosen strategy could be divided into primary benefits and secondary benefits. With primary benefit considers people who gain jobs from the strategy, while the secondary benefit considers people who gain quality of life improvement such as improved digital access and transportation from the proposed strategy.

The job creation could be estimated using the same approach in section 3.2.5, where direct job creation is vehicle operators and factory workers, and indirect job creation could be estimated using the economic multiplier. The selected strategies would provide over 4,380 direct jobs and 2,190 indirect jobs which amount to 6,570 total job creation. Calculating from the Brazilian national minimum wage on the 1st of January 2024, which is BRL 1,412 per month (Máximo, 2024), this will inject at least 22.3 million USD into the local yearly.

The improved digital access in the 18 towns where the factories are located would allow its residents to have better internet access boosting productivity and education in the region. Based on the 2022 population census by the Brazilian government (Gov.br, 2022), the total population in the 18 towns which would benefit from the improved digital access would be 1,456,068 people in total.

The vehicle's utilisation in the supply chain would unfortunately be underutilised during the non-harvesting season. The total cargo capacity for 364 vehicles would amount to 18469 tonnes. These available cargo spaces however could be repurposed during such seasons to become transportation vessels for the local residences. With an assumption that the Brazilian average weight is 77.7 kg (NCD Risk Factor Collaboration (NCD-RisC), 2024), the excess cargo space could carry up to 227,444 people per day.

In summary, this strategy would have the potential to benefit almost 1.7 million people to a varying degree without taking into account the people benefiting from the economic growth in the area. This number equates to about 6% of the Amazon rainforest population.

3) Cost and Breakeven Point

The rough estimate of cost for the chosen strategy could be achieved by calculating the fixed cost (investment) and variable cost (Cost over time). The transport fixed cost involved the initial investment in the construction of factories, and purchasing vehicles, which amount to 289,360,000 USD. The variable cost involves the variable transportation cost (Oil cost) of 125,583,725 USD per year and labour cost calculated from Brazil's average wage of 2,659 BRL or 531 USD per month per person (Statista, 2022) and 6,570 job creation, the total yearly cost is 167,506,895 USD. The revenue per year estimated from the total production value of the three bioeconomic products in 2022 amounted to 344,161,220. This gives the pre-tax profit of 176,654,325 USD per year, and after 15% Brazilian Co-operate, tax gives 150,156,176 USD profit per year. This suggested that the strategy would break even the earliest after 1.9 years of full-scale operation.

Table 3.39 Cost and Break-even Point Estimation

E1 Transport Cost ($)	182,160,091
E2 Transport Cost ($)	22,133,974
Total transport cost ($)	204,294,065
Price of all vehicles ($)	203,950,000
Variable cost per day (Oil cost) ($)	344,065
Variable cost per year (Oil cost) ($)	125,583,725
Labour Cost per year ($6381/person/year) ($)	41,923,170
Total Cost per year ($)	167,506,895
Revenue per year ($)	344,161,220
Pre-tax profit per year ($)	176,654,325
After Co-operate tax 15% profit per year ($)	150,156,176
Initial Investment ($)	289,360,000
Break-even time (Year)	1.927

4. Conclusion and Suggestions

4.1 Visualisation of Preferred Strategy

An interactive map is created to visualise our optimal transport strategy. It is based on folium, a library in Python, and can be viewed in a web browser (see Appendix I). Fig 4.1. to 4.5 show different layers of the map. A range of information is attached to the displayed elements, which is detailed in Table 4.1.

Table 4.1 Explanations of the map

Layers	Description	Information	Expression
Source	Production sites for bioeconomy products	Town; description; production	Dark-salmon points
Factory	Factories needed to be built	Town; description; quantity (processed in the factory)	Dark-cyan points
Port	Export ports for bioeconomy products	Town; description; quantity (processed in the port)	Firebrick points
Factory Allocation - Water	Water transport from sources to factories	Source; factory; mode; quantity (on the vehicle)	Steelblue lines (thin)
Factory Allocation - Road	Road transport from sources to factories	Source; factory; mode; quantity (on the vehicle)	Chocolate lines (thin)
Port Allocation - Water	Water transport from factories to ports	Factory; port; mode; quantity (on the vehicle)	Steelblue lines (thick)
Port Allocation - Road	Road transport from factories to ports	Factory; port; mode; quantity (on the vehicle)	Chocolate lines (thick)

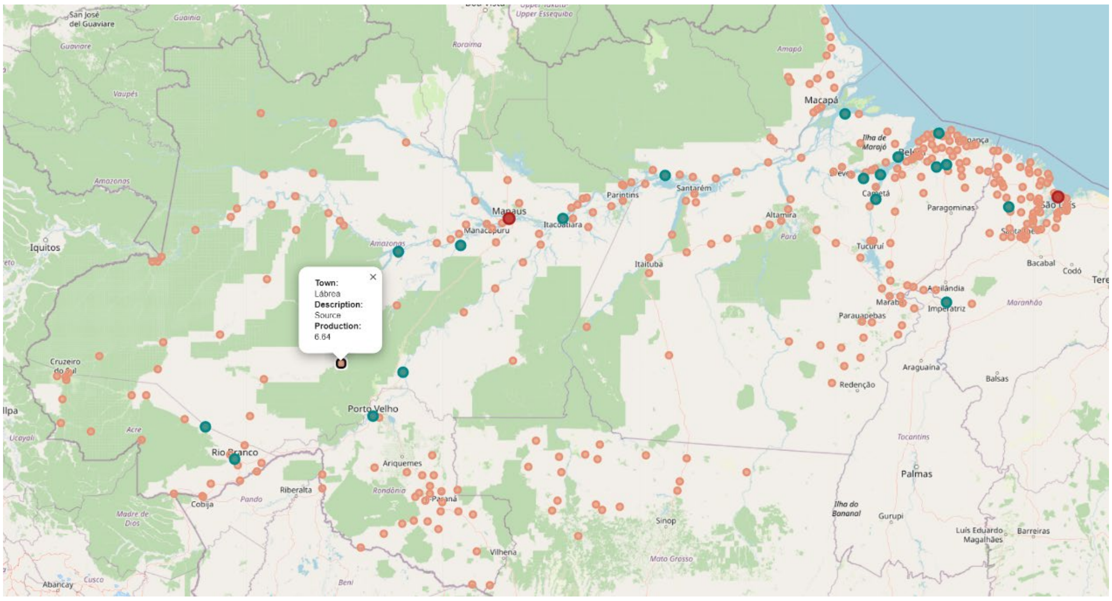

Fig 4.1 Sources, factories and ports

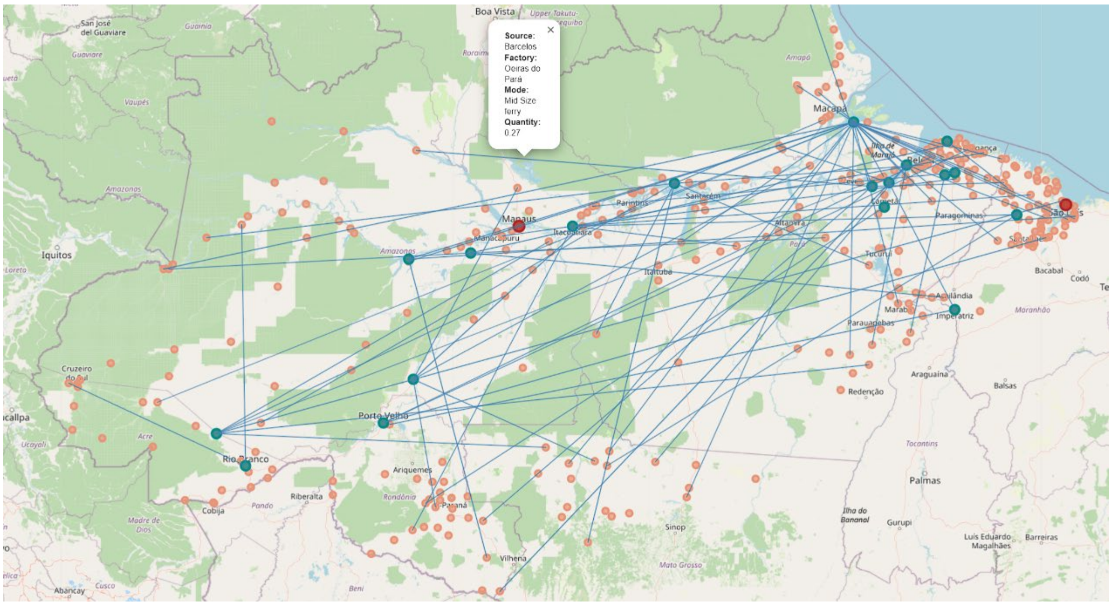

Fig 4.2 Water transport from sources to factories

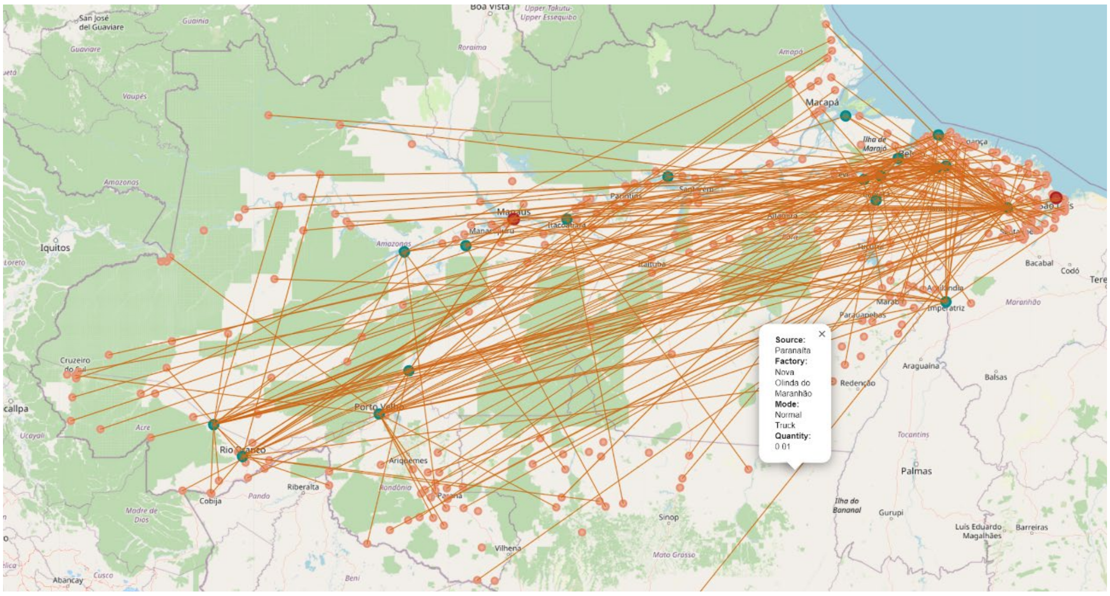

Fig 4.3 Road transport from sources to factories

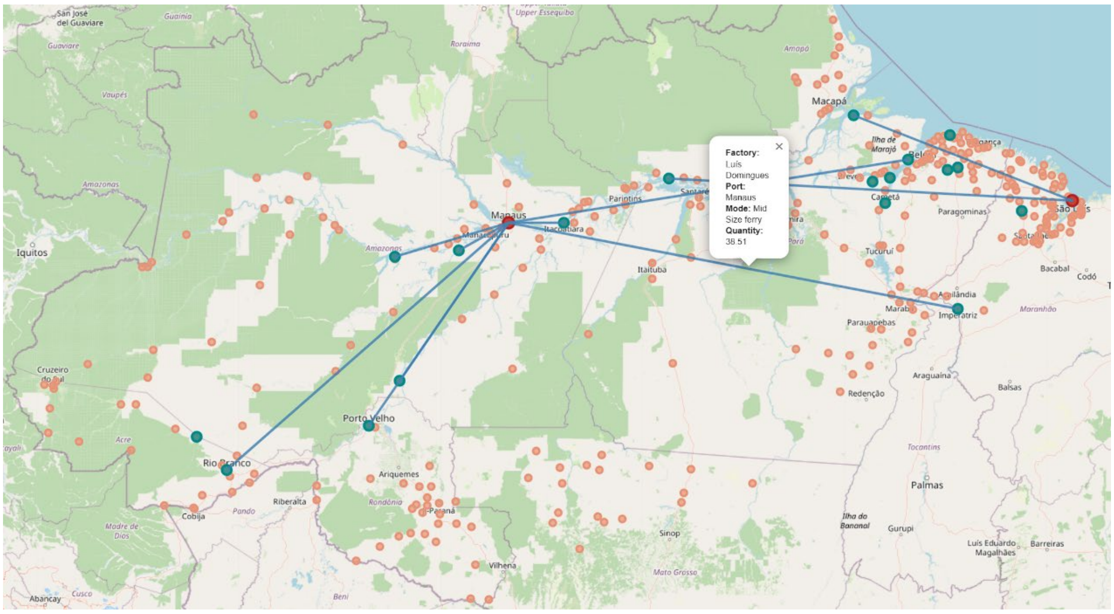

Fig 4.4 Water transport from factories to ports

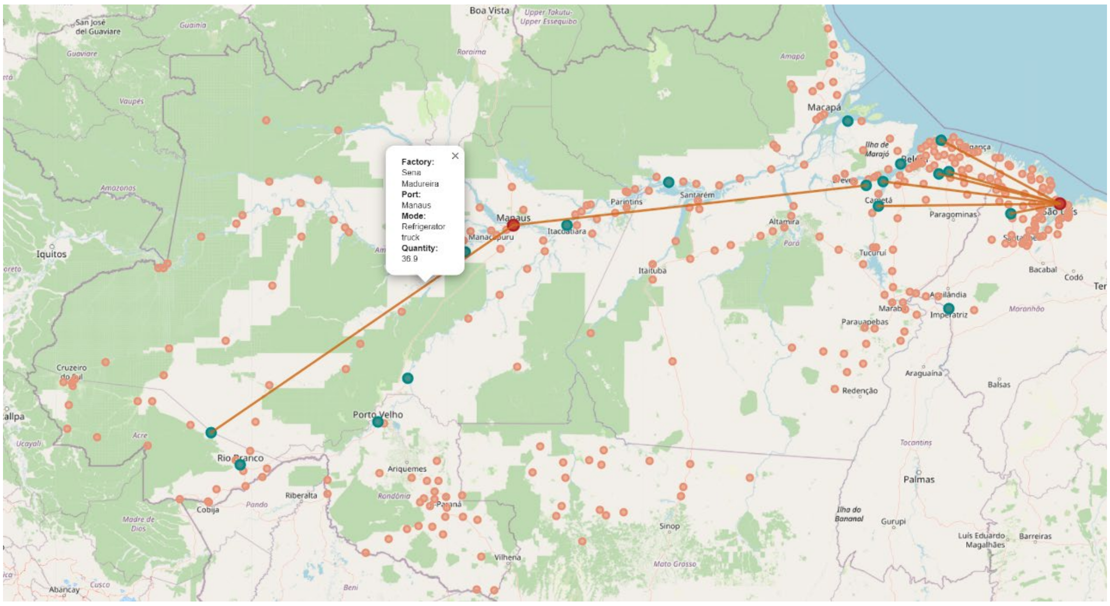

Fig 4.5 Road transport from factories to ports

4.2 Roadmap for Delivering Our Preferred Strategy

1) **Phase 1:** Project Initiation and Planning for 2 weeks

a. Define the Goal and Scope

   i. Determine the project's goals, scope, and deliverables, then document them.

   ii. Analyse the stakeholders to learn about their influences and areas of interest.

b. Gather Project Team

   i. Form a team with representatives from key stakeholders, including local communities, local authorities, local associations, national governments, private companies, banks, customers, and environmental NGOs.

c. Develop Project Plan

   i. Create a detailed project plan outlining tasks, timelines, resources, and responsibilities of each party.

Milestone 1: Project Plan Approved

2) **Phase 2:** Gathering and Analysing Data for 2 weeks

a. Collect Data

   i. Gather relevant data from sources like IBGE, IBAMA, and other local websites on the transportation networks, production sites, locations of ports & airports, and other useful information

b. Examine the Current Infrastructure

   i. Examine the current transportation infrastructure and identify the challenges.

c. Determine the Bioeconomy Product Transportation Needs

i. Establish the transport requirements for the main bioeconomy products like Açaí, Brazil nuts, and Pirarucu.

Milestone 2: Data Collection and Preliminary Analysis Completed.

3) **Phase 3:** Develop and Assess Transport Strategies for 4 weeks

a. Specify the Evaluation Criteria

   i. Establish evaluation criteria for transportation initiatives that consider several factors including energy efficiency, digital access, construction and maintenance cost, potential volume growth, job creation, environmental impact, climate sensitivity, and safety & security.

b. Develop Transport Strategies

   i. Suggest various transport strategies, considering a variety of transportation modes, such as waterways, roads, railways, and air, as well as their combinations.

c. Assess the Strategies

   i. Use the defined criteria to evaluate each transport strategy, quantifying their benefits, costs, and impacts.

Milestone 3: Preferred Transport Strategy Selected

4) **Phase 4:** Detailed Design and Planning for 4 weeks

a. Detailed Design of Preferred Strategy

   i. Develop detailed designs for the preferred strategy.

b. Risk Assessment and Mitigation

   i. Identify potential risks and develop mitigation actions to address them.

c. Develop Implementation Plan

   i. Create a comprehensive implementation plan

Milestone 4: Detailed Design and Implementation Plan Approved

5) **Phase 5:** Implementation for 2 years

a. Infrastructure Development

   i. Number of factories to be built: 18 factories

   ii. Location of the factories to be built: Afuá, Beruri, Coari, Humaitá, Itacoatiara, Limoeiro do Ajuru, Luís Domingues, Marapanim, Mocajuba, Nova Olinda do Maranhão, Óbidos, Oeiras do Pará, Ponta de Pedras, Porto Velho, Rio Branco, São Domingos do Capim, São Miguel do Guamá, Sena Madureira

   iii. Each factory construction time: 2 years

   iv. Each factory construction cost: 4.75 million$

   v. Each factory capacity: 150t of products a day

b. Develop Transport Network

i. Production Sites and Daily Production: Top 5 sites: Limoeiro do Ajuru:34.20 tons/day, Codajás: 25.56 tons/day, Oeiras do Pará: 23.28 tons/day, Afuá: 8.06 tons/day, Mocajuba: 7.62 tons/day.
ii. Transport Modes: 8 ferries with freezer (8 for echelon 1 + 0 for echelon 2), 235 mid-size ferries (71 for echelon 1 + 164 for echelon 2), 354 refrigerator trucks (178 for echelon 1 + 176 for echelon 2), 83 normal trucks (83 for echelon 1 + 0 for echelon 2)
iii. Port Location: São Luís, Manaus
iv. Port Capacity: Assumption: Capacity will always be enough

Milestone 5: Infrastructure Completed

6) **Phase 6:** Complete Implementation and Supervision for 1 year

a. Full Implementation
    i. Execute the transport plans throughout the designated regions in the Amazon area.

b. Monitoring and Assessment
    i. Keep a close eye on the implementation to evaluate its effectiveness and progress.
    ii. Make necessary adjustments after conducting periodic assessments to make sure that the strategies are meeting the goals.

c. Reporting and Communication
    i. Maintain transparent communication with all stakeholders involved, providing regular updates on progress and outcomes.

Milestone 6: Full Implementation Achieved

7) **Phase 7:** Review and Optimisation for 6 months

a. Post-Implementation Review
    i. Conduct a thorough project evaluation to determine the project's success and identify lessons learned.
    ii. Break even time: 1.93 years

b. Continuous Improvement
    i. Apply any necessary modifications based on the review findings to better optimise the transport plans.

Milestone 7: Project Closure

4.3 Summary and Conclusions

The bioeconomy has been a rising economic gold mine in the Amazon Forest for the past decades, however, lack of optimisation and planning could result in deforestation and harm to the delicate ecosystem in the region. In this report, we proposed methodologies to approach this problem. Data gathering methods and data analysis of key stakeholders and geographical landscapes ensure data-driven models and strategic planning. Exploration in network and sequential supply chain optimisation proposes six strategies with the goal of minimising cost and/or time. The literature review allows us to weigh eight critical factors namely, energy efficiency, digital access, construction and maintenance cost, potential volume growth, job creation, environmental impact, sensitivity to climate change, and safety and security. These weighted KPIs are then used to quantify the benefits of each strategy. The network optimisation with minimising time as the objective function provided the highest beneficial impacts and thus is selected to be the optimal strategy. The strategy has the potential to generate over 6570 jobsjobs, 150,156,176 USD profit, and under 2 years return of investment after full-scale operation. Furthermore, we have proposed the visualisation and roadmap which could provide implementation guidelines. Though the research was conducted using Açai berry, Brazil nuts, and Pirarucu as the three main bioeconomic products, we developed the methodology, proposed technology, and optimisation algorithms with the aim for general bioeconomics in mind, thus allowing this study to be adapted and utilised within the bioeconomic supply chain logistic market.

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Appendix: Code Access

The following list of codes can be found using the GitHub link provided in this section.

The code included in the GitHub are

1. Forecast: Using Holt-Winter forecasting to predict the Acai and Brazil nuts production

2. Location Extraction: Using Geocoder python library to extract coordinates of all towns with Acai and Brazil nuts production, then plotting the location on the world map

3. Model 1-Network Optimisation: Factory allocation and all echelon routing in one network optimisation algorithm

4. Model 2-Sequential Optimisation: 2 optimisation steps, 1. Capacitated factory location (Town --> Factory) 2. Port routing (Factory --> Port)

5. Visualisation: Plotting facility location and route for Model 1 Min Time Strategy

GitHub link: https://github.com/BhuminTechakul/GDP_6/tree/main