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Optimization of the Design of Cycle Networks: Application in the City of Rio de Janeiro

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Abstract*– Cycling networks are an attractive and important factor for the use of bicycles as a means of transport. These networks consist of bike routes, which can be separated from motorized traffic or not. The goal of the cycling network is to connect cyclists' points of origin and destination, offering the most suitable routes between points of interest. The work proposes a mathematical model to optimize the design of these cycling networks, applying it in the neighborhoods of Botafogo and Urca, in Rio de Janeiro. Travel-generating hubs were identified through GIS modeling using QGIS software. The AIMMS software was employed to apply the mathematical model for optimizing the cycling network. There is also an argument in favor of a systemic approach in selecting infrastructure projects, aiming to minimize costs compared to simpler approaches. The study recommends increasing the number of bike racks to make the multimodal transportation system more efficient.

Keywords*-- Cycling networks; Bike routes; Mathematical model; Travel-generating hubs; Geographic information system.

I. INTRODUCTION

Amid so many crises that have occurred in recent years, political, economic, health, and environmental, cities have been gripped by tensions and this has been reflected in their appearance and social relations. According to Reference [1], the transport sector suffered significant impacts caused by the implementation of social isolation policies, to contain the population's contamination by the Covid-19 virus. This fact generated a drop in demand for public transport, in all systems, both bus and rail modes, leading to negative economic and financial impacts for operating companies. Despite all these problems, social isolation favored the use of active modes and the bicycle had great prominence.

Encouraging the use of bicycles as a mode of transport can be the most economical way to facilitate the population's access to various daily activities in cities, such as work, studies, services, public facilities, and leisure. In addition to facilitating access, active modes are good for the individual's health, as they promote physical activity, preventing diseases caused by a sedentary lifestyle and contributing to improving people's quality of life. The use of bicycles is also important for the environment, as it is a means of transport that does not emit greenhouse gases, which can help improve air quality in cities.

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According to Reference [2], between 2002 and 2012, there was a growth of more than 100% in the use of individual transport by cars in the world and Brazil followed this trend. However, it is important to say that the country has more than 80% of the population living in urban areas, therefore it is necessary to implement efficient, integrated transport systems that mainly promote quality of life for its inhabitants.

Some factors can influence the user's decision between choosing one mode of transport or another, such as safety, comfort, waiting time, travel time, distance, fare value and others.

Therefore, the implementation of cycling networks can be an attractive factor for the use of this means of transport. Cycle networks are bicycle routes that can be defined with cycle paths, cycle lanes, or cycle routes. These sections may or may not be segregated from motorized traffic. The purpose of these networks is to connect cyclists' points of origin and destination, offering the most appropriate routes between points of interest.

The purpose of this research is to suggest a mathematical model that optimizes the configuration of cycle networks. This model will be applied specifically to the neighborhoods of Botafogo and Urca, in the city of Rio de Janeiro, to integrate the proposed network with the existing network in the city.

II. LITERATURE REVIEW

It is important to develop tools that help public managers and decision-makers in choosing the best configuration for cycle networks. These tools need to have parameters capable of bringing possibilities to maximize system efficiency and minimize implementation and maintenance costs.

A qualitative study carried out in the Portland region of the United States revealed that the main barrier to bicycle use is related to adverse conditions, such as high traffic volumes and lack of safety [3]. Furthermore, the lack of cycle paths or cycle paths close to their homes and workplaces is identified as the second biggest barrier faced.

In the research carried out in Reference [4], on the impacts of interventions to encourage active transport through bicycles. They evaluated 139 studies and concluded that cities that adopted blunt packages with multiple interventions have experienced large increases in the number of trips and the proportion of bicycle users.

Reference [5] propose mathematical models to optimize multimodal transport systems that include shared bicycles and networked public transport. The models consider different demand groups, route options, vehicle capacity, waiting time, travel time, and transfer penalties, to minimize the total cost of the system, including the passenger cost and the operator cost.

Reference [6] propose a new formulation for the network design problem related to adapting existing road infrastructure for bicycles, while Reference [7], present a mathematical model to design bicycle networks that integrate with public bus transport services in urban areas. The model maximizes 14 objectives and 14 constraints related to pavement comfort, safety, path objectivity, network connectivity, intermodality with bus service, and budgets.

Reference [8] propose a methodology to design an equitable network of cycle paths in urban areas, taking into account the principles of equity and accessibility. Reference [9] present a cycle path network design problem, that aims to maximize accessibility, minimize the number of intersections, maximize the level of bicycle service, and minimize the total construction cost, subject to space-time restrictions and budget.

Reference [10] discuss the development of an assessment index for urban cycle paths based on 14 criteria related to social, technical, and environmental aspects. The study presents the history of cycle paths in Rio de Janeiro and the need for a more realistic evaluation method adapted to the real conditions of streets and cycle paths. The Viable Bike Lane Index (VBI) is divided into three dimensions and six themes and is intended to be used as a practical tool by municipal authorities, transportation planners, traffic engineers, and others to determine the quality of bike lanes. The VBI is simple and quick to apply on a cycle path and is intended to be a useful tool for bodies managing cycle paths in the city of Rio de Janeiro and its surroundings and can also be used in cities with similar characteristics.

Several factors can interfere with the user's choice of whether or not to use a particular mode of transport. In the approach taken in Reference [11] it is necessary to take into account variables related to thermal comfort. In the research, they analyze the feasibility of using an outdoor heat demand-temperature function to predict long-term heat demand in a district heating system. In another stage, they also discuss the development of a comfort matrix for cyclists based on computational fluid dynamics, to help in the planning of new cycling routes and the development of intelligent projects for urban buildings.

III. METHODOLOGY

As evidenced in the literature, the definition of an optimized route considers the determination of demand, points of interest and flow-generating poles, minimum paths, and infrastructures. Therefore, the choice of method and material used was based on studies carried out in Reference [6], where the objective is to connect all origin-destination pairs with paths that meet or exceed a lower limit of cycling service level.

At this stage, the study required the demarcation of a specific perimeter, where two contiguous neighborhoods were designated, Botafogo and Urca. The selection of these neighborhoods was carried out randomly, to validate the proposed mathematical model. However, the choice of traffic zones to be analyzed within these neighborhoods was made taking into account the demand of users in the region. The essential data to establish this delimitation were obtained from the publicly accessible database provided by the City of Rio de Janeiro, known as DataRio. Additionally, georeferenced data from the city was extracted, such as a map with traffic zones and public areas.

Then, the Geographic Information System (GIS) was used through the QGIS software for spatial analysis. In this context, it was necessary to identify the intersections between the public places to obtain the network nodes and the connections between these nodes, which are the links. After this step, it was possible to extract the distance matrix, which constitutes the data basis for obtaining the spreadsheets necessary in the network optimization phase using appropriate software.

In this next phase, which can be considered as the data processing phase, where it is necessary to build spreadsheets, using the distance matrix obtained in the previous phase. The configuration of these sheets is determined by the optimization software. The software used in this study was AIMMS (Advanced Integrated Multidimensional Modelling Software). It is possible to obtain a guidance manual for parameterizing the mathematical model and inserting data through Microsoft Excel spreadsheets or other similar logical support.

After the data processing stage, the network optimization phase begins with the help of the AIMMS software. It is essential to insert all the parameters described in the mathematical model into the system, as mentioned previously. To make construction easier, there are instructions provided within the software itself. Subsequently, it is necessary to insert the spreadsheets created in the previous phase and then run the model to obtain the optimized network. At this stage, the software provides all possible routes within the network and highlights the optimal route according to the parameters and constraints of the mathematical model.

The final phase consists of analyzing the results, in which the arcs or links selected after network optimization are identified. In this way, it was possible to establish the proposed network between the chosen origin and the suggested destination. This allows additional analyzes to be performed as described in the Results section.

IV. MATHEMATICAL MODEL

The optimal configuration of cycle paths, cycle lanes, or cycle routes in a given urban area is a complex process that involves the consideration of several criteria. These criteria include minimizing the distance travelled by cyclists, maximizing connectivity between different points in the city, minimizing conflicts with motor vehicle traffic, maximizing safety for cyclists, and optimizing available resources.

The proposed model for the optimal network configuration has as its premises the minimization of distances, subject to restrictions on implementation costs, network maintenance, and available budget.

Sets

- i, j, k: Nodes in the network
- o: Origen nodes in the network
- d: Destination nodes in the network

Parameters

- lv_{ij}: Arc Distance (i, j)
- LR^{od}: Maximum distance a cyclist is willing to cycle to cover the pair (o, d)
- c_C: Unit cost for the construction or expansion of a road
- B_C: Budget for road construction
- c_M: Unit cost for maintenance on a track
- B_M: Budget for road maintenance per year
- M: large number

Decision variables

$$P_{ij}^{od} = \begin{cases} 1, \text{ if the arc } (i,j) \text{ is select to hedge the pair } (o,d) \\ 0, \text{ Otherwise} \end{cases}$$

$$X_{ij} = \begin{cases} 1, \text{ if the arc } (i,j) \text{ is select} \\ 0, \text{ Otherwise} \end{cases}$$

Objective function

$$Min\ Z = \sum_i \sum_j lv_{ij} X_{ij} \quad (1)$$

Restrictions

$$\sum_i P_{oi}^{od} = 1 \quad \forall o, d \quad (2)$$

$$\sum_j P_{jd}^{od} = 1 \quad \forall o, d \quad (3)$$

$$\sum_j P_{kj}^{od} - \sum_i P_{ik}^{od} = 0 \quad \forall o, d, k \quad (4)$$

$$\sum_o \sum_d P_{ij}^{od} \leq M X_{ij} \quad \forall i, j \quad (5)$$

$$\sum_o \sum_d P_{ij}^{od} \geq X_{ij} \quad \forall i, j \quad (6)$$

$$\sum_i \sum_j lv_{ij} P_{ij}^{od} \leq LR^{od} \quad \forall o, d \quad (7)$$

$$\sum_i \sum_j c_C lv_{ij} X_{ij} \leq B_C \quad (8)$$

$$\sum_i \sum_j c_M lv_{ij} X_{ij} \leq B_M \quad (9)$$

$$X_{ij} \in \{0,1\} \quad \forall i, j \quad (10)$$

$$P_{ij}^{od} \in \{0,1\} \quad \forall o, d, i, j \quad (11)$$

The proposed modelling aims to determine an optimized network, considering as decision parameters the shortest distance between nodes, defined by the objective function (Equation 1), associated with the lowest construction and maintenance cost, respecting budget limits and the maximum distance that a cyclist is willing to ride a bicycle to leave an origin and reach a destination.

The restrictions of the proposed model are described as follows: Constraint (2) ensures that an origin is selected for each destination. Constraint (3) guarantees the selection of a destination for each origin. Constraint (4) guarantees the flow at an intermediate node for each origin-destination. Constraints (5) and (6) help establish whether an arc (i, j) is selected. Constraint (7) guarantees that the maximum distance that a cyclist is willing to travel to cover each origin-destination is respected. Constraint (8) guarantees that the budget for road construction is respected. Constraint (9) guarantees that the budget for road maintenance per year is respected. Constraints (10) and (11) define the domain of the decision variables.

V. RESULTS

The city of Rio de Janeiro was designated as the location for carrying out experimental studies. Two adjacent neighborhoods, Botafogo and Urca, were identified as the zones for implementing the model and carrying out the analyzes. Information on public places was acquired from the DataRio open data repository. However, some routes had to be discarded due to their topographical peculiarities. All roads located in Morro Dona Marta were removed due to its significant elevation. According to data obtained from the topographic map platform, the minimum altitude in the area is 3 meters, while the maximum altitude reaches 565 meters. Additionally, some local roads with limited access to non-residents were also excluded from the data set.

To calculate the cost of implementing and maintaining cycle paths. Using the specifications for the implementation of cycling projects, version 2014, provided by the entity responsible for urban management, it was possible to analyze the costs associated with the construction of cycling infrastructure, including cycle paths, cycle lanes, and cycle routes. This cost composition allowed the estimation of maintenance costs, as well as the preparation of the necessary budget for the construction and subsequent maintenance of the cycle network.

TABLE I.
PARAMETERS USED IN OPTIMIZATION

	c_C (R$/m)	c_M (R$/m)	B_C (R$)	B_M (R$)
Scenario 1	12.06	6.03	54323.57	27161.79
Scenario 2	12.06	6.03	31922.12	15961.06

The selection of neighborhoods was based on socioeconomic indicators and transportation needs. The district of Urca, selected for scenario 1, is marked by the existence of public facilities that generate movement during working days. Furthermore, the area has a significant tourist demand and a diversity of services provided by establishments such as bars and restaurants.

Considering these attributes, the installation of cycle paths emerges as a justified proposal, especially taking into account the restricted supply of public transport in the region. Currently, the neighborhood is served by only three bus lines. The first line, originating from Central do Brasil, operates with a frequency of 15 minutes at the busiest times, between 7 am and 9 am. The second line, which starts at the Botafogo metro station, has a frequency of 30 minutes at peak times between 7 am and 9 am. It is worth noting that these lines do not operate on Sundays. There is also a third line, originating in Copacabana and heading to Urca, this has a frequency of 30 minutes at the times mentioned above for the other lines [12].

The area in focus in the second scenario is Favela Santa Marta, a community established in the Botafogo neighborhood. This location is characterized by its proximity to various public facilities, due to its location in a high-income region in the city of Rio de Janeiro. Public transport is widely available, with the nearest bus stop less than a kilometer from the top of the hill. This bus stop offers access to five bus lines, providing connections with all regions of the city. Furthermore, the nearest metro station is approximately 5 kilometers away. Due to the high slope of the region, Favela Santa Marta has an inclined plane equipped with five stations.

Based on data released by Fundação Getúlio Vargas, as presented in Reference [13], it is possible to analyse the per capita income of the general population, segmented by neighborhoods, as well as the population living in favelas. According to the 2010 Demographic Census, the per capita income of the city of Rio de Janeiro was R$1,421.76. In contrast, the per capita income of the population residing in Favela Santa Marta was R$459.00, representing approximately 32% of the average income of the Rio population. However, in the Urca region, the per capita income is R$3219.00, which is 2.26 times greater than the city's per capita income. Given these contrasting scenarios, and without disregarding the specific needs of each population about access to the city's transport infrastructure, the need to provide access to these facilities for both the high-income population and the low-income population becomes justifiable income, aiming to guarantee equal access to these structures.

A. Scenario 1: Urca (Origin - Alameda Floriano Peixoto (Escola Superior de Guerra) / Destination – Avenida Pasteur Cycle Path)

The decision for the specific location was made based on a meticulous analysis carried out in situ, taking into account data relating to the availability of public transport (buses) and the proximity of a high-capacity transport station (Botafogo Station – Metro), located to distance of 3.6 km. In addition, socioeconomic data were considered, as mentioned previously.

The distance LR^{od} chosen to cover the origin-destination (OD) pair was established at 7 km, assuming that this is the maximum distance that a cyclist would be willing to travel. The roads in the region are one-way and allow parking along them. Therefore, given the results obtained, the most appropriate road configuration for this case would be cycle routes.

Fig. 1 Area corresponding to scenario 1.
The origin is located at the red point (Escola Superior de Guerra) close to node 24. Nodes 148, 100 and 93 are the destination nodes, which is the closest existing cycle path, represented in figure by the blue line.

After complete insertion of all data concerning the origin-destination nodes and intermediate nodes, the computational result revealed the determination of an optimized route, whose distance reached 2252.221 meters.

When selecting nodes and arcs along this route, reference was made to Figure 2, which showed three potential destinations, namely, nodes 148, 100 and 93. Notably, node 148 emerged as the optimal destination, i.e., the smallest possible target as outlined by the previously mentioned parameters.

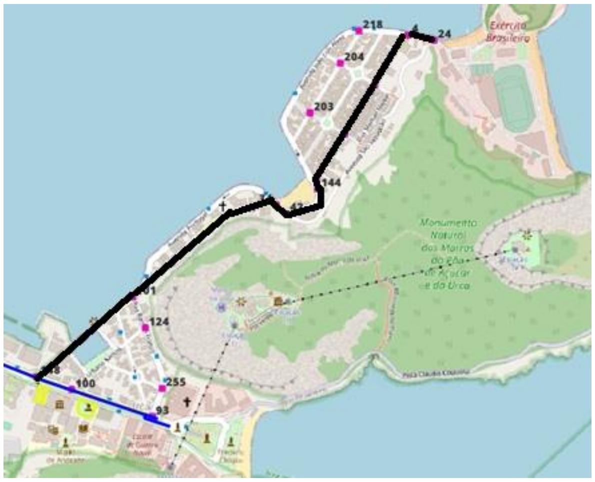

Fig. 2 Optimal route for implementing a complementary cycle network.

B. Scenario 2: Botafogo (Origin – Favela Santa Marta /Destination – Ciclovia Rua Mena Barreto)

The choice for the point was made based on data on public transport (buses) and with an approximate distance of 2 km to high-capacity transport (Botafogo Station – Metro). And again, socioeconomic data were considered, as mentioned previously.

The distance LR^{od} selected to cover the origin-destination (OD) pair was 7 km, as adopted. However, it is important to highlight that in the area corresponding to Morro Dona Marta, there is an urban cluster called the Santa Marta favela. As mentioned previously, this region is characterized by a steep topography, which makes the implementation of a cycle path unfeasible, with only the implementation being possible from the lowest part of the community.

Fig. 3 Area corresponding to scenario 2.
The source is located at the red dot close to node 134. Nodes 16, 74 and 253 are the destination nodes. The existing cycle path is indicated in blue.

A computational result was obtained that revealed an optimal route, with a distance of 1323.471 meters. In this section, nodes and arcs were selected as illustrated in Figure 4, with node 74 chosen as the optimal destination.

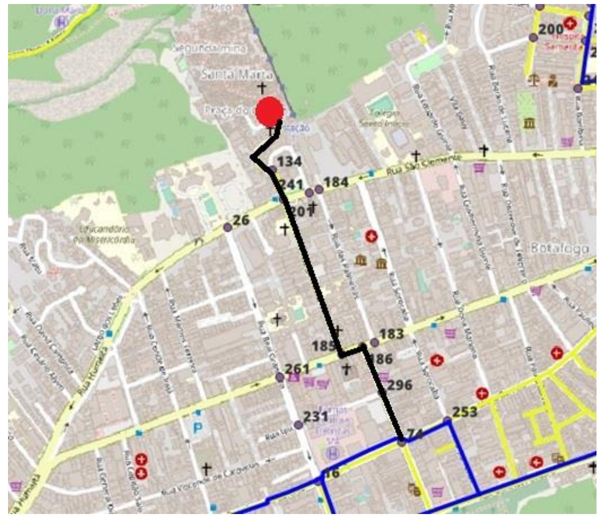

Fig. 4 Optimal route for implementing a complementary cycle network.

VI. DISCUSSIONS AND CONCLUSIONS

This work aims to investigate the design of an optimized cycle network, with the objective of minimizing the total distance subject to cost and budget restrictions. To achieve this end, a mathematical model was used to identify the most efficient route between the desired origins and destinations, considering the nodes and arcs of the network. It is important to highlight, however, that decisions regarding the implementation of a cycle network are not restricted to mathematical analysis alone. They must also incorporate other technical factors that can be integrated into mathematical modelling, but which can also constitute autonomous tools for decision-making, regardless of the results obtained in the modelling.

When analyzing some of the results presented, it can be seen that the proposed mathematical model was executed as expected. Several iterations were carried out from the origin until reaching the ideal distance. In the second scenario, the AIMMS software carried out 18 iterations under its guidance to find the ideal path for implementing the cycle network, integrated into the existing network, following the parameters and restrictions that the model proposed. In the first scenario, on the other hand, fewer iterations were required, totaling 12 iterations.

The optimal distance from the first scenario, starting at Alameda Floriano Peixoto in Urca, connecting with Rua João Luiz Alves, then passing through Alameda Gomes Pereira and reconnecting with Rua João Luiz Alves, moving forward entering Rua Cantuária and arriving at Avenida Pasteur via Avenida Portugal, was determined through the proposed mathematical model. However, there are technical factors that can make implementing this optimized route difficult. One factor that may be important when making a decision is the direction of the road, especially for cycle routes, where it is recommended that the cyclist travel in the same direction of the road. In some cases, the proposed cycling network may conflict with the direction of traffic flow, making it difficult to implement the suggested route.

The suggested model provides economic and financial support with the purpose of gathering information to build the most efficient cycling network possible. It is important to highlight that it is possible to incorporate more parameters for the analysis of the ideal network, including aspects related to road safety, cyclist comfort and the location of facilities, such as bike-sharing stations and bike racks.

It is advisable to develop new analysis scenarios, in particular more decentralized scenarios, which cover other areas of the suggested neighborhoods and other areas of the city, with the aim of integrating the entire cycling network in Rio de Janeiro. This can be achieved through the analysis and proposal of integration points with other modes of transport in the city, using the demands of using public and private transport.

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