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AN INTEGRATED INTELLIGENT ROUTING APPROACH FOR THE SUSTAINABLE OPTIMIZATION OF URBAN FREIGHT TRANSPORT IN RIO DE JANEIRO

JÉSSICA WANDERLEY SOUZA DO NASCIMENTO[1], CÍNTIA MACHADO DE OLIVEIRA[2], GABRIEL NAKALSKI FARIAS[3], LUÍS EDUARDO SANTOS FORTES[4] & GLAYDSTON MATTOS RIBEIRO[5]

[1]M.Sc., Senior Research Scientist, OPTGIS, COPPE/UFRJ, Rio de Janeiro, Brazil, jessica.souza@ufrj.br;
[2]Ph.D. in Transportation Engineering, Full Professor, PPGES, CEFET/RJ, Rio de Janeiro, Brazil, cintia.oliveira@cefet-rj.br;
[3]Civil Engineer, M.Sc., OPTGIS, COPPE/UFRJ, Rio de Janeiro, Brazil, gabriel.farias@pet.coppe.ufrj.br;
[4]Ph.D. in Transportation Engineering, Associate Professor, COENP, CEFET/RJ, Rio de Janeiro, Brazil, luis.fortes@cefet-rj.br;
[5]Ph.D. in Applied Computing, Full Professor, OPTGIS, COPPE/UFRJ, Rio de Janeiro, Brazil, glaydston@pet.coppe.ufrj.br

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ABSTRACT: This study proposes an intelligent routing model designed to sustainably optimize urban freight transportation within the road network of Rio de Janeiro. Geographic Information System (GIS) techniques were integrated with geospatial data on road infrastructure and logistical parameters to simulate different distribution scenarios using a multi-objective optimization mathematical model aimed at minimizing travel distance, travel time, and greenhouse gas (GHG) emissions. The results indicate that the proposed routing model reduced the total distance traveled by 20.4% (−22.9 km), yielding a 22.3% gain in logistics efficiency and an average 18.7% reduction in CO_2 emissions, with no significant variation observed for conventional methods. These findings reinforce the potential of the model as a robust and replicable tool for the sustainable management of urban freight transportation.

KEYWORDS: Urban logistics, Sustainable optimization, CO_2 emissions, GIS.

ABORDAGEM INTEGRADA DE ROTEIRIZAÇÃO INTELIGENTE PARA OTIMIZAÇÃO SUSTENTÁVEL DO TRANSPORTE URBANO DE CARGAS NO RIO DE JANEIRO

RESUMO: Este estudo propõe um modelo de roteamento inteligente para otimizar de forma sustentável o transporte urbano de cargas na malha viária do Rio de Janeiro. Técnicas de Sistemas de Informação Geográfica (SIG) foram integradas com dados geoespaciais da infraestrutura viária e parâmetros logísticos para simular diferentes cenários de distribuição utilizando um modelo matemático de otimização multiobjetivo para minimizar a distância percorrida, o tempo de deslocamento e as emissões de gases de efeito estufa (GEE). Os resultados indicam que o modelo de roteamento proposto reduziu a distância total percorrida em 20,4% (−22,9 km), resultando em um ganho de 22,3% em eficiência logística e uma redução média de 18,7% nas emissões de CO_2, sem variação significativa observada para os métodos convencionais. Essas averiguações reforçam o potencial do modelo como uma ferramenta robusta e replicável para a gestão sustentável do transporte urbano de cargas.

PALAVRAS-CHAVE: Logística urbana, Otimização sustentável, Emissões de CO_2, SIG.

INTRODUCTION

Urban freight logistics faces increasingly complex challenges driven by the growing demand for deliveries, saturated road infrastructure, and increasingly stringent environmental requirements (Nascimento et al., 2025). In the context of the city of Rio de Janeiro, the interaction between its heterogeneous geographic configuration and high levels of traffic congestion exacerbates the environmental impacts of freight transport, particularly with regard to greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), as highlighted by the IPCC (2019).

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Given this scenario, it is essential to adopt strategies that combine operational efficiency with environmental sustainability. In this regard, intelligent routing, structured on logistical, spatial, and environmental variables and integrated with Geographic Information Systems (GIS), enables not only the generation of optimized route plans but also the mitigation of the environmental impacts inherent to urban distribution operations (Wills et al., 2019).

Contemporary approaches indicate that intelligent routing with controlled variability, when combined with GIS (considering road network elements such as networks length, average speed, and topographic factors) and coupled with optimization techniques, can result in significant reductions in urban CO_2 emissions (Jabir et al., 2015; Guan et al., 2022). Despite these advances, methodological gaps remain in the Brazilian urban context, particularly in densely populated metropolitan areas such as Rio de Janeiro, where applications in highly complex road networks integrating GIS and multi-objective mathematical optimization models are still in their early stages (Konstantakopoulos et al., 2020).

In this way, this study aims to implement an intelligent multi-objective routing model integrating georeferenced data and environmental metrics to sustainably optimize urban freight transport in Rio de Janeiro. This approach seeks to establish consistent technical relationships across different scenarios and to develop a robust, adaptable analytical tool to support strategic decision-making in public policy and urban logistics management.

MATERIALS AND METHODS

The methodology adopted in this study was structured into four interdependent stages that, in an integrated manner, enabled the development, implementation, and evaluation of the intelligent routing model within the urban context of Rio de Janeiro.

In the first stage, geospatial data of the urban road network of the municipality of Rio de Janeiro were collected and structured. This stage involved extracting information from cartographic databases and open data sources, such as OpenStreetMap (OSM), complemented by records from the Rio de Janeiro Traffic Engineering Company (CET-Rio) covering the period from 2018 to 2022. The criteria considered included: functional classification of roads (road hierarchy), number of lanes, traffic directions, speed limits, presence of traffic restrictions (truck-restricted zones, school zones, loading/unloading areas), and the location of freight-generating points (distribution centers, supermarkets, commercial and industrial hubs). The dataset was subsequently processed in the QGIS 3.34.4 Geographic Information System (GIS) environment to ensure consistent road network topology, remove duplicate records, and standardize geometries.

The second stage consisted of integrating operational logistics data with the geospatial database, thereby creating a robust foundation for simulation. The information included: delivery volumes per destination, delivery time windows, vehicle load capacities, route frequencies, and types of vehicles employed. These data were gathered from the analysis of technical reports, such as the Sustainable Urban Logistics Plan of Rio de Janeiro (2019) and the National Inventory of Atmospheric Emissions from Road Motor Vehicles (IBAMA, 2021), as well as case studies available in specialized literature (e.g., Marujo et al., 2018). This integration allowed for the construction of realistic scenarios aligned with urban freight transport operations.

Once the database was consolidated, the third stage involved the mathematical modeling of different routing scenarios based on the Multi-Vehicle Traveling Salesman Problem (VRP), adapted to address multiple objectives. The adopted formulation simultaneously considered three optimization criteria: (i) minimization of total travel distance; (ii) minimization of total travel time; and (iii) minimization of greenhouse gas (GHG) emissions. Emissions were estimated according to the emission factors established by both the IPCC (2019) and the National Emissions Inventory, considering variables such as vehicle type, average operating speed, and road characteristics. The mathematical model incorporated the following variables (Equation 1):

- Objective function for the minimization of:

$$Z = \alpha \sum D_{ij}x_{ij} + \beta \sum T_{ij}x_{ij} + \gamma \sum E_{ij}x_{ij} \quad (1)$$

- Subject to:

$$\alpha + \beta + \gamma = 1 \; (The\ weights\ are\ calibrated\ according\ of\ the\ scenario\ under\ analysis)$$

Where: D_{ij} distance between nodes i and j [km];

T_{ij} estimated travel time between nodes i and j, derived from the traffic profile [hours];

E_{ij} estimated greenhouse gas (GHG) emissions along the route from node i to node j [kg CO_2-eq];

x_{ij} binary decision variable, equal to 1 if the route from node i to node j is selected, and 0 otherwise.

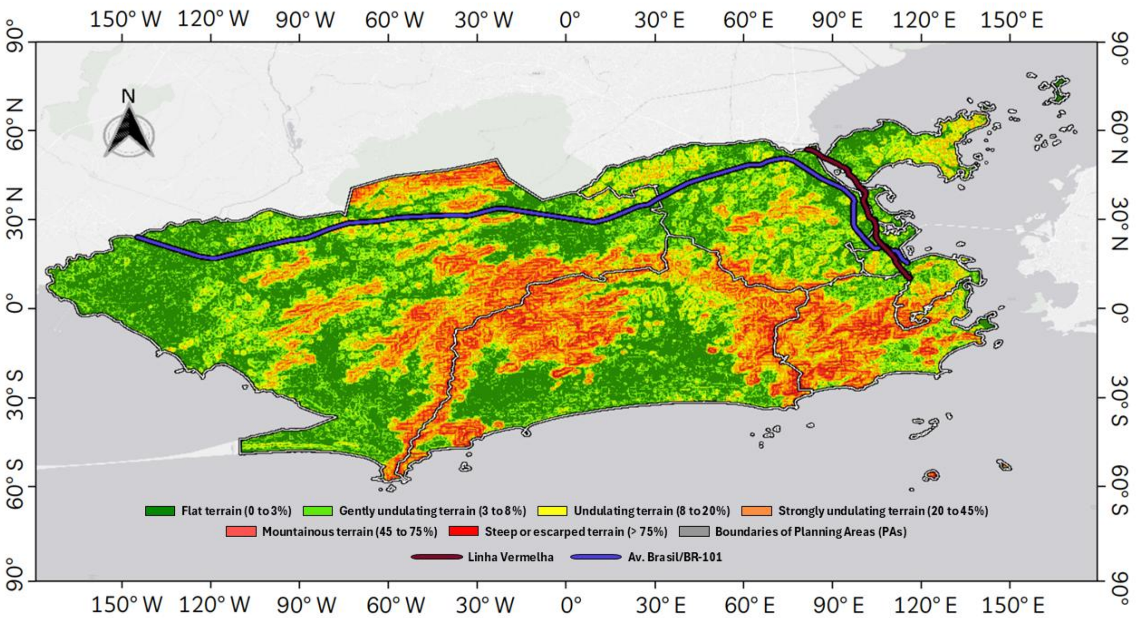
Finally, comparative analyses were performed against conventional routing approaches, including linear routing and Euclidean proximity routing, with the objective of quantifying the operational efficiency improvements and environmental impact reductions achieved by the proposed model.

RESULTS AND DISCUSSION

Following the acquisition of spatial datasets and the integration of thematic layers (including traffic restrictions, altimetry, and emission control zones) the multi-objective mathematical model was implemented in Python® (version 3.13.5) using the PyMoo optimization library. The computational experiments were conducted on a workstation equipped with an Intel® Core™ i7-7500U processor (6 cores, 12 threads, 3.9 GHz), 16 GB of RAM, running Microsoft Windows 11 (64-bit). The model formulation and solution process employed the PuLP® solver (version 2.9.0) and was integrated with a Geographic Information System (GIS) to extract relevant spatial variables corresponding to the geographic coordinates of the proposed solutions.

Based on this information, the optimized routes were concentrated along high-traffic arterial roads, most notably Avenida Brasil and Linha Vermelha, thereby avoiding areas subject to greater environmental restrictions, such as the city center, hospital zones, and areas adjacent to educational institutions (Figure 1).

Figure 1. Slope and topographic features derived from GIS.

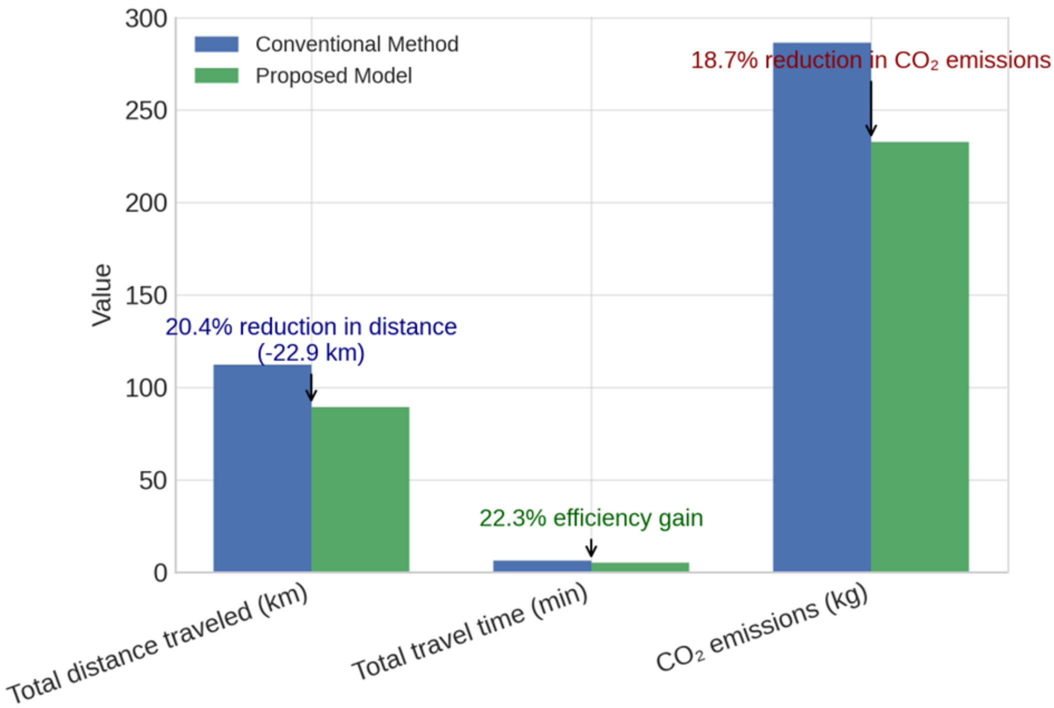


The selection of these routes is justified not only by their traffic-handling capacity (averaging approximately 170,000 vehicles per day on Avenida Brasil and 140,000 on Linha Vermelha) but also by their logistical relevance and the comparatively lower environmental impact associated with their use. Furthermore, spatial analysis indicated a reduction in route overlap and a more balanced geographical distribution, resulting in a more efficient logistics network with reduced operational redundancy.

With respect to environmental criteria, the proposed model achieved an average 18.7% reduction in CO_2 emissions, whereas conventional routing methods exhibited no significant variation (0%) in this indicator (Figure 2). This improvement is intrinsically linked to the adoption of routes optimized for topography, traffic flow, and restricted areas, as well as to the shorter distances traveled. Such a reduction is particularly relevant in densely populated urban contexts such as Rio de Janeiro, where greenhouse gas (GHG) concentrations in the transportation sector are notably high. Additionally, the application of emission factors aligned with both IPCC (2019) guidelines and the National Emissions Inventory reinforces the methodological robustness of the estimates presented.

These patterns reflect substantial operational improvements achieved with the proposed routing model when compared to conventional approaches. Specifically, the total distance traveled decreased by 22.9 km, equivalent to a 20.4% reduction, which directly contributed to shorter travel times and lower fuel consumption. This improvement translated into a 22.3% gain in logistics efficiency, representing a significant advancement in the overall performance of distribution operations, and corroborating the findings of Konstantakopoulos et al. (2020), who also reported marked reductions in CO_2 emissions and logistics costs.

Figure 2. Operational performance improvements as determined by the established evaluation criteria.



Ultimately, these results underscore the synergistic benefits of integrating environmental and operational optimization in route planning, where efficiency improvements are combined with tangible environmental gains. Such advancements directly contribute to reduced logistics costs, greater delivery reliability, and improved fleet utilization, thereby aligning distribution practices with the principles of sustainable logistics.

CONCLUSIONS

The implementation of the intelligent routing model proposed in this study resulted in substantial advances in both logistics performance and environmental sustainability within the urban context of Rio de Janeiro. By integrating geospatial road network data with specific logistical parameters through the application of Geographic Information Systems (GIS) techniques within a multi-objective optimization framework, it was possible to construct realistic operational scenarios with high potential for replication in urban centers sharing similar logistical characteristics. This integration ensured that the optimized routing solutions were not only operationally efficient but also aligned with sustainability goals in complex urban environments, thereby establishing a robust foundation for the significant performance improvements observed.

Among the main results, the most notable was the significant reduction in CO_2 emissions, demonstrating the effectiveness of intelligent routing in addressing climate change and improving urban mobility. Thus, the model not only delivers measurable quantitative gains but also serves as a strategic decision-support tool for the formulation of public policies aimed at sustainable urban logistics management.

For future research, it is recommended to incorporate real-time data through the application of Internet of Things (IoT) technologies, as well as the use of Machine Learning (ML) algorithms for traffic prediction, in order to enhance the adaptability and accuracy of the proposed models.

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