Assessing and Improving Accessibility to Public Transport in Montevideo, Uruguay

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Montevideo – Uruguay
Diciembre de 2024

UNIVERSIDAD
DE LA REPUBLICA
URUGUAY

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Tesis de Maestría presentada al Programa de Posgrado in Investigación de Operaciones, Facultad de Ingeniería de la Universidad de la República, como parte de los requisitos necesarios para la obtención del título de Magíster en Investigación de Operaciones.

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Montevideo – Uruguay
Diciembre de 2024

Perera Nemer, Sara

Assessing and Improving Accessibility to Public Transport in Montevideo, Uruguay / Sara Perera Nemer. - Montevideo: Universidad de la República, Facultad de Ingeniería, 2024.

XI, 55 p.: il.; 29, 7cm.

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Tesis de Maestría – Universidad de la República, Program in Investigación de Operaciones, 2024.

Bibliography: p. 52 – 55.

I. Massobrio, Renzo, Nesmachnow, Sergio, . II. Universidad de la República, Postgraduate Program in Investigación de Operaciones. III. Title

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Montevideo – Uruguay
Diciembre de 2024

ABSTRACT

Public transport plays a key role in expanding the distances that people can travel using active modes of transport. Studying walking accessibility to public transportation systems is highly relevant since walking to stops can be particularly challenging for the elderly, citizens with disabilities, and the general population during bad weather conditions or in pedestrian-unfriendly cities. The first objective of this work is to present a study on walking accessibility for the public transport system in Montevideo, Uruguay. The proposed methodology combines information from the bus stops and lines that operate in the city, the road infrastructure, and demographic data to compute walking accessibility indicators to the public transport system. The results of the analysis suggest that 92.38% of the population can access at least one stop when walking up to 400 meters. This value is lower than previous figures reported by the transport authorities that estimated a value of 97% for the same indicator using a less comprehensive methodology. Results also show that accessibility values are not evenly distributed among the population, with young citizens and men showing lower levels of potential mobility compared to their counterparts. Making use of this indicator, the second objective of this work is to define and address the bicycle parking facilities location problem. The goal of this optimisation problem is to improve accessibility by finding suitable locations for bicycle parking facilities to encourage cycling as an alternative access mode. Two types of algorithms are explored to solve this problem: a greedy heuristic and an iterated local search. Results obtained by the algorithms show that the percentage of the population with access increases to 93.41 % by installing just five of these facilities. These improvements help reduce the gap between population groups, with men and children getting a greater benefit from the investments.

Keywords:
accessibility, public transport, bicycle parking facilities, optimal location.

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Acronyms

BRT Bus Rapid Transit 7

BSS Bicycle Sharing System 11, 12, 14, 16

GIS Geographic Information System 12

ILS Iterated Local Search 25, 41, 44, 46, 49, 50

IM Intendencia de Montevideo 31

INE Instituto Nacional de Estadística 28, 29, 31, 32, 35, 37

QoS Quality of Sevice 5

RN Road Network 17

SA Service Area 17

TRSE Transport Related Social Exclusion 6, 15

Contents

Chapter 1

Introduction

The organisation of transport systems conditions the mobility of people, limiting their ability to participate in society and generating different forms of social exclusion (Audirac, 2008). In particular, geographic exclusion consists in the lack of auto-mobility and access to public transport systems. The importance of ensuring mobility for non–automobile users to reach destinations beyond normal walking range is key for the mitigation of this type of exclusion.

Public transport systems complement the use of active modes of transport (e.g., walking, cycling) by extending their range. Thus, an increase in the use of public transport can deliver significant health benefits, as this mode almost always includes a stage with physical activity (van Soest et al., 2020). In particular, studying walking accessibility to public transport is relevant since the majority of users access networks in this manner. Passengers make their route choice based on the entire trip, including entering and exiting the public transport network (Brand et al., 2017), and tend to have an aversion towards long walks. However, passengers accept longer access and egress distances to and from the public transport network when the characteristics of the transport service (e.g., speed and frequency) improve. Moreover, time is valued differently by passengers on each part of the trip. It is estimated that passengers value walking time up to 1.65 times more compared to in-vehicle time (Abrantes and Wardman, 2011). Therefore, a reduction in access times would render a greater reduction in the perceived total travel time for passengers.

On the other hand, the use of bicycles as an access mode to public transport systems can increase their coverage. Compared to walking, people who cycle to public transport travel 2.7 times further to reach an entry point on average (Rijsman et al., 2019). Thus, by encouraging the use of bicycles, the catchment areas of public transportation stops or stations can be extended without making major changes to the systems. However, research on cycling as an access mode has been mainly centered on their influencing factors while bicycle parking has received little attention, despite the fact that bicycles are parked most of the time (Heinen and Buehler, 2019). Even if the level of evidence on the importance of bicycle parking is limited, there is a consensus that bicycle parking supply and quality are determinants of cycling for current and potential cyclists (Heinen and Buehler, 2019). A way of encouraging cycling to public transport is to install bicycle parking facilities near the stations or stops. Nevertheless, locating them to maximise the coverage of the system is not a trivial task. Works that have addressed similar optimisation problems have developed tailor-made solutions with different types of algorithms (Chien and Qin, 2004; Mix et al., 2022; Taplin and Sun, 2020).

This thesis addresses walking accessibility to public transport networks and how to improve it by installing bicycle parking facilities. Also, it presents a case study focusing on Montevideo, Uruguay; where these issues are thoroughly addressed and avenues for enhancing access are explored. Therefore, the research reported in this thesis has two main objectives:

- Assess waking accessibility to public transport in Montevideo, Uruguay, from a potential mobility approach.
- Propose a solution to increase the coverage of the system that involves encouraging the use of bicycles as an access mode by finding suitable locations for bicycle parking facilities.

The main contributions of this thesis are:

1. A review of the literature on walking and bicycle accessibility to public transport systems.
2. A review of the literature on optimal location of bicycle parking facilities in the context of public transport.
3. An assessment of walking accessibility to public transport in Montevideo, Uruguay, along with three different accessibility indicators built through a geospatial analysis.
4. A mathematical formulation for the bicycle parking facilities location problem, an optimisation problem consisting of finding suitable locations

for bicycle parking facilities in order to maximise the added accessibility to the public transport system.

5. The implementation of two different heuristics to solve the bicycle parking facilities locations problem and their experimental evaluation.

Regarding the first objective, the results of the accessibility indicators suggest that 92.38% of the population can access at least one stop when walking up to 400 meters. This value is lower than previous figures reported by the transport authorities that estimated an accessibility of 97% using a less comprehensive methodology. Results also show that accessibility values are not evenly distributed among the population, with young citizens and men showing lower levels of potential mobility compared to their counterparts. Regarding the second objective, the results of the algorithms to find the best locations for the bicycle parking facilities show that the percentage of the population covered by the system can be improved to 93.41% by installing five of these facilities.

This thesis has led to the publication of two conference articles. The details of the publications, along with a brief description of their contents, are presented next.

- Perera et al. (2022) presented at ICSC-CITIES 2022: V Congreso Ibero-Americano de Ciudades Inteligentes, outlines the methodology and initial findings of walking accessibility indicators for the case study Montevideo, Uruguay.
- Perera et al. (2023) presented at XXII PANAM 2023: Pan American Congress on Transport and Logistics, outlines the outcomes of walking accessibility indicators and the initial findings of bicycle parking facility locations, employing a greedy algorithm approach for Montevideo, Uruguay.

Additionally, the work presented in this thesis has been accepted for inclusion in a book titled *Making Way for Accessibility*, part of the series *Routledge Advances in Regional Economics, Science, and Policy*.

The remainder of this thesis is structured as follows. In Chapter 2, a review of the most relevant related works in the context of this thesis is presented. Chapter 3 provides a comprehensive outline of the proposed methodology, delving into the accessibility indicators and the optimisation algorithms. In

Chapter 4, the case study and the main results are shown, along with the limitations and issues that arose in the process. Finally, Chapter 5 presents the main results and conclusions along with the main lines of potential future work.

Chapter 2

Related work

This chapter presents the reviewed related literature. Section 2.1 offers an overview of existing works concerning walking accessibility to public transport systems. In Section 2.2 the focus shifts to prior research on identifying optimal locations for bicycle parking facilities. Finally, Section 2.3 provides a summary of the reviewed works and reflects on the contribution of this thesis to the existing literature.

2.1. Accessibility and access modes to public transport

Sustainable urban development requires replacing private means of transport with the use of public transport services. This mode change can only happen if the quality of public transportation increases along with its attractiveness. Thus, Susnienė (2012) stated that improving the inefficiencies of public transport systems helps with increasing its engagement. The authors proposed the application of a model to assess the Quality of Sevice (QoS) to provide valuable information for transport service companies on necessary improvements. Conclusions revealed that one of the numerous deficiencies a public transport system may exhibit is the long distances required to access the public transport network.

The literature identifies various forms of exclusion stemming from the organisation of transportation and its interaction with the urban environment. Audirac (2008) categorised these dimensions as physical, fear-based, geographic, economic, time-based, and social exclusion. These barriers condition the mobility of people and consequently restrict their participation in society. In the context of this thesis, geographic exclusion is particularly pertinent, as it involves traveling distances beyond the typical walking range to access public transportation systems.

Luz and Portugal (2022) presented an in-depth analysis of the specifics of Transport Related Social Exclusion (TRSE) and provided a framework that considers how individuals may be prevented from accessing valued opportunities. Three big groups on the dimensions of accessibility were proposed: abilities of individuals, transport, and land use. Within land use, the most relevant category in the context of this thesis is the sub-category of geographical exclusion. Geographical exclusion occurs when residence location hinders access to transportation services. The work concluded that the spatial coverage of transport networks and connectivity are factors that limit the capabilities of citizens.

Studying walking accessibility to public transportation is highly relevant in order to assess and mitigate exclusion. Also, the walk to stops or stations is generally challenging for children, the elderly, citizens with disabilities, and the general population during bad weather conditions or in pedestrian-unfriendly cities. To delve further into accessibility to public transportation, two different approaches have been applied in the literature to study the matter: observed and potential mobility. This thesis follows a potential mobility approach, which is strongly related to accessibility (Black, 2002; Martens, 2015). Potential mobility indicators seek to identify the number of opportunities individuals have under a specific cost parameter in terms of time or distance. When studying accessibility to public transportation, the access method consists of walking through the streets and each stop in the system is considered as an opportunity to enter the public transportation network. The most common approach when computing the accessibility of a transportation network is considering the proportion of the population that can access the network by walking up to a certain predefined distance or time threshold. Conversely, observed mobility measures the distance (or time) walked to access a public transportation network in the most accurate manner for a specific sample of trips. Previous works based on this approach use information from surveys stating the origin points and the access points to the public transportation network or reporting the approximate distance or perceived time of the walk for users (Daniels and Mulley, 2013; García-Palomares et al., 2013; Rijsman et al., 2019).

Regarding potential mobility, Martens (2015) put forth a framework that simultaneously assessed accessibility and potential mobility provided by the transport system. The authors asserted that is important to appraise both matters because potential mobility does not guarantee accessibility as having the potential to move does not automatically translate into easy access to different places. Even if there are transportation options available, other factors such as connectivity, efficiency of transportation networks, and land use planning influence how accessible different locations are. Hence, the authors aim to provide a more comprehensive approach to accessibility to assess the performance of the public transport system.

Black (2002) linked transport sustainability with potential mobility, emphasising the necessity of explicitly considering the level of potential mobility that the economy can sustain. Specifically, they propose an index based on the difference between the level of sustainability and the level of potential mobility, standardised for population size and units of measurement. Moreover, the index was computed for a number of different policy and regulatory situations. Finally, the limitations of the index were presented along with some recommendations to mitigate them.

Even if this thesis has a potential mobility approach, there is substantial knowledge to derive from observed mobility. van Soest et al. (2020) presented an extensive review on walking accessibility to public transport. The authors examined existing literature on how walking relates to the use of public transport and studied walking access and egress distances. The authors concluded that distances depend on the particular location and circumstances, ranging from an average distance of 170 m to buses in Calgary, Canada (Lam, 1982) to an average of 1392 m to terminal Bus Rapid Transit (BRT) stations in Jinan, China (Jiang et al., 2012).

García-Palomares et al. (2013) analysed the role of accessibility by walking to traffic for the Madrid Metro network through a mobility survey from November 2004. The survey provides the coordinates for the origin of the trips and the name of the station where the subway was boarded. This information, together with street network layers and sociodemographic data at the zone level, made it possible to calculate access distances and the population covered by the system. Also, different decay functions were estimated and the sensitivity of the population groups was measured. Two indicators based on decay functions were proposed to measure the quality of access and potential demand. The results showed that young people and adults, men, immigrants, and the captives of public transport were willing to walk longer distances. The access quality indicator showed that the group in the worst situation is children.

Daniels and Mulley (2013) investigated the factors influencing the distances walked to access public transport for each transport mode. The authors found that the median walking distance is 364 m for buses, while the average is 461 m. The analysis was conducted using information from the Sydney Household Travel Survey. The walking distance traversed from the residence of the individual to the public transport stop was computed as the most direct route possible via the road network. The authors concluded that the mode of transport was the most influential variable in the distance of the walk. Another remark is that city planners often make assumptions about the walking distance to access public transport and that the guidelines are usually to use a distance of 400 m. The origin of these commonly used guides is unclear, although it may be related to the article by Neilson and Fowler (1972).

Brand et al. (2017) argued that transport planners and service operators often fail to include the entire journey made by users. This omission is of utter importance since passengers make their choice of transport network and mode based on the entire trip, including entering and exiting the network. The authors modeled total travel time as the sum of entry, waiting, in-vehicle, and exit times. The valued time of each of these travel stages was determined by multiplying the travel time by a weighting factor. Abrantes and Wardman (2011) demonstrated the significance of this weighting, as time holds varying value throughout each segment of the journey. The factor for in-vehicle time was 1, for waiting time was 1.70, and for both entry and exit time was 1.65. Hence, waiting time emerged as the most esteemed aspect of the journey, nearly doubling in value compared to time spent in-vehicle. The authors concluded that passengers accept longer entry and exit distances when the characteristics of the bus service are better, such as higher speeds and frequencies.

Rijsman et al. (2019) demonstrated that walking is the most common access mode to public transport systems but the use of bicycles can increase the catchment areas of public transport stops. A survey was conducted on board for four tram lines in The Hague, Netherlands. Results showed that the median distance walked to access the network is 380 m while the median distance cycled as an access mode is 1025m. The walking distance was calculated as the distance through the road network from the point of origin to the station of entry to the transport system. With this survey and a regression analysis, it was found that the stop density and the chosen access mode are the most significant factors in defining the access distance. Also, the choice of access mode, the density of stops, the availability of a bicycle, and the frequency of use are considered influential.

Advani and Tiwari (2006) reported results on cycling as an access mode in Delhi, India. The results were derived from a survey conducted among bus commuters utilising various bus routes. Key findings revealed that the access trip distance for bicycles as the access mode ranged from 3 km to 8 km. The results also highlighted unmet needs, as individuals who own bicycles refrain from using them due to the lack of parking facilities at bus stops and inadequate cycling infrastructure along the roads.

Regarding accessibility through public transport in the specific case study of Montevideo, Uruguay, there are several relevant works pertinent to this thesis. Hernandez et al. (2020) addressed accessibility to employment opportunities, while Hernández and Rossel (2022) analysed accessibility to hospitals, and Hernandez (2018) explored accessibility to education centers. However, none of these studies specifically addressed access to or egress from the public transport network.

Mauttone and Hernández (2017) summarised the principal findings of a household mobility survey conducted in Montevideo in 2016. The primary aim of the survey was to obtain a comprehensive overview of mobility within Montevideo. In this survey, participants were asked to provide rough estimates of their walk to stops for those trips involving public transport. However, since the survey primarily concentrated on mobility instead of public transport, walking to public transport was divided into two categories: walks less than five blocks and walks equal to or exceeding five blocks, with the latter being considered a distinct trip segment. Because of this, the data collected can be misleading to analyse walking to public transport.

The transport authorities suggested certain figures regarding walking accessibility to public transport in the press. Menoni (2022) stated that nearly 97% of the population in Montevideo is covered by the public transport network when considering a walking threshold of 400 m. The distances depicted in these figures were determined using stop buffers based on Euclidean distance, a method that may overestimate coverage by not considering the actual walking routes through the road network. However, these figures do corroborate that the city planners of Montevideo similarly adhere to a fixed distance of 400 m as guidelines, offering a reference accessibility value for comparison.

Finally, regarding the contribution of this thesis to the existing literature, its significance lies in the absence of prior studies focusing on walking accessibility to public transport for Montevideo, Uruguay. As far as I am aware, this thesis represents the inaugural endeavor for this case study filling a gap in prior research.

2.2. Optimal location for bicycle parking facilities

In a public transportation system where the main method to access and egress is walking, encouraging the use of bicycles can extend the coverage as the catchment areas of the access points increase without making major changes in its infrastructure. An expensive alternative, of course, would be adding stops to the system but that would require changing the line routes as well, impacting on the planning and operation of the system.

Gutiérrez et al. (2020) studied the willingness of citizens to change from their habitual mode of transport to cycling. The authors analysed change in daily commutes to work or study during the morning peak in Santiago, Chile. Results showed that the willingness to change to cycling diminishes with the length of the trip and the age of the individual. Also, people more used to their current mode are less willing to change it. Moreover, conclusions also determined a need for structural changes to diminish the latent perception of insecurity held by less experienced cyclists.

This is highly relevant for the specific case of Montevideo, Uruguay. Nesmachnow and Hipogrosso (2022) concluded that bicycle is not currently regarded by users as a convenient access mode for public transportation, due to the lack of infrastructure for safely parking bicycles in the city. The study was conducted in a residential zone in Parque Rodó neighborhood and applied the Transit Oriented Development paradigm to assess the current mobility situation. Main results indicated that the studied area has a very good potential for developing sustainable mobility.

In recent years, cycling research has been more focused on the different factors that can promote cycling in comparison to bicycle parking studies, which have received less attention. Heinen and Buehler (2019) conducted a comprehensive review of the scientific literature on bicycle parking. Almost 100 peer-reviewed papers were taken into account between 1995 and 2017. The authors concluded that the level of evidence on the importance of bicycle parking is limited. However, the results also indicated a consensus on the importance of the supply and quality of bicycle parking for both current and potential cyclists.

Taplin and Sun (2020) addressed an optimal location problem with accessibility measurements. The authors examined the problem of designing an internal feeder bus route as an integral part of residential planning. Bus stops were located in places that provided the best access from dwellings and the route was fitted to the stops. A walking distance response function was used to reflect the increasing disutility of travelling further to get the bus. The optimisation problem was set to find the best locations for the bus stops by maximising total utility of the walking interaction between dwellings and bus stops. A genetic algorithm was applied to solve this problem through a systematic search to determine the optimum solution.

Similarly, Chien and Qin (2004) developed a mathematical model to optimise the number and locations of bus stops for a simple case study: a portion of a bus route with predefined potential locations. The cost function was the sum of the increased supplier and user costs, including the access, wait, and in-vehicle costs. An ad-hoc optimisation algorithm was applied to obtain the number and locations of bus stops that minimise the cost.

Even if the evidence in the literature on bicycle parking is limited, there is a similar problem that has been extensively studied in recent years concerning Bicycle Sharing Systems (BSSs). A BSS is a service that provides shared bicycles to individuals for short-term use. Users can rent bicycles from designated stations, typically located in urban areas, and return them at any other station within the system after completing their journey. It is a convenient and sustainable transportation option for short trips within a city. One of the most challenging aspects of these systems is finding the best places to install them, a problem that is very similar to the one addressed in this thesis.

Bahadori et al. (2021) conducted a systematic review of the literature on station location methodologies for BSSs. The review involved 24 relevant publications from scientific publication databases. The authors grouped Location modeling techniques into three categories: *mathematical algorithms*, *multi-criteria decision making*, and *GIS*. The most similar approach to the one in this thesis is the *mathematical algorithms*, which consists in applying adaptations of different types of renowned optimisation algorithms a case study. There is a wide variety of algorithms used, from commercial optimisation software packages to customised hybrid greedy evolutionary algorithms.

Mix et al. (2022) explored an integrated approach to model the demand for bike-sharing trips and the optimal location of stations in the system. The modeling incorporated the built environment and accessibility variables. Maximum demand coverage models were developed to allocate the bicycle-sharing stations across various proposed scenarios in Santiago de Chile. The outcomes of the optimal location models differed significantly from the observed spatial distribution of stations in Santiago, with higher density in central areas and along corridors with cycling infrastructure. This showed the benefit of an integrated modelling of the trip generation and the station location to foster higher public bicycle usage.

In a similar vein, Romero et al. (2012) presented a methodology to simultaneously model private car and public bicycle transport modes, considering their interactions. The model was used to optimise the location of docking stations in a public sharing bicycle system, to achieve a transport system as efficient and sustainable as possible. The bi-level mathematical programming model was addressed with a combination of a genetic algorithm and a stochastic process. The proposed approach was applied to the case study of Santander, Spain. A comparative analysis between the current situation and the proposed model provided valuable insights for decision-making entities.

Conrow et al. (2018) located BSSs stations across an urban region in the city of Phoenix in the United States by combining a spatial optimisation with a commercial solver based on Geographic Information System (GIS). The authors applied a covering model to assess how many bicycle stations were needed and where they should be located, so that no user would have to travel too far to access the system. Thus, at a given investment level, stations were selected to optimise access to the bike path network for the maximum number of potential users.

Consistently, Caggiani et al. (2020) proposed a BSS station location model to maximise coverage and accessibility including equality aspects. The model aimed to reduce disparities in bicycle-public transport mobility across observed population groups while simultaneously upholding predetermined standards of accessibility and coverage. The performance of the model was evaluated on a test network and a sensitivity analysis was conducted according to the available budget. Results showed that prioritising either accessibility or coverage alone, without accounting for equality, could result in an uneven distribution of accessibility across the population, potentially leading to discrimination between different demographic groups.

Based on the reviewed literature, the problem addressed in this thesis is highly important since there are few studies linking the location of bicycle parking facilities to the accessibility levels of public transport systems, and no prior studies focused on the case study of Montevideo, Uruguay; to the best of my knowledge. Since the bike infrastructure in the city is at the early stages of development, previous works focused on proposing a bike infrastructure design (Correa et al., 2023; Mauttone et al., 2017) and on evaluating the eligibility of the city for sustainable mobility initiatives (Nesmachnow and Hipogrosso, 2022).

2.3. Summary

Firstly, the literature related to assessing walking accessibility to public transportation was reviewed. Table 2.1 lists all the reviewed works and provides a brief description of each one. Based on the reviewed literature, the method proposed in this thesis can be characterised as a potential mobility approach. In contrast to observed mobility, potential mobility does not need measurements of actual distance walked to access or egress from a public transportation network as it seeks to identify the number of opportunities individuals have under a specific cost parameter. Therefore, the data needed to assess accessibility is merely the street network, the stops of the public transport system, and population data. Several approaches have been proposed to measure the distance from the origin point to the entry point of the transportation network. Nevertheless, most recent works use the shortest distance traveled through the road network from origin to the stop or station of access (Daniels and Mulley, 2013; García-Palomares et al., 2013; Rijsman et al., 2019). In that manner, the proposed methodology follows this guideline. Regarding the walking distance threshold, there is a consensus in the literature about using a distance of 400 m (Daniels and Mulley, 2013). Also, some articles have shown that this assumption is quite realistic on average (Daniels and Mulley, 2013; Rijsman et al., 2019). Few articles have studied the distance for the bicycle as an access mode and results vary depending on the case study. The median distance cycled as an access mode is 1025 m for the public transportation system in The Hague, Netherlands (Rijsman et al., 2019) while the access trip distance for the bicycle as an access mode varied between 3 km 8 km in the city of Delhi (Advani and Tiwari, 2006). The chosen distance for estimating coverage of cycling as an access mode in the case study presented in this thesis is 1000 m, which is a conservative estimate adapted to the case study of Montevideo, Uruguay.

Secondly, the literature review focused on the problem of finding the best locations for bicycle parking facilities. Table 2.2 summarises the works that were included in the review. Studies show that the level of evidence on the importance of bicycle parking is limited but there is a consensus on the importance of its supply and quality for current and potential cyclists (Heinen and Buehler, 2019). Even if the evidence on the literature on bicycle parking is limited, a similar problem that has been intensively studied in recent years is finding the best places to locate BSS facilities. A review of the literature on station location techniques for BSS is presented by Bahadori et al. (2021). They grouped location modeling techniques into three categories, being *mathematical algorithms* the one that best fits the approach taken in the present work. Within the studies belonging to this category, there is a wide variety of algorithms used, some of them applying similar heuristics to the ones addressed in this thesis. Two types of algorithms are explored in this thesis, a greedy heuristic and an iterated local search.

Overall, this thesis contributes to the existing literature by adapting and applying an existent approach to assess walking accessibility to the public transport system of Montevideo, Uruguay. Furthermore, it proposes a formulation for the problem of locating bicycle parking infrastructure with the goal of improving accessibility to the transport network. The problem is solved using two different strategies, which are evaluated and compared, providing new insights to the existing literature on a specific variant of the cycling infrastructure location problem.

Table 2.1: Summary of the related works included in the literature review on accessibility and access modes to public transport

Author	**Summary**
Susnienė (2012)	Application of QoS model for transport service companies.
Audirac (2008)	Categorisation of forms of exclusion in public transport.
Luz and Portugal (2022)	Segmentation and deep analysis on TRSE.
Martens (2015)	Framework to assess accessibility and potential mobility of a system.
Black (2002)	Relationship of transport sustainability with potential mobility.
García-Palomares et al. (2013)	Indicators on quality of access and potential demand in the Metro of Madrid.
Daniels and Mulley (2013)	Analysis on distances walked to public transport on Sydney.
Rijsman et al. (2019)	Comparison on walking and bicycle catchment areas in The Hague.
van Soest et al. (2020)	Literature review on walking access and egress distances
Jiang et al. (2012)	BRT station walk access patterns in rapidly urbanising Jinan, China.
Neilson and Fowler (1972)	Walking distances on Florida retirement area.
Brand et al. (2017)	Provide a model for total travel times in public transport.
Abrantes and Wardman (2011)	Shows time is valued differently in the individual parts of the trip.
Advani and Tiwari (2006)	Survey on access trip distances to buses for bicycles in Delhi.
Hernandez et al. (2020)	Accessibility to job opportunities by public transport in Montevideo.
Hernández and Rossel (2022)	Accessibility to health care by public transport in Montevideo.
Hernandez (2018)	Accessibility to jobs and education by public transport in Montevideo.
Mauttone and Hernández (2017)	Survey on mobility in the metropolitan area of Montevideo.

Table 2.2: Summary of the related works included in the literature review on optimal location for bicycle parking facilities

Author	**Summary**
Gutiérrez et al. (2020)	Analysis on the willingness to adopt cycling as mode of transport in Santiago.
Nesmachnow and Hipogrosso (2022)	Assess the mobility situation of a neighbourhood in Montevideo.
Heinen and Buehler (2019)	Review of the scientific literature on bicycle parking.
Taplin and Sun (2020)	Design an internal feeder bus route as an integral part of residential planning.
Chien and Qin (2004)	Optimise the number and locations of bus stops for a portion of a bus route.
Bahadori et al. (2021)	Review of the literature on station location techniques for BSS.
Mix et al. (2022)	Model demand of bike-sharing trips and optimal location of stations.
Romero et al. (2012)	Model private to optimise the location of docking stations for BSS.
Conrow et al. (2018)	Model to assess how many and where bicycle stations should be located.
Caggiani et al. (2020)	Model to maximise coverage with equality aspects for locating BSS.
Correa et al. (2023)	Model to design a bicycle network maximising modal shift.
Mauttone et al. (2017)	Optimisation framework for urban bicycle network design.

Chapter 3

Methodology for assessing and improving accessibility

The main objective of this chapter is to introduce the proposed methodology. In Section 3.1, the steps followed to compute the indicators of walking accessibility to public transport are described. In Section 3.2, the proposed approaches to solve the optimisation problem of locating bicycle parking facilities are presented.

3.1. Walking accessibility to public transport

Accessibility indicators are based on a Service Area (SA) geospatial analysis. This method consists of delimiting the portion of the Road Network (RN) from which a stop (s) can be reached within a fixed walking distance threshold (d).

The following data sets are needed to compute the walking accessibility indicators to public transport systems:

- Zoning of the studied area
- Road network of the studied area
- Population of each zone
- Geographical location of stops or stations
- List of public transport lines that operate on each stop or station

An example of service area calculation is shown in Figure 3.1. The road network is displayed in grey, the stop is marked with a green circle and an

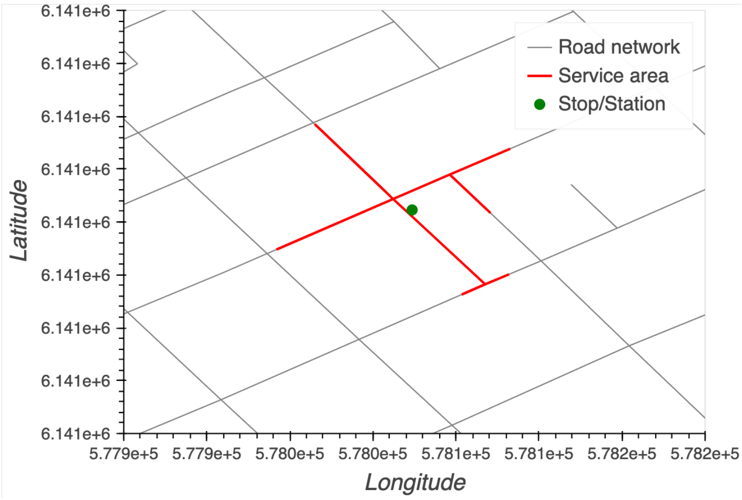

Figure 3.1: Example of service area analysis

example service area for the stop is defined in red. Since stops or stations can be located on the sidewalks, it is necessary to first project them to the nearest point in the road network before computing the service area.

Formalising the previous idea, the service area SA_i for a stop s_i, given the road network RN and a threshold walking distance d is formulated in Equation 3.1.

$$SA_i = sa(s_i, RN, d) \tag{3.1}$$

To calculate accessibility indicators in an aggregated way, a zoning of the area of study is required. Depending on the nature of the analysis, coarser or finer zonifications may be considered. The road network is often used as the delimitation of the zones. Hence, it is advisable to take a small buffer for each zone to consider roads right on the edges. Figure 3.2 shows an example of a zone that corresponds to a block, the buffer plotted in orange allows considering the portion of the road that delimits the zone in blue. Without this buffer, no portion of the road network would be considered to be inside the zone. Hence, given a predefined set of zones $z_1, z_2, ..., z_n$, the portion of the road network within each zone is considered as $rn_1, rn_2, ..., rn_n$. This idea is formally expressed in Equation 3.2, where $\cap$ is the geospatial intersection operation and $b(z_j, B)$ is the resulting polygon of applying a geospatial buffer operation of B units to zone z_j. In order not to significantly distort the calculations, it is advisable for B to be small.

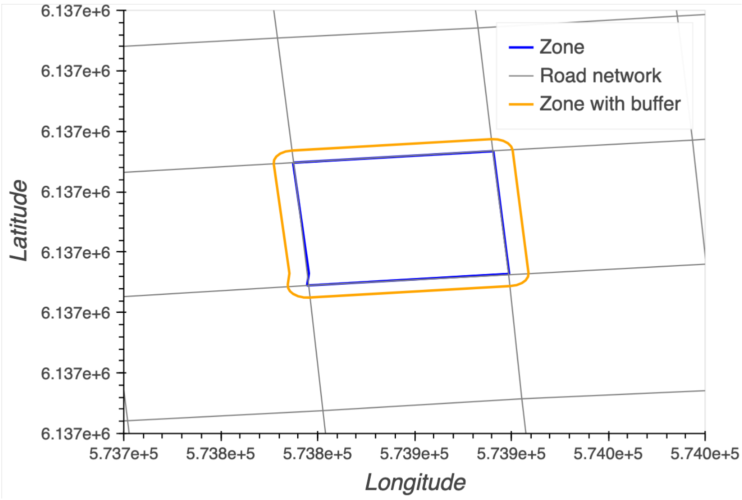

Figure 3.2: Example of zone with buffer

$$rn_j = RN \cap b(z_j, B) \tag{3.2}$$

Therefore, taking into account the previous formulations, the definition of whether a stop s_i covers a zone z_j is presented in Equation 3.3.

$$s_i \text{ covers } z_j \iff rn_j \cap SA_i \neq \emptyset \tag{3.3}$$

Moreover, given the service area of each stop and the road network portions within each zone, the overlap between these is computed to determine the coverage c_j at the zone level. A formal definition of this idea is formulated in Equation 3.4. In this manner, the coverage of a particular zone is determined by the percentage of the road network within it that is covered by the union of all service areas of the stops or stations of the system. The coverage of a zone is at 100% only if the road network within that zone is entirely covered by service areas.

$$c_j = (SA_1 \cup SA_2 \cup ... \cup SA_n) \cap rn_j \tag{3.4}$$

With these definitions, three accessibility indicators at the zone level are proposed:

1. Number of stops covering each zone at d meters
   It corresponds to the number of stops that comply with Equation 3.3 at zone level for a walking distance threshold of d. The more stops that cover the zone, the better; since it gives residents of that zone more

options to access the public transport system.

2. Number of lines covering each zone at d meters
   It is calculated as the number of different lines that operate on the stops or stations that comply with Equation 3.3 at zone level with a walking threshold distance of d. This indicator provides an estimation of the provision of public transport at those stops or stations.

3. Percentage of population covered by at least one stop at d meters
   Given the strong assumption that the population is evenly distributed in the road segments of each zone, coverage is estimated through Equation 3.4. This indicator gives the percentage of residents of the zone covered by the system at a walking threshold of d meters. These can be aggregated and also give the overall percentage of coverage for the studied area. The zoning of the studied area is of utter importance here; the finer the zoning, the more accurate the indicator will be.

3.2. Bicycle parking facilities location problem

The bicycle parking location problem consists on finding the best points to install a given number of bicycle parking facilities to maximise the accessibility to the public transport system. The underlying assumption is that individuals are willing to cover longer distances by cycling compared to walking, thereby enhancing the accessibility to public transport. In this problem formulation, any existing stop or station of the system is a potential location to install a bicycle parking facility. The following datasets are needed to define an instance of the problem:

- Zoning of the studied area
- Road network of the studied area
- Population of each zone
- Geographical location of stops or stations

Additionally, two distance thresholds need to be defined, one for walking (d_w) and one for cycling (d_c). The installation of a bicycle parking facility in a given stop results in an expansion of the catchment area of that stop, encompassing a broader coverage of the road network. Consequently, the stop becomes accessible to a more extensive demographic, accommodating a larger number of individuals and improving accessibility. Figure 3.3 shows a visualisation of how the extension of a catchment area of a stop looks like. The original catchment area of the stop is marked in red and the extension is marked in pink.

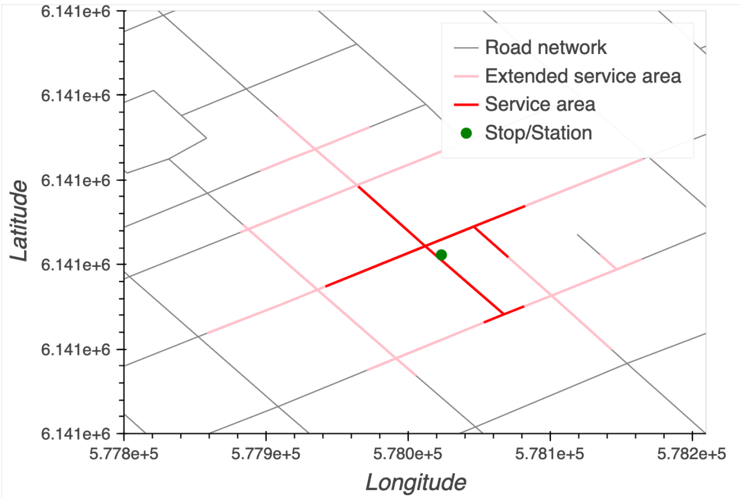

Figure 3.3: Example of an expanded service area after installing a bicycle parking facility

The mathematical formulation for the problem considers the following elements:

- A set of zones $z_1, z_2, ..., z_j, ..., z_n$ that partition the city
- The population for each zone $p_1, p_2, ..., p_j..., p_n$
- A buffer function $b(z_j, B)$ applied to each zone z_j expanding it B meters to consider the road network right in the edges of the zone, as explained in Section 3.1
- A set of stops $s_1, s_2, ..., s_i, ..., s_m$ within the city
- The road network RN of the city
- The portion of road network rn_j within the buffered census zone z_j as $rn_j = RN \cap b(z_j, B)$
- A walking distance threshold d_w and a cycling distance threshold d_c

$$
\begin{aligned}
&\text{maximise} \quad \sum_{j=1}^{n} \frac{\bigcup_{i=1}^{m} sa(s_i, RN, d_i) \cap rn_j}{rn_j} \times p_j \\
&\text{subject to} \\
&\qquad\qquad \sum_{i=1}^{m} e_i = E \\
&\text{where} \\
&\qquad\qquad e_i = \begin{cases} 1 & \text{if parking is in } s_i \\ 0 & \text{otherwise} \end{cases} \\
&\qquad\qquad d_i = \begin{cases} d_c & \text{if parking is in } s_i \\ d_w & \text{otherwise} \end{cases}
\end{aligned} \tag{3.5}
$$

The goal of the problem is to find the set of stops in which to install bicycle parking facilities in order to maximise the objective function defined in Equation 3.5. The objective function is the sum of the product of the coverage fraction of the road network (c_j) and the population (p_j) of each census zone (z_j). The percentage of road network for a census zone z_j from which at least one stop can be accessed by walking or cycling as $c_j = \frac{\bigcup_{i=1}^{m} SA_i \cap rn_j}{rn_j}$, in line with indicator 3 in Section 3.1. Service areas (SA_i) for selected stops are calculated with the cycling distance threshold (d_c); while for the remaining stops, the service areas are calculated with the walking distance threshold (d_w). The only constraint of the problem is the one that limits the number of parking facilities to allocate (E), which includes:

- A set of distance thresholds $d_1, d_2, ..., d_i, ..., d_m$ that correspond to each stop. The distance d_i is equal to d_c if a parking is allocated in s_i and equal to d_c otherwise.
- A set of binary elements $e_1, e_2, ..., e_i, ..., e_m$ that correspond to each stop, e_i is equal to 1 if a parking is allocated in s_i and equal to 0 otherwise. Where $\sum_{i=1}^{m} e_i = E$, being E the number of facilities to allocate.

Before getting into the different algorithm implementations to address the bicycle parking location problem, some considerations are presented. Firstly, a criterion for evaluating the potentiality of expanding the catchment area for each of the stops is introduced. Both service area variants for each stop s_i are formally defined in Equation 3.6.

$$
\begin{aligned}
SA_i &= sa(s_i, RN, d = d_w) \\
SA_i^* &= sa(s_i, RN, d = d_c)
\end{aligned} \tag{3.6}
$$

In this manner, given the service areas of each stop, an estimation of the impact of extending the catchment area from d_w to d_c meters is calculated for every stop of the system. In this thesis, this value is refereed to as potential coverage for a given stop and defined as the difference between walking and cycling distance service areas. This measure reflects the potential number of additional individuals who gain accessibility through the stop by installing a parking facility on it. This idea of potential coverage pc_i for s_i is formally defined in Equation 3.7.

$$
\begin{aligned}
pc_i = &\sum_{j=1}^{m} [(SA_1 \cup \ldots \cup SA_i^* \cup \ldots \cup SA_n) \cap rn_j] \cdot p_j \\
&- \sum_{j=1}^{m} [(SA_1 \cup \ldots \cup SA_i \cup \ldots \cup SA_n) \cap rn_j] \cdot p_j
\end{aligned} \tag{3.7}
$$

For some stops, potential coverage may be equal to zero. That is just a consequence of the catchment area already being served by another stop. Extending the catchment area in such cases does not lead to enhanced coverage. With the results of potential coverage for each stop of the system, the search space (i.e., the set of potential solutions to the problem) is defined. Additionally, a minimum potential coverage threshold (PC) is set to discard stops that would have a marginal contribution to accessibility if a bicycle parking facility is installed and are therefore not worth considering. Depending on the size of the problem and the available computing resources, a higher or lower threshold for discarding stops can be set.

Secondly, since more than one parking facility is usually going to be installed, some combinations of stops can be ignored as they are too close together. When two stops are close, they redundantly cover the same areas and the combination is not worth exploring. To ignore potential solutions that have this closeness issue between two or more stops, a distance matrix among all stops in the system is defined. A formulation of this matrix is defined in Equation 3.8.

$$C_{nxn} = \begin{bmatrix} c_{11} & c_{12} & \dots & c_1n \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{bmatrix} \tag{3.8}$$

As elements c_{ii} correspond to the distance between stop i and stop i, the matrix C has all 0 on its diagonal. Also, C is a symmetric matrix as $c_{ij} = c_{ji}$. The closeness threshold CT is set to discard candidate solutions that contain stop i and stop j, where $c_{ji} < CT$. Pre-calculating C is recommended as it proves beneficial for discarding solutions during the iterations of the algorithms.

Firstly, greedy algorithms offer a balance between simplicity and efficiency. The method consists of a constructive search, on which the first solution component is the stop that has the highest value of potential coverage. Once the first component is determined, all stops are reassessed, and the second stop is chosen based on its ability to cover the greatest number of people along with the first one. This process continues iteratively until the number of stops equals E. The approach has a straightforward implementation and is computationally efficient. However, despite their speed and ease of implementation, greedy algorithms possess inherent limitations. Its approach favours locally optimal choices at each step, which can lead to sub-optimal solutions. Consequently, the approach is prone to overlook globally optimal solutions. A pseudo-code of the greedy algorithm implementation for the bicycle parking facilities location problem is shown in Algorithm 1. The algorithm begins with the initialisation of parameters, *expl_solutions* and *cand_solution* which are the memory states of the results for explored solutions and for the partial solution that is being built, respectively. The while loop keeps adding stops to the partial solution until its length reaches E elements. Within the while, the for loop iterates over all candidate stops that are above the potential coverage threshold PC. If the partial solution contains stops that are spaced closer together than the predefined closeness threshold CT, it is skipped and disregarded; otherwise, it undergoes evaluation. The evaluation of a partial solution implies calculating the number of people who can access at least one stop by walking or cycling. Once all stops are assessed, the stop that has the best results in combination with the previous elements of the partial solution persists. The algorithm terminates and provides its output when the candidate solution comprises a total of E elements.

Secondly, an Iterated Local Search (ILS) implementation is considered. Local search algorithms start at some location in the search space and subsequently move from the present location to a neighboring location. Each location has a relatively small number of neighbors and each of the moves is determined by a decision based on local knowledge only. The neighborhood criterion is defined as a 1-exchange neighborhood, wherein two solutions are neighbors if they vary in at most one stop. The normalised measurement of potential coverage per stop serves as the probabilistic criterion for selecting the first E stops and initialising the algorithm. Also, with the results of potential coverage, an estimation of the total potential coverage for a candidate solution is calculated just by adding the potential coverage of each of the components of the solution. This potential coverage at the candidate solution level is used as the sorting criteria of the neighbours in the algorithm, determining the order of the exploration. A pseudo-code of an ILS implementation for the bicycle parking facilities location problem is shown in Algorithm 2. The algorithm begins with the initialisation of parameters. The memory state of the results for explored solutions is *expl_solutions*. The candidate solution is initially chosen through a randomised process, wherein the probability of selecting a stop is determined by its potential coverage. Stops with high potential coverage have a higher probability of being selected compared to the ones with lower potential coverage. The while loop at lines 13 to 40 iterates until the termination predicate. Within the loop, the neighbour solutions to the candidate solution are defined. Then, they are reduced to the neighbours that do not contain stops that are spaced closer together than the predefined closeness threshold CT and finally ordered according to the potential coverage criteria. The while loop at lines 19 to 36, iterates over the neighbours until a better candidate solution or a local maximum is found. If a better candidate is found, a step forward is taken and the process starts again at line 13. On the other hand, if a local maximum is found, a perturbation is performed over the candidate solution. This perturbation implies randomly changing two stops within the candidate solution. All stops have the same probability of being selected as a new element to the solution. Ultimately, the algorithm terminates when a predefined effort is reached.

Algorithm 1: Pseudo-code of Greedy

```
Initialisation:
E = quantity of parking facilities to allocate
PC = potential coverage threshold
stops = stops[potential coverage > PC]
C = distance matrix between stops
CT = closeness threshold
expl_solutions = {}
cand_solution = []
while length(cand_solution) < E do
    for stop in stops do
        if not check_closeness(cand_solution, C, CT) then
            cand_solution.append(stop)
            cand_evaluation = evaluation(cand_solution)
            expl_solutions[cand_solution] = cand_evaluation
            cand_solution.remove(stop)
        end
    end
    cand_solution = max(expl_solutions)
end
```

Algorithm 2: Pseudo-code of ILS

```
Initialisation:
E = quantity of parking facilities to allocate
PC = potential coverage threshold
stops = stops[potential coverage > PC]
C = distance matrix between stops
CT = closeness threshold
cand_solution = select_stops(stops, E, pot_coverage)
cand_evaluation = evaluation(cand_solution)
expl_solutions = {}
expl_solutions[cand_solution] = cand_evaluation
best_evaluation = cand_evaluation
termination = False
while not termination do
    neighb = neighbours(cand_solution)
    neighb = reduce_by_proximity(neighb, C, CT)
    neighb = ordered_neighbours(cand_solution, stops, pot_coverage)
    step = False
    n = 0
    while not step do
        cand_solution = neighb[n]
        if cand_solution not in expl_solutions.keys() then
            cand_evaluation = evaluation(candidate_solution)
            expl_solutions[candidate_solution] = candidate_evaluation
            if cand_evaluation > best_evaluation then
                step = True
                best_evaluation = max(expl_solutions.values())
            end
            else
                n = n + 1
            end
        end
        if length(neighb) + 1 = n then
            cand_solution = perturbation(cand_solution)
            step = True
        end
    end
    if length(expl_solutions) > effort then
        termination = True
    end
end
```

Chapter 4

Experimental analysis

In this chapter the application of the proposed methodology for a specific case study is presented. In Section 4.1, the case study of Montevideo, Uruguay, is introduced. An overview of the city and its public transport system is provided. In Section 4.2 , walking accessibility to the public transport system for the case study is addressed. The accessibility indicators are calculated and analysed. Lastly, in Section 4.3, the optimisation problem of finding the best locations for bicycle parking facilities is applied to this specific case study. An experimental evaluation and a comparison of the different algorithms applied to the problem are presented and the main findings are described and discussed.

4.1. Case study: Montevideo, Uruguay

Montevideo is the capital and most populated city of Uruguay, situated on the southern coast of the country. Montevideo has a population of 1,3 million inhabitants, which constitutes 40% of the total population of the country. A heat-map portraying the population distribution of the city is shown in Figure 4.1 [1]. The size of Montevideo is 201 km^2 and therefore, has roughly 6.5 thousand inhabitants per km^2.

The Instituto Nacional de Estadística (INE) divides the Uruguayan territory for statistical purposes into three three levels:

- *Section*: Montevideo is divided into 27 Sections, according to the limits established in the census of 1963. Sections are shown in Figure 4.2 with

[1] The penitentiary complex at Santiago Vázquez is excluded from the plot for the sake of clarity as it distorts the population distribution.

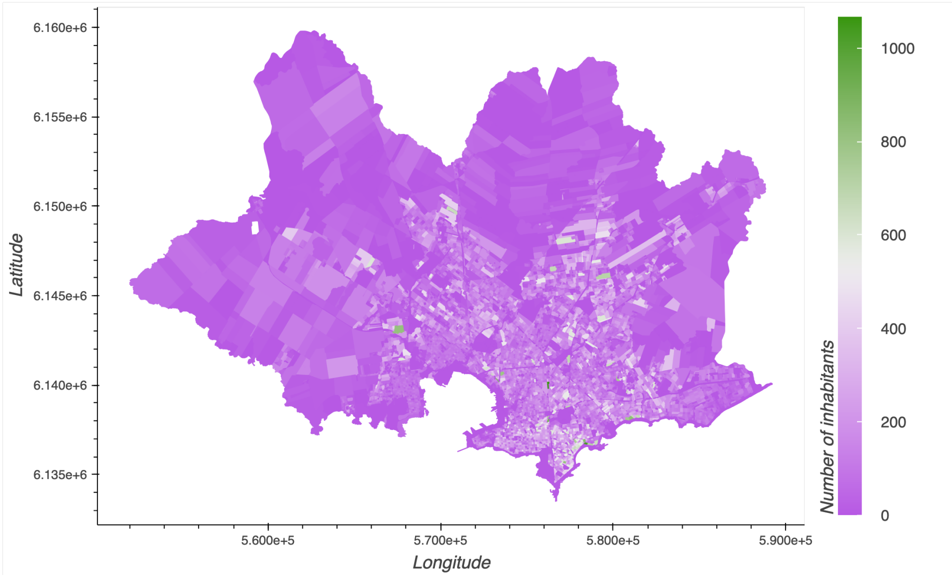

Figure 4.1: Population distribution in Montevideo

dark purple lines.

- *Segment*: each Section is subdivided into Segments, which consist of a set of blocks. Montevideo is comprised of 1 063 Segments, which are marked in fuchsia in Figure 4.2.
- *Zone*: is the smallest identifiable zoning defined by INE. Each Segment is divided into several Zones. In densely populated parts of the city, Zones usually coincide with a single block. In rural areas, Zones correspond to portions of territory defined by natural or artificial limits (e.g., watercourses, highways, local roads, railways). Figure 4.2 shows the 13 606 Zones of Montevideo in light pink.

Public transport plays an important role in the city. Results from the Mobility Survey of the Metropolitan Area of Montevideo 2016 show that bus trips represent 25% of all trips (Mauttone and Hernández, 2017). The public transportation system in Montevideo operates through a fleet of nearly 1 500 buses. The system comprises a total of 4 643 unique stops and 634 different bus lines. Figure 4.3 outlines the road network, bus lines, and bus stops of Montevideo. It is easy to distinguish the central parts of the city as the density of bus stops increases and most lines converge to it.

As was mentioned in the methodology in Chapter 3, specific datasets are needed to compute walking accessibility to public transport and to address the bicycle parking location problem. In Table 4.1, the sources of the datasets and

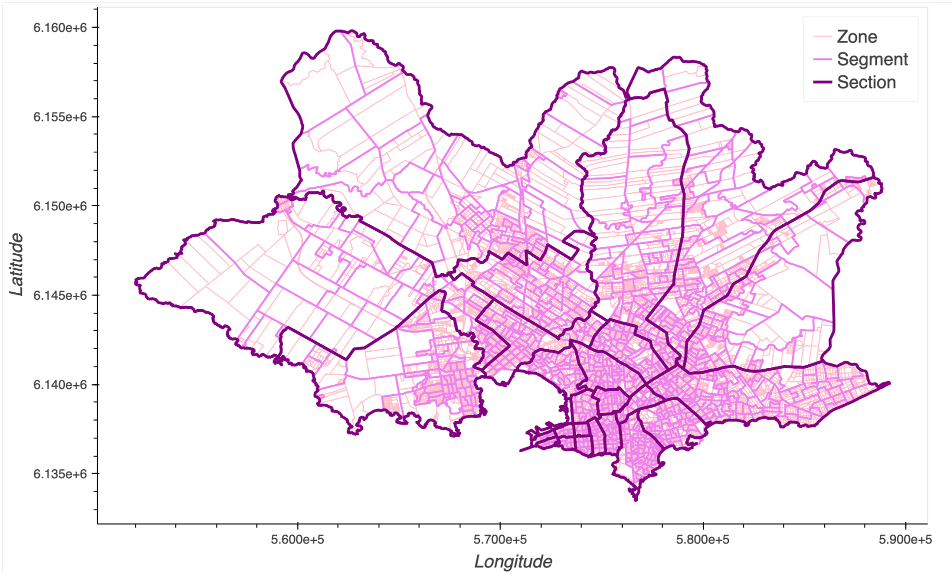

Figure 4.2: Subdivision of Montevideo into Sections, Segments, and Zones

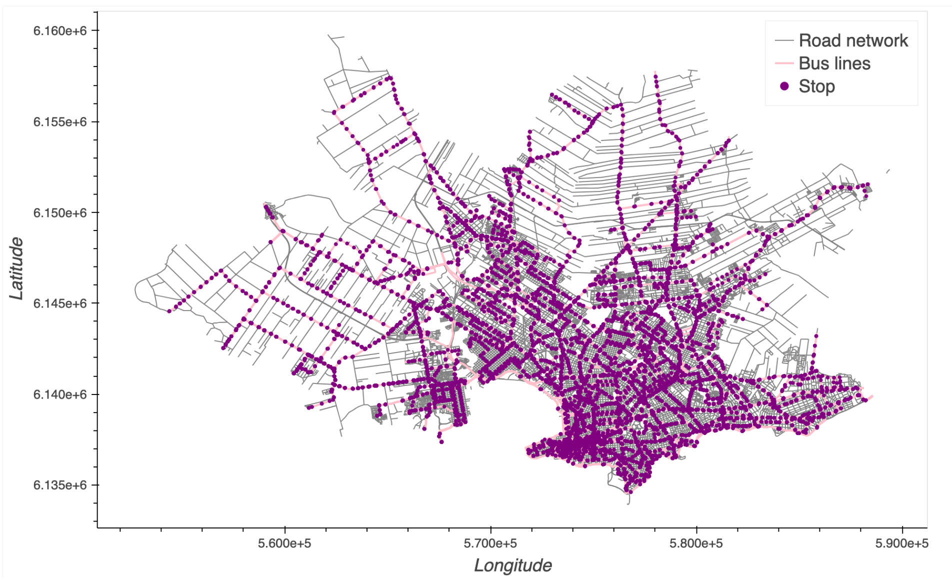

Figure 4.3: Road network and public transport system in Montevideo

a brief description of each of them are provided. The main sources are the open data catalog of Intendencia de Montevideo (IM) and INE. All data sets were downloaded on 18/03/2022.

Table 4.1: Datasets for the experimental analysis

Dataset	**Source**	**Site**	**Description**
Zoning of the studied area	INE	https://www.gub.uy/instituto-nacional-estadistica/datos-y-estadisticas/estadisticas/mapas-vectoriales-ano-2011	Vector cartography of geostatistical units for the 2011 census that divides Montevideo into Sections, Segments and Zones.
Road network of the studied area	IM	https://ckan.montevideo.gub.uy/dataset/vias-de-transito	Road network of Montevideo maintained in the Geomatics Service by the Nomenclature and Numbering Unit of IM.
Population of each zone	IM	https://ckan.montevideo.gub.uy/dataset/poblacion-por-zona-censal-en-montevideo	Population information by zones surveyed in 2011. Information was obtained from INE and re-processed by the Statistics and Management Information Unit of the IM.
Geographical location of stops	IM	https://ckan.montevideo.gub.uy/dataset/transporte-colectivo-paradas-puntos-de-control-y-recorridos-de-omnibus	Point shapefiles with the locations of bus stops for Montevideo.
Public transport lines per stop	IM	https://ckan.montevideo.gub.uy/dataset/lineas-de-omnibus-origen-y-destino	Bus lines with their stop of origin, route and stop of destination for Montevideo.

The datasets underwent necessary cleansing processes. The road network cleaning consisted simply in correcting invalid geometry errors using the predefined Check Validity function provided by QGIS Development Team (2024) topology checker plugin. Bus lines and stops data cleaning comprised a series of consistency checks. A first approach with the data was enough to rule out a line that is active only during the Carnival season in Montevideo and was therefore removed from the lines and stops data set. Another verification carried out was through a full join between the data set of lines and the data set of stops, to check that all lines have associated stops and that all stops have at least one corresponding bus line. As a result of this analysis, one line was removed because it did not have corresponding stops in the set. Finally, all the bus stops that were located outside of Montevideo were removed and the lines that operate beyond the department were cut short.

4.2. Walking accessibility to public transport

The three accessibility indicators are computed according to the methodology presented in Section 3.1. To compute them, some considerations and parameters need to be defined:

- The primary zoning for the studied area of Montevideo, Uruguay, is based on the finest zoning provided by INE, which consists of 13,606 zones. Additionally, the largest zoning provided by INE, comprising 27 sections, will also be considered to gain a broader perspective of the city.
- The parameter B that corresponds to the buffer taken for each zone is set to 10 m.
- As outlined in the review of related works in Chapter 2, there is a consensus in the reviewed literature about the walking distance that city planners take as a guide, which is around 400 m. Therefore, the walking distance threshold to access public transport networks is defined as $d = 400\,m$.

With this parameter configuration, the results of the accessibility analysis are presented next.

The first accessibility indicator shows the number of bus stops that cover each zone considering a walking distance threshold of 400 m. Results are shown in the map in Figure 4.4, where darker shades of red indicate a higher number of bus stops reachable from the zone. The city center, located in the south-central area on the map, can be easily distinguished given the higher density of bus stops. Some peripheral zones also stand out, since zones in the periphery are larger and therefore may have access to a higher absolute number of stops. Utilising the broadest zoning delineated by the INE, a more comprehensive overview of the indicators is gained in Figure 4.5, where the location of the main bus terminal of the city stands out prominently as it is colored in the darkest shade of the map.

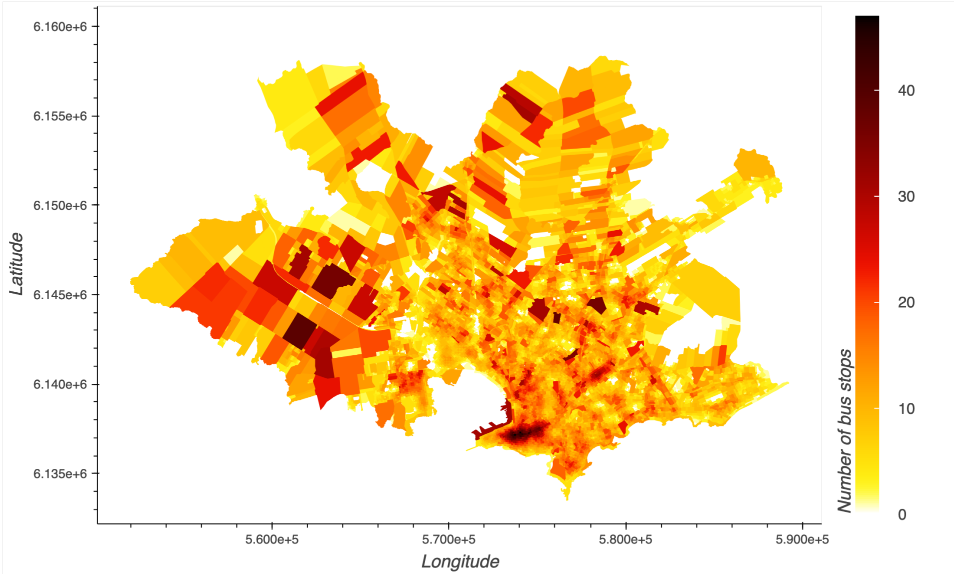

Figure 4.4: Number of bus stops accessible when walking up to 400 meters per zone in Montevideo

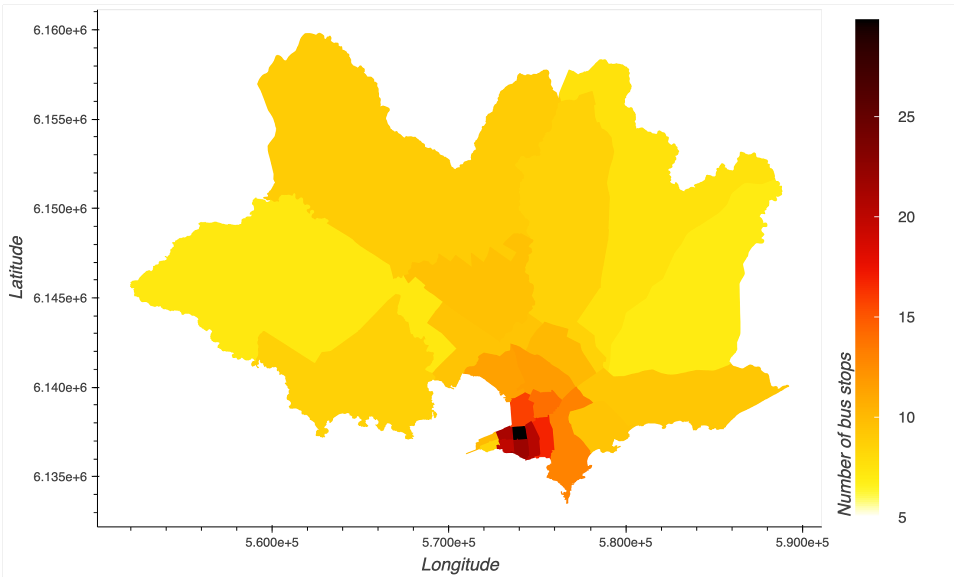

Figure 4.5: Number of bus stops accessible when walking up to 400 meters per section in Montevideo

The mean number of bus stops accessible by a given zone is 9.2; whereas the median is 9.0. A histogram of the distribution of the number of bus stops is presented in Figure 4.6. The shape of the distribution—with alternating peaks and valleys—can be explained by the fact that bus stops tend to be placed on each side of the road to service both directions of bus lines. Thus, it is more likely to reach an even number of bus stops.

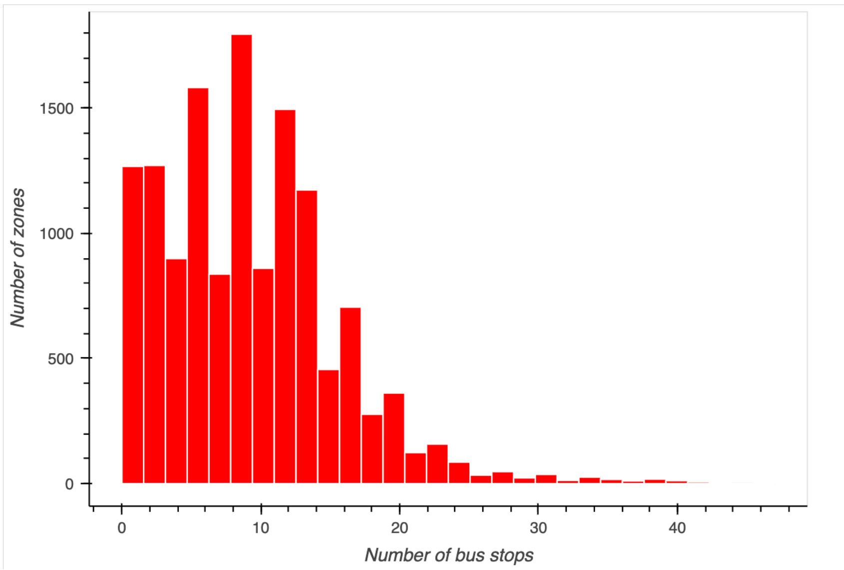

Figure 4.6: Distribution of the number of bus stops accessible when walking up to 400 meters per zone in Montevideo

Finally, a sensitivity analysis on the walking distance threshold is presented. In Figure 4.7 the average number of bus stops per zone when varying the walking distance threshold from 100 m to 1 000 m is displayed. The relation between the average number of accessible stops and the walking distance threshold does not follow a straight line but a curve, indicating a polynomial trend. This observation is reasonable as more stops are considered accessible as the threshold expands.

The second accessibility indicator relates to the number of accessible bus lines for each zone when considering a walk of 400 m. Results are shown in the choropleth map in Figure 4.8, where darker shades of green indicate a larger number of accessible lines. The city center in this map is notable compared to other areas since many different bus lines converge there. Also, the main arteries of the city, going East (Avenue 18 de Julio and Avenue Italia) and North (Boulevard Artigas) from the city center, can be distinguished because of the density of bus lines that operate over those main roads. Moreover, comparing Figure 4.4 with Figure 4.8, a softening of peripheral areas can be appreciated, suggesting that while some zones in the periphery access a large number of stops, these stops provide access to a smaller number of bus lines.

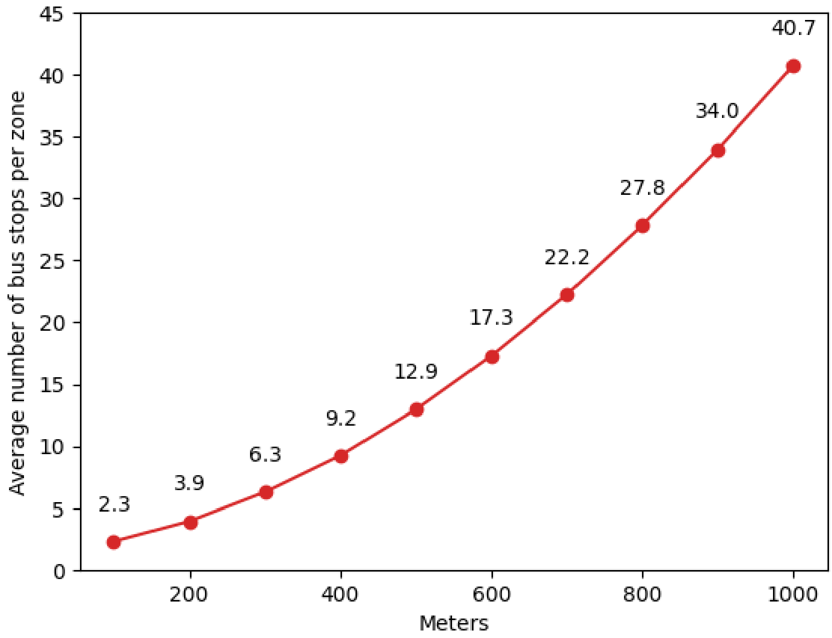

Figure 4.7: Number of bus stops accessible per zone when varying the walking distance threshold

Figure 4.9 illustrates the widest zoning classifications established by the INE, with this perspective the southeastern part of the city appears in deeper shades of green compared to the surrounding areas, indicative of the high density of bus lines operating in that region.

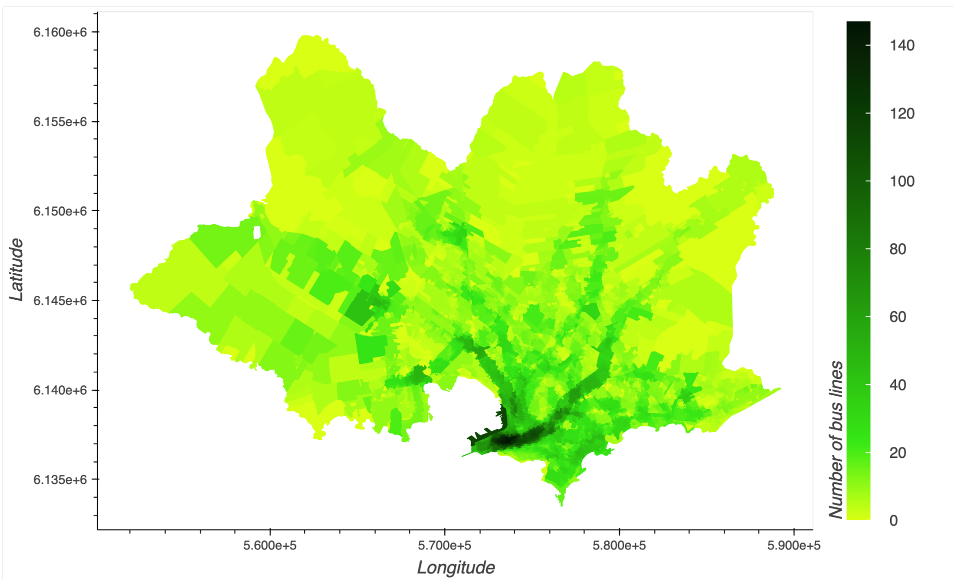

Figure 4.8: Number of bus lines accessible when walking up to 400 meters per zone in Montevideo

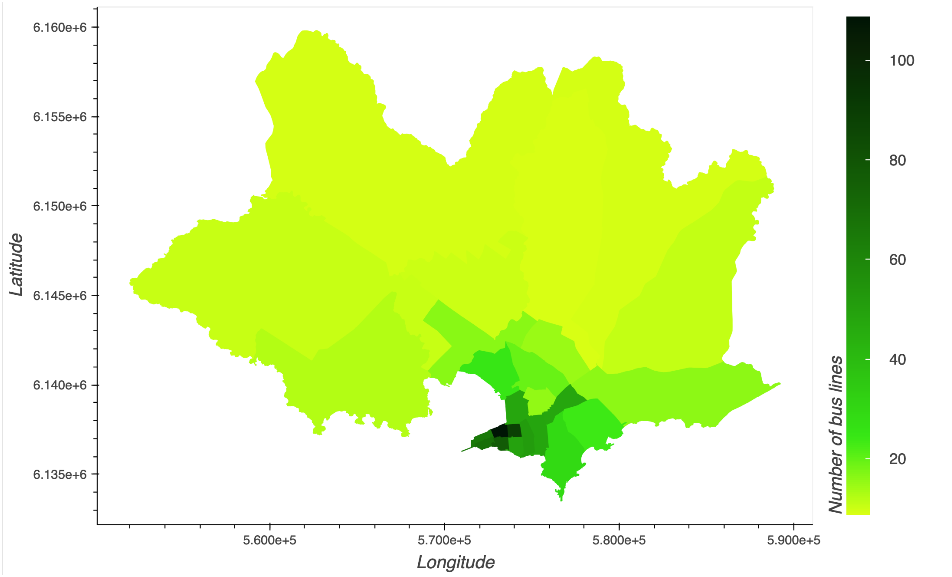

Figure 4.9: Number of bus lines accessible when walking up to 400 meters per section in Montevideo

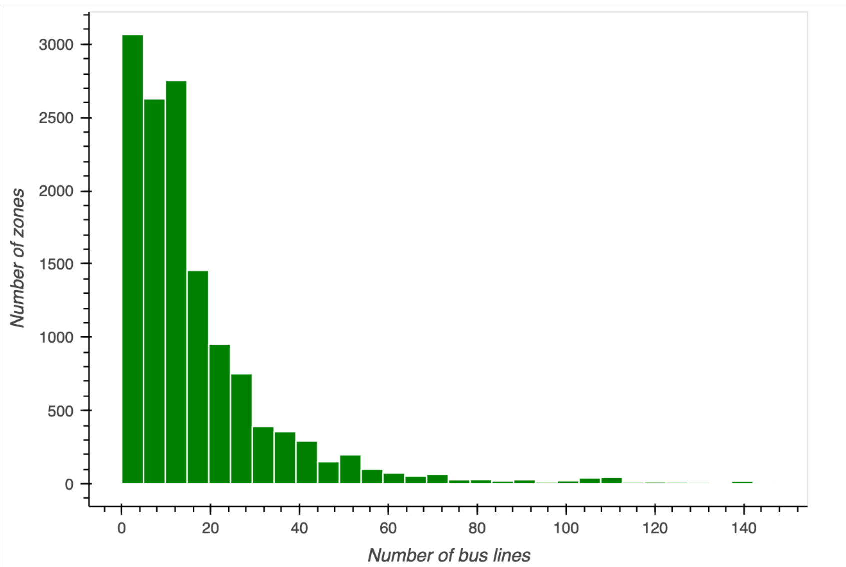

Figure 4.10: Distribution of bus lines accessible when walking up to 400 meters per zone in Montevideo

The distribution of the number of bus lines accessible is shown in Figure 4.10. The mean number of lines accessible per zone is 16.7 and the median is 10.0.

The sensitivity analysis on the walking distance threshold is presented in Figure 4.11. The relationship between the number of accessible bus lines and the walking threshold is practically linear. Compared with Figure 4.7, despite a potential polynomial increase in the number of stops, the number of lines does not correspondingly rise.

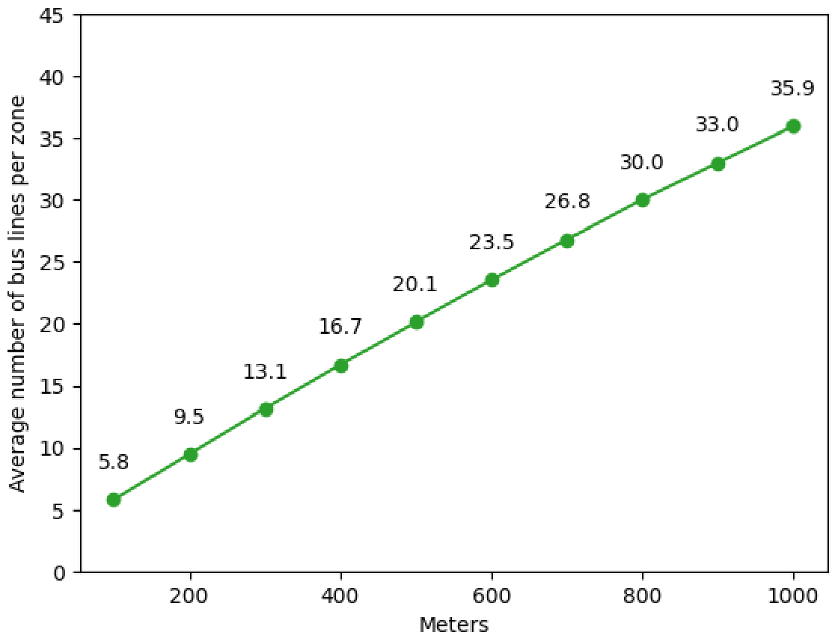

Figure 4.11: Number of bus lines accessible per zone when varying the walking distance threshold

The third and last accessibility indicator illustrates the percentage of the population that lives within a 400 m walking distance from a bus stop. Results are shown in the map in Figure 4.12. Similar to the preceding two accessibility indicators, the city center (South-Central area) once again excels with its elevated levels of accessibility. A wider view is gained through Figure 4.13 when using the broadest zoning delineated by the INE. This illustration reaffirms the conclusion on the gap between central and peripheral sections of the city. Most central sections present accessibility levels at 100% while the peripheral ones range from 80% to 90%.

A histogram of the distribution of coverage is shown in Figure 4.14. The mode of the distribution is 100%, indicating that in 9 798 zones of Montevideo (72.0% of total zones), the entire population has accessibility to at least one bus stop within a walking distance of 400 m. Nevertheless, 947 zones of Montevideo (6.96% of total zones) have zero coverage at 400 m.

Given the assumption that the population is evenly distributed on the road network, the percentage of the population of Montevideo covered by at least one bus stop at 400 m or less is 92.38%. Results considering sociodemographic

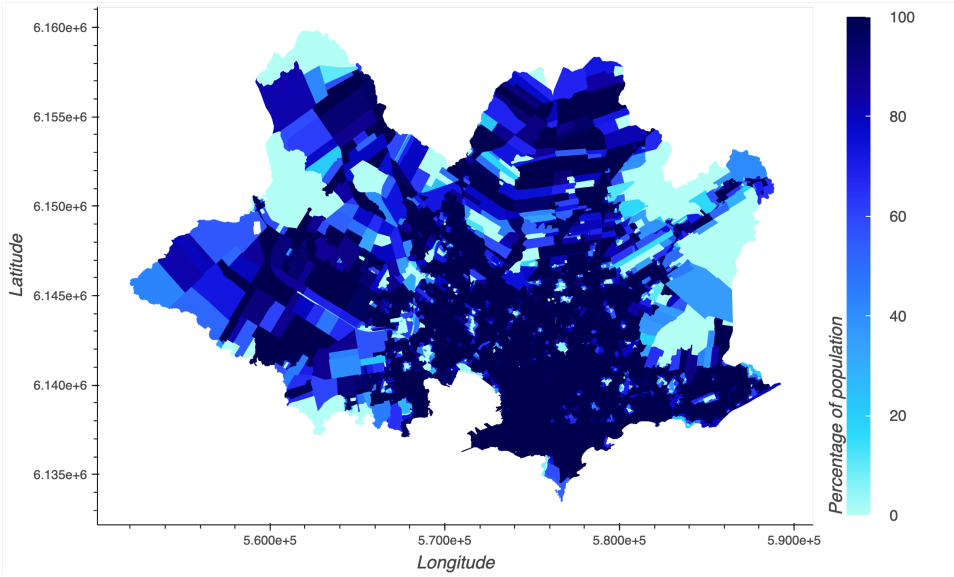

Figure 4.12: Percentage of the population with access to a bus stop when walking up to 400 meters per zone in Montevideo

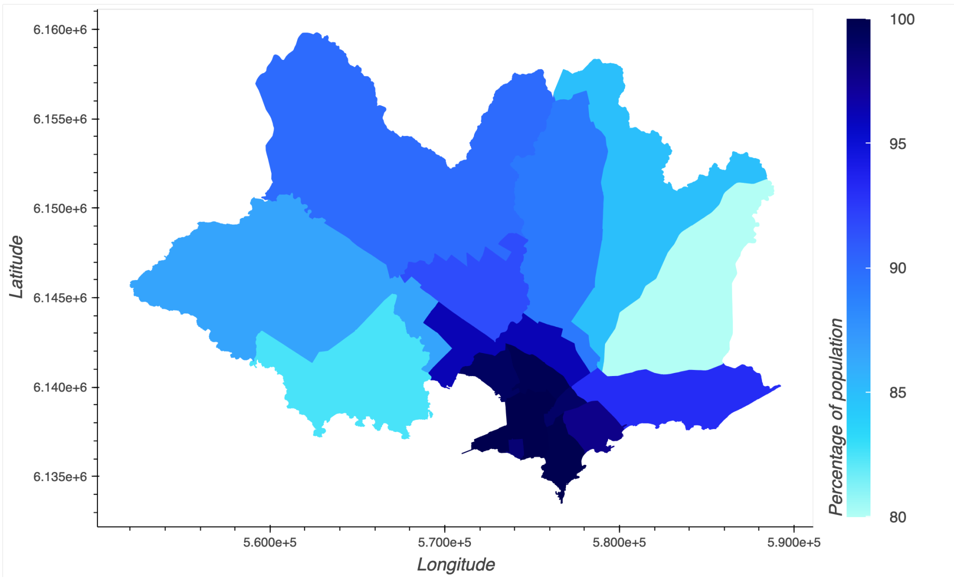

Figure 4.13: Percentage of the population with access to a bus stop when walking up to 400 meters per section in Montevideo

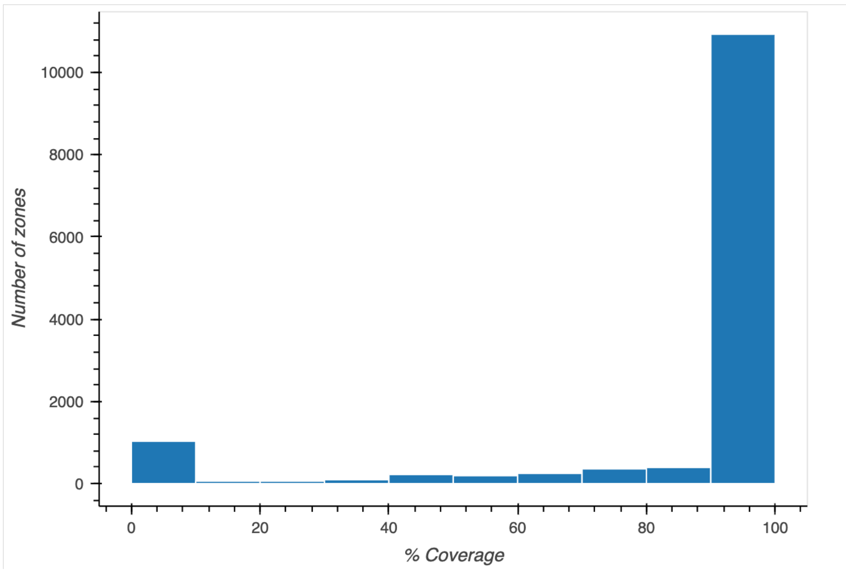

Figure 4.14: Distribution of the percentage of the population with access to a bus stop when walking up to 400 meters per zone in Montevideo

characteristics are shown in Table 4.2. When considering the population split by gender, women (92.65%) present a slightly higher percentage of coverage than men (92.06%). In regards to age, young citizens (0 to 14 years old) present the lowest levels of accessibility with a coverage of 89.09% whereas senior citizens (65 or more years old) present the best values of accessibility with 95.35%.

Demographic group	**Percentage**
Men	92.06
Women	92.65
0 to 14 years old	89.09
15 to 64 years old	92.64
More than 65 years old	95.35

Table 4.2: Percentage of people that can access at least one bus stop considering a walking of 400 meters or less

A sensitivity analysis on the walking distance threshold on the percentage of the population with accessibility to a bus stop is presented in Figure 4.15. Differing from the previous sensitivity analysis, the relationship between the walking threshold and the percentage of the population with accessibility appears to be logarithmic. The rise in the population with accessibility diminishes as the walking distance threshold increases.

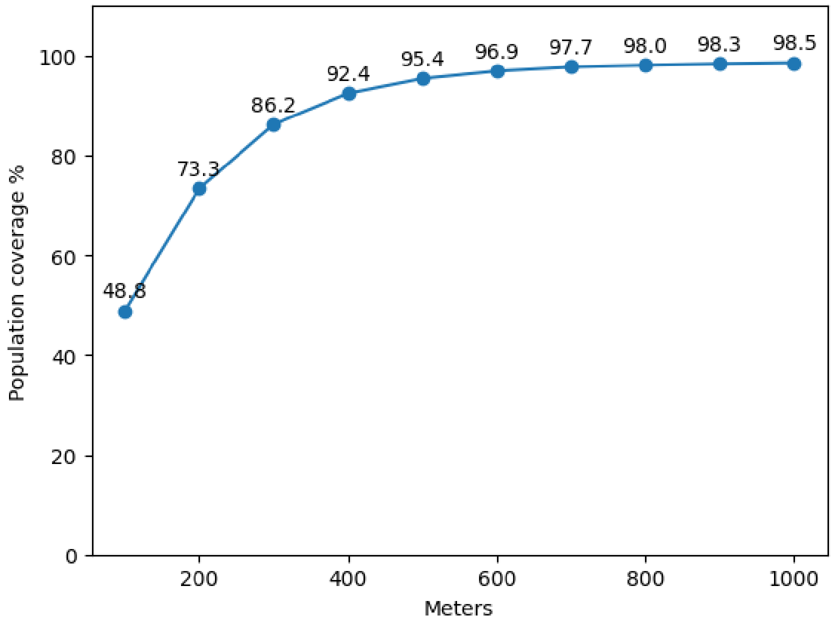

Figure 4.15: Sensitivity of the percentage of the population with access to a bus stop when varying the walking distance threshold

In conclusion, the accessibility analysis to the public transport network in Montevideo, Uruguay, has been conducted based on the three key indicators. The three indicators unanimously highlight the city center (South-Central area) as exhibiting the highest levels of accessibility. However, while the first indicator may not clearly delineate the gap with the periphery, this distinction becomes more pronounced in the latter two indicators. The primary conclusion drawn is that 92.38% of Montevideo's population has access to at least one bus stop within a walking distance of 400 m. Contrasting this figure with the one disclosed by transport authorities in the press, as noted by (Menoni, 2022), which asserts that almost 97% of Montevideo's population is covered by the public transport network within a 400 m walking threshold, suggests a potential overestimation due to a less comprehensive calculation methodology.

4.3. Bicycle parking facilities location problem

Two algorithms to solve the bicycle parking facilities location problem are implemented according to the methodology in Section 3.2. Both algorithms, Greedy and ILS, are implemented in the Python programming language.

The following considerations and parameters are defined:

- As outlined in the reviewed literature in Chapter 2, the distance threshold for considering cycling as an access mode to public transport is 1000 m, which is a conservative estimate adapted to the presented case study. Therefore, walking threshold is $d_w = 400\,m$ and cycling threshold is $d_c = 1\,000\,m$.
- The number of bicycle parking facilities to allocate E is set to 5, to model a conservative initial installation of new infrastructure with a limited investment.
- Potential coverage at bus stop level pc_i is pre-calculated and acts as an input parameter to the algorithms. The minimum threshold for potential coverage at stop level PC is 150 inhabitants. This implies that if the stop itself possesses a lower potentiality than the threshold, it will not be deemed a viable location for installing a parking facility. Out of the 4 643 unique stops comprising the public transport system of Montevideo, 1 677 (36.1% of the total) surpass the potentiality threshold and are therefore being considered as feasible locations.
- The proximity matrix between stops $C_{n\times n}$, is pre-calculated and serves as an input parameter for the algorithms.
- The closeness threshold CT between stops, measured in a straight line, it is set at 400 m. The primary aim of this threshold is to prevent combinations of bus stops with a substantial overlap in the served area.

Firstly, the greedy approach is considered. The selected stops to install the bicycle parking facilities with the Greedy approach are shown in Figure 4.16. The map also displays the initial levels of accessibility prior to the installation of the new parking infrastructure. It is visible that each stop is situated in a zone with a lighter shade of blue, indicating an effort to accommodate the long distances to the nearest stop. The installation of bike parking infrastructure on these stops increases the percentage of people with at least one accessible stop by walking 400 m or cycling 1000 m from 92.38% to 93.41%. This variance of 1.03 percentage points suggests that the installation of these five bicycle parking facilities would extend access to approximately 13,583 individuals.

The Greedy approach, based on a constructive search strategy, adheres

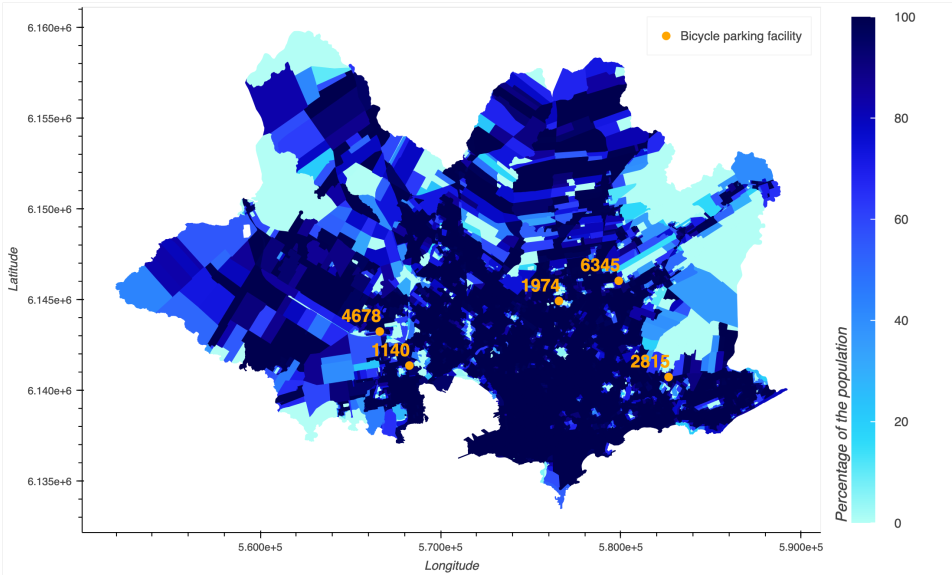

Figure 4.16: Selected stops to install the bicycle parking facilities by the Greedy approach

to a specific sequence for integrating bus stops into the solution. This is outlined in Table 4.3, which presents the percentage of people with at least one accessible stop and the contribution of each stop as they are incorporated into the solution. Notably, it becomes evident that the marginal contribution of each stop decreases with its order of inclusion.

Order	Stop	Accessibility (%)	Contribution (difference)
-	-	92.38	-
1	1974	92.60	0.22
2	4678	92.82	0.22
3	2815	93.02	0.20
4	6345	93.22	0.20
5	1140	93.41	0.19

Table 4.3: Order and accessibility results of Greedy approach solution components

The results, delineating the population split by gender and age, are displayed in Table 4.4. The most notable increase is observed in men and young citizens, contributing to narrowing the gap slightly.

The top 10 solutions for the Greedy approach, ranked by accessibility results, are detailed in Table 4.5. Each solution differs by only one stop, reflecting the constructive search strategy employed by the algorithm.

Demographic group	Original percentage	Enhanced percentage	Variation
Men	92.06	93.14	1.08
Women	92.65	93.64	0.99
0 to 14 year old	89.09	90.72	1.63
15 to 64 years old	92.64	93.64	1.00
More than 65 years old	95.35	95.80	0.45
Total	92.38	93.41	1.03

Table 4.4: Variation of the percentage of people that can access at least one bus stop by walking of 400 meters or cycling 1 000 meters

Selected stops	Percentage
1140, 1974, 2815, 4678, 6345	93.4124
1107, 1974, 2815, 4678, 6345	93.4068
1106, 1974, 2815, 4678, 6345	93.4007
1081, 1974, 2815, 4678, 6345	93.3995
1080, 1974, 2815, 4678, 6345	93.3963
1653, 1974, 2815, 4678, 6345	93.3930
1637, 1974, 2815, 4678, 6345	93.3897
5008, 1974, 2815, 4678, 6345	93.3888
3902, 1974, 2815, 4678, 6345	93.3814
5794, 1974, 2815, 4678, 6345	93.3753

Table 4.5: Top 10 results of Greedy on selected stops to install the bicycle parking facilities on the percentage of population with accessibility

Secondly, the ILS approach to select the best locations for the bicycle parking facilities is analysed. Over 30 000 candidate solutions were evaluated. Due to the high computational effort required to execute the algorithm, the parallelised execution was performed using the high performance computing infrastructure of National Supercomputing Center, Uruguay (ClusterUY) (Nesmachnow and Iturriaga, 2019). The optimal bus stop combinations for installing bicycle parking facilities identified by the ILS align with those determined by the Greedy approach. However, the ILS analysis underscores that bus stops 6345 and 6351 are practically interchangeable as potential locations for installing bicycle parkings due to their close proximity, both yielding identical accessibility results of 93.41%. Similarly, installing bicycle infrastructure at stops in 1974 and 1966 offers nearly identical accessibility rates of 93.4124% and 93.4105%, respectively, rendering them virtually interchangeable. This observation is illustrated in Figure 4.17 and a closer look in Figure 4.18. The map again displays the initial accessibility levels prior to the installation of the bicycle parking infrastructure. With this approach, it is also noticeable that each stop is situated in a lighter shade of blue, in an attempt to cover for citizens with poorer accessibility.

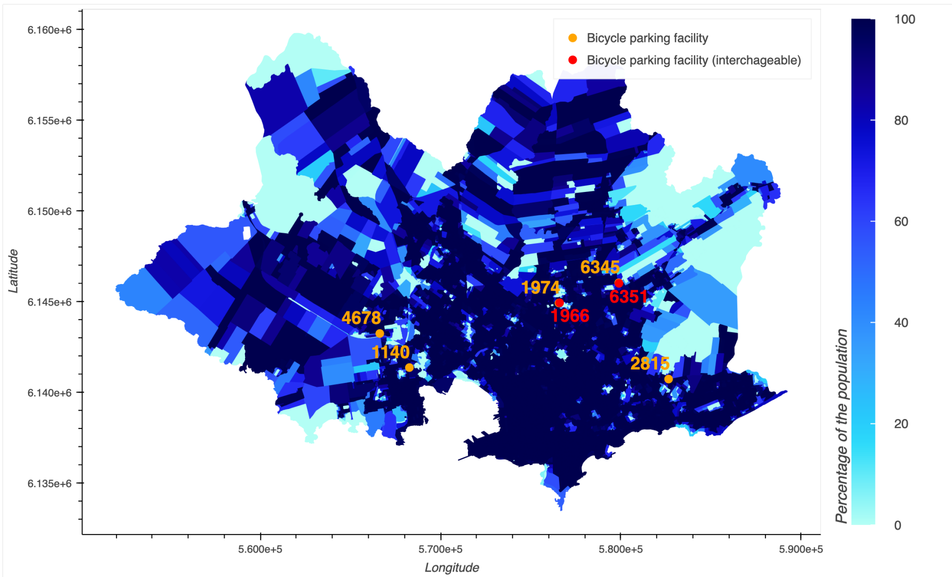

Figure 4.17: Selected stops to install the bicycle parking facilities by the ILS approach

The top ten solutions generated by the ILS are displayed in Table 4.6. Contrasting with the Greedy approach, solutions derived from the ILS may differ in more than one stop due to the nature of the approach.

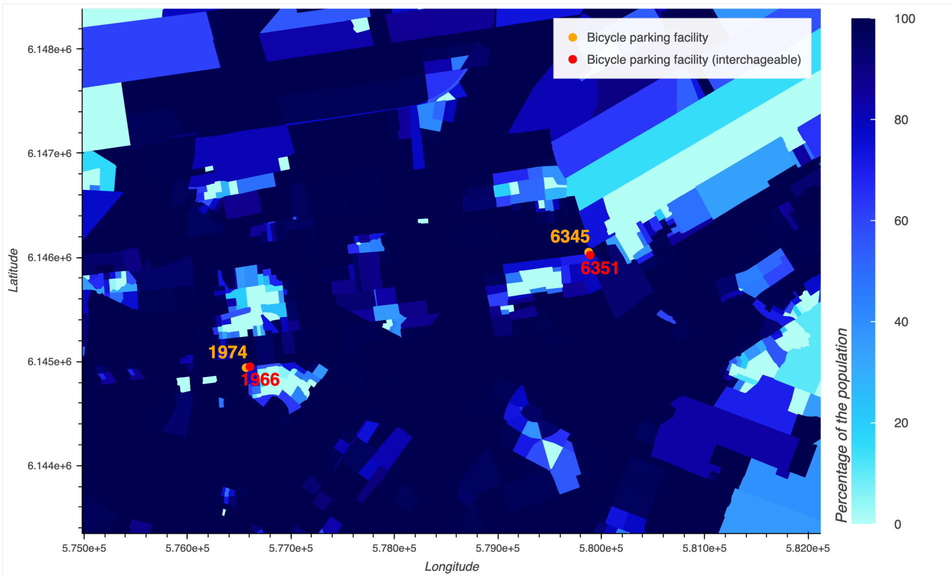

Figure 4.18: Zoom on interchangeable bus stops according to the ILS approach

Selected stops	Percentage
1140, 1974, 2815, 4678, 6345/6351	93.4124
1140, 1966, 2815, 4678, 6345/6351	93.4105
1140, 1974, 2042, 2815, 4678	93.4094
1140, 1966, 2042, 2815, 4678	93.4076
1107, 1974, 2815, 4678, 6345	93.4068
1107, 1966, 2815, 4678, 6345	93.4049
1107, 1974, 2042, 2815, 4678	93.4038
1140, 1974, 2815, 4678, 4894	93.4021
1107, 1966, 2042, 2815, 4678	93.4020
1140, 1974, 2046, 2815, 4678	93.4009

Table 4.6: Top 10 results of ILS on selected stops to install the bicycle parking facilities on the percentage of population with accessibility

As this heuristic is based on a perturbative search, the algorithm starts at an initial candidate solution and iterates by searching within the neighbouring solutions. This implies that the underlying structure of the search process can be illustrated with a graph. Some examples of search trajectories followed by the executions are shown in Figure 4.19. The graph depicts the trajectories of 18 distinct initial candidate solutions, all converging towards a local maximum highlighted in purple. The local maximum is the best combination of bus stops for allocating bicycle parking facilities achieved by both the Greedy and ILS approaches. Around the local maximum, numerous cycles emerge in the graph, attributable to the perturbation process inherent in the ILS algorithm once a local maximum is reached.

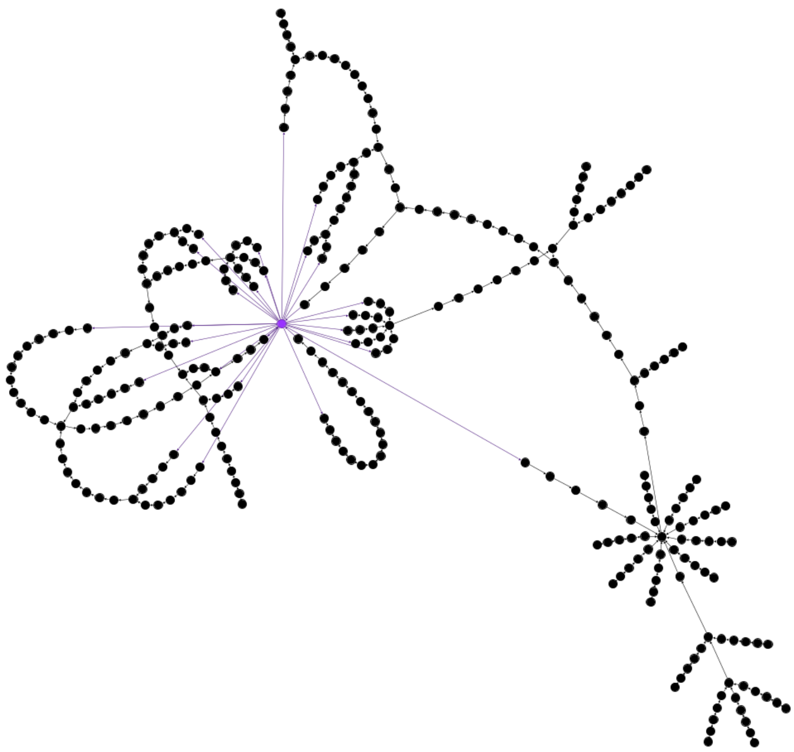

Figure 4.19: Search trajectories of ILS

Summarising, two distinct algorithms, the Greedy method and the Iterated Local Search (ILS) algorithm, were employed to address the bicycle parking location problem. Both algorithms converge on identifying optimal combinations of bus stops for facility allocation. However, the ILS offers additional options featuring interchangeable stops within the solution, resulting in practically equivalent accessibility outcomes. The percentage of the population with access to at least one stop increases from 92.38% to 93.41% with a minimum inversion of just 5 bicycle parking facilities. Furthermore, discernible improvements among demographic groups are observed, notably benefiting young citizens and men, thereby contributing to a modest reduction in disparities.

Chapter 5

Conclusions and future work

In this final chapter, the key findings and conclusions from the research presented in this thesis are outlined, along with the main directions for future work.

5.1. Conclusions

This thesis studied accessibility to public transport systems using Montevideo, Uruguay, as a case study and formulated and addressed the bicycle facilities location problem, with the goal of improving accessibility to public transport by installing parking facilities that promote cycling as an access mode.

The study on walking accessibility was approached from a potential mobility perspective. This involved calculating how many stops individuals could reach within a specified distance, treating each stop as an opportunity to enter the public transport network. The method for computing the number of stops accessible to an individual was based on a service area analysis, where a stop was considered accessible if it could be reached within a certain distance through the road network from the point of origin. A walking distance threshold of 400 meters was chosen due to a consensus found in the reviewed literature (Daniels and Mulley, 2013; Rijsman et al., 2019). As public transport in Montevideo is based on buses, the main data sets considered were bus stops and lines, the road infrastructure, and demographic information. Three accessibility indicators were considered. The first indicator measured the number of bus stops accessible within a 400 m walking distance. Results showed high accessibility levels in the city center, attributed to the dense concentration of bus stops. Additionally, some peripheral areas also showed notable accessibility. These zones tend to encompass larger areas potentially providing access to a greater absolute number of stops. The second accessibility indicator accounted for the number of bus lines reachable within a distance of 400 m. Once more, the city center stood out notably due to the convergence of numerous bus lines. Conversely, there was a discernible decrease in accessibility in the peripheral areas. This finding suggested that while certain peripheral zones may have access to a significant number of stops, these stops may offer access to fewer bus lines. The third and final accessibility indicator examined the proportion of the population with access to at least one bus stop within a walking distance of up to 400 meters. This indicator revealed that 92.38% of Montevideo's population can reach at least one bus stop within this distance. Furthermore, the analysis highlighted disparities in walking accessibility concerning gender and age groups, with young citizens (aged 0 to 14) and men exhibiting lower accessibility levels compared to their counterparts. The results differed with figures previously reported by transport authorities in the press claiming a 97% of accessibility for an equal threshold. The discrepancy between the two figures can be attributed to the simpler methodology employed by the authorities, which relies on buffer areas, in contrast to the more precise approach outlined in this thesis based on service areas and accounting for the street network.

This thesis also proposed improving accessibility by finding suitable locations for bicycle parking facilities to promote cycling as an alternative access mode to public transport. The rationale behind this proposal is that people tend to cycle longer distances compared to walking. Additionally, this proposal is particularly relevant since accessibility results showed that young citizens experience lower levels of accessibility compared to other age groups. The chosen distance threshold for cycling as an access mode was set to 1000 m, which is a conservative estimate adapted to the case study of Montevideo, Uruguay. The optimisation problem consisted of finding the set of stops in which to install bicycle parking facilities that maximises accessibility to public transport. Any existing stop or station of the system was a potential location to install a bicycle parking facility. The only constraint of the problem was the one that limits the number of parking facilities to allocate, which is set to five in the experimental analysis of this thesis. The two algorithms proposed to address the problem were a greedy approach and an ILS. Both approaches were able to find the same set of bus stop combinations for installing bicycle parking facilities that maximise the increase in accessibility. The installation of the parking facilities on the selected stops could improve accessibility from 92.38% to 93.41% with a very modest investment in infrastructure. This would lead to noticeable benefits across demographics, particularly for young citizens and men, thereby contributing to a reduction in disparities.

Summarising, this thesis made several key contributions. Firstly, it provided a comprehensive review of related works on walking and cycling accessibility to public transport. Secondly, it introduced a methodology to calculate three distinct walking accessibility indicators and presented the results of applying these indicators in the case study of Montevideo, Uruguay. Additionally, it offered a mathematical formulation for the problem of optimally locating bicycle parking facilities to maximise accessibility to public transport. Finally, two algorithms (Greedy and ILS) were implemented to address the bicycle parking location problem and evaluated in a real case-study in Montevideo, Uruguay. The research reported in this thesis resulted in publications including two conference articles presented at V Congreso Iberoamericano de Ciudades Inteligentes (Perera et al., 2022) and XXII Pan-American Conference on Transportation Engineering and Logistics (Perera et al., 2023). Additionally, it has been accepted for inclusion in a book titled *Making Way for Accessibility*, part of the series *Routledge Advances in Regional Economics, Science, and Policy.*

5.2. Future work

The research presented in this thesis represents a pioneering analysis of accessibility to public transport in Montevideo, Uruguay. Consequently, there are lines of work that hold the potential to deepen comprehension and foster the discussion in the area.

Key lines for future work regarding accessibility indicators include accounting for bus line schedules in the accessibility indicators. This would enable an analysis of how accessibility fluctuates throughout the day, reflecting variations in the service level provided. Additionally, integrating the routes of bus lines can illustrate the extent to which different parts of the city can be reached, offering valuable insights into transportation accessibility.

Expanding upon the idea of installing bicycle parking facilities, further investigation could explore the impact of varying the number of facilities to install across the city. The relationship between the number of facilities and accessibility levels could be assessed to reach an optimal number of facilities to allocate. An aspect overlooked in this thesis, regarding the costs of installations, warrants reevaluation. The expenses associated with installing these facilities may vary based on their locations. For instance, certain areas might need additional infrastructure like sidewalks or proper signalisation. However, incorporating such factors into the analysis demands a thorough examination of infrastructure of the city.

Additionally, incorporating the bike lane network of the city into the problem could help prioritise bus stops in proximity to these lanes. Even if the bike lane infrastructure is currently limited in the case of Montevideo, this approach could incentivise the extension of such network throughout the city, thereby enhancing accessibility and promoting cycling as a viable transportation option.

Finally, exploring the use of these indicators as inputs for optimisation problems could greatly enhance the efficacy of transportation planning with respect to accessibility. Even in studies where accessibility is not the primary focus, by incorporating them into the decision-making process, transportation planners can better assess the potential impact of policies and investments on accessibility levels.

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