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Methodology for Assessing Walkability in Urban Centers: Proposal for Accessible Routes

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ABSTRACT

Rapid urbanization has turned urban mobility into one of the biggest challenges for modern cities. Intense competition for public spaces in downtown areas of medium and large cities leads to accidents, congestion, increased costs and travel time, and environmental pollution caused by individual motorized and public transport. Searching for a contribution to social, economic, and environmental sustainability this work, considering walking as an essential form of mobility in an urban center of developing countries, proposes a methodology for supporting citizens who arrive at the downtown public bus terminal to select the best walking route to reach essential public services places in the city. Three macro indicators are considered in determining the best walking route: The ambiance indicator results from six sub-indicators, representing physical characteristics of the walking space; the Comfort indicator results from two sub-indicators, representing the visual attractiveness and local comfort; and the Safety indicator results from four sub-indicators; representing public and personal sensations of safety. The proposed methodology is based on two steps: the first reduces the twelve sub-indicators of each route segment to three main indicators. In the second step, a multi-objective optimization problem is formulated to determine the best route from the origin point (public urban terminals) to the citizen interest point. The identification of the most suitable downtown walkability areas can assist local authorities in developing improvement strategies for their ambiance, safety, and comfort standards, actions that will contribute to environmental sustainability and providing urban areas with walking spaces that meet the citizen's expectations.

Key words: Walkability, sustainability, routes, urban mobility, destination choice

1 INTRODUCTION

Rapid urbanization has turned the city's downtown mobility into one of the biggest challenges for urban planners. The current mobility model encourages intense disputes over the use of the various spaces between residents, individual motorized transport, and public transport leading to conflicts, accidents, and contributing to environmental pollution.

The population density contributes to the high cost of housing close to urban centers, now disputed by commercial and service activities, and together with other local variables, such as urban violence, forcing the residents to settle further and further away from them. (AGUIAR et al, 2014). Now, providing commercial and service activities, the downtown becomes an attractive space in size and scale with the capacity to attract the suburban population generating a high number of daily accesses to places such as shopping malls, hypermarkets, hospitals, universities, public transport stations, multipurpose arenas, stadiums, cargo terminals, among others, that provide specific services to the population (SAADI, 2021).

Points of great attractiveness impact the traffic-generating, cause congestion, increase travel time, vehicle operating costs, pollution, decreased comfort in travel, and introduce difficulties in accessing internal city areas and parking lots. These points, located in a restricted space in the urban center, require specific mobility solutions. In this scenario, walking emerges as a sustainable alternative for downtown mobility in the to build a city that is more intelligent and human.

Considering walking as a suitable form of mobility for short distances and part of a sustainable city, providing substantial socio-economic and environmental benefits, mainly for developing countries, this work seeks to answer the following questions:

- How do city managers and governors promote walking in the center of a city?

- What actions should be taken to encourage the citizens to walk?
- What should be the socio-economic and environmental benefits of promoting walking in the city center?

To answer these questions this paper proposes a conceptual framework for selecting the best route for the citizen that arrives at public terminals, coming from the suburban area, to reach their interest point in an urban center. Downtown gains a social character when proposing that the urban center be planned with routes that help citizens to go from the urban terminals to essential public service delivery points. Identifying such routes supports the city manager in installing street indicators to drive the citizens on their downtown walk. The research is innovative, helping the periphery citizens of developing countries reach essential public services places, such as medical insurance centers, Municipal Market, Mail Agency, Central Post Office, Palace of Justice, Traditional Churches.

The remainder of this paper is structured into five sections as follows. The next section discusses the previous research work. Section 3 presents the material and methods. Section 4 explains the characteristics of the study area and presents the case study determining the best route from the Central Terminal to some important places. Final considerations are presented in Section 5.

2. LITERATURE REVIEW

Walking is one of the best forms of physical activity suitable for people of all ages. It is the only mobility activity that produces no emissions, is always available, does not require any equipment, and is safe and free of charge (ERNAWATI, 2016). It is characterized as the citizen's displacements in short distances without using motorized means and occurs between origin and destination points due to a lack of motorized options. However, adherence to it depends on the distance to be covered, adequate infrastructure, neighborhood aesthetics, commercial activities, and safety on the route, characteristics inserted into the concept of “life in the city happens on foot”. The interest in walking decreases when the bandwidth of households is greater than 2,4 km, but the proximity between the origin and destination points in the city center incentivizes the walking activity also influenced by the multidimensional attractiveness of the surroundings. Recognizing it, Krizek Forsyth and Baum (2009) state that the walking decision is related to citizen motivations, from one side, influenced by policies and infrastructure developed to make it attractive and other side by barriers. However, the number of factors to be considered in determining the best route makes it a difficult task to solve in large urban areas (MANZOLLI et al, 2012).

Walking mobility has received much attention in recent literature. In the Portland study, Oregon, a model for generating walking trips was proposed, based on the built environment around the family homes (TIAN; EWING, 2017). The authors identified that Sociodemographic characteristics associated with the built environment influence the generation of walking. The main factors are land use whether residential and/or commercial, the quality of the street, accessibility to urban amenities, and safety (KRIZEK, FORSYTH, and BAUM, 2009) (WEI, et al, 2016). Also, factors that incentive the development and practice of walking are areas with a higher density of activities, areas with a greater differentiation of land use composed of public and private services, residences and commerce, and areas with a quality urban design, (TIAN & EWING, 2017). These motivators are associated with factors of the built environment, related with pedestrian perceptions, and the level of service of the sidewalks, factors that influence the option for foot mobility.

Kielar and Borrmann, (2016) examine people's mobility by analyzing Origen-Destination routes through an interest function model based on the psychological concept of goal-related memory accessibility and fundamental coherences found in pedestrian-related measurable data. Taking the study set in a developing country’s city center context, Kumar and Ganguly, (2017) stated the research question as which factors influence the walking behavior of people to access the public service points of developing countries and to what extent. Xiao and Wei (2021) point out that an individual trip decision considers detailed information about segments of routes around Origin-Destination and that tools and research for modeling this problem are scarce.

Saad et al. (2021) in their literature review of walkability in urban environments, point to existing work on objective and subjective measurements of walkable environments. Some studies focus on pedestrian flow, volume, and sidewalk capacity. Other dedicated to safety indicators, such as vehicle speed and volume and buffers from traffic, or to evaluate pedestrian-scale lighting, shade trees, and benches, or exploring urban structures and socio-economic factors. The authors highlight the focus of those studies was on walkability scores and on the existing infrastructure/physical environment generally conducted at nationwide or citywide scales.

Visvisi et al. (2021), conceptualizing walking and walkability, from a micro-level perspective, relate that the experience of walking in the city space may be enhanced by applications geared toward route optimization. In their work, the criteria of optimality may be diverse and include sightseeing, green areas, shops, coffee places, routing and destination/location identification assistance, and health benefits. That is, involving public and private services. Rahul and Manoj (2020) state that the route orientation in the city center aims to improve citizen accessibility to public space.

The mobility choice may significantly differ from the developed countries to the developing countries and from the objective of the citizens. The focus of this proposal is on the developing country where the citizens who reside in the suburbs and come by bus to the city center, do not have intimacy with global position systems (GPS), and don’t know the best way to go from where they are to meet points as the Municipal Market, Mail Agency, Central Post Office, Palace of Justice, Traditional Churches.

2.1 Walking and Walkability Concepts

Walking is the action of displacement resulting from one's effort, without the use of a motorized system through the available road such as sidewalks, boardwalks, or walkways, among others, from an origin to a destination, or as the means for integration with other mobility modes such as buses, vehicles, and bicycles to a destination point.

Walking is the main mode of mobility for human beings in the world and the most accessible because it is the cheapest and requires fewer infrastructure resources, Asadi-Shekari et al. (2014). It is part of a healthy life, mitigating the negative effects of modern life externalities such as being overweight and obesity. Several studies on health and urban planning point out that the existence of adequate infrastructure is directly related to walking rates and, therefore, to a healthier life (PUCHER et al., 2010; ASADI-SHEKARI et al. 2019). At the same time, walking influences other negative externalities associated with motorized travel, such as fuel consumption, air and noise pollution, and safety issues.

Visvity et al. (2021) define walking as the act of moving by foot across the city space to serve a purpose or for leisure and walkability as a multi-scalar characteristic of the built environment that incentivizes or not the walking citizen inhabitants. Following the authors from the broad perspective walking and walkability are viewed as a function of four main perspectives: Built environment, infrastructure, regulatory framework, and individuals' perception of value.

However, there are different pedestrians' perceptions and expectations between developed and developing countries, that do not occur only in terms of economy and geography, but about the Pedestrian Level of Service (PLOS). Authors, such as Bloomberg & Burden (2006), point out that pedestrian perception plays an important role in the decision to walk, influenced by three main indicators: Built Environment, Flow Characteristics, and Users' Perception.

Bivina and Parida (2019) observed that the decision to walk undergoes an analysis of four main criteria: Personal Safety, General Safety, Comfort and Convenience, and Mobility and Infrastructure, divided into 17 sub-criteria. The authors submitted a pedestrian questionnaire to point to different scales for different sub-criterion. Also, the results of the study pointed out the existence of significant differences in the prioritization of needs related to the walking environment depending on sex and age group. The pedestrians reported safety and security as more critical indicators, probably due to the research country being India. The authors highlighted that care must be taken as most respondents do not have deficiencies, they do not see the importance of this requirement, which leads to a negligible weighting for this indicator.

Nag et al., (2020) in their review study PLOS - Pedestrian Level of Service, found 389 sub-criteria with frequently duplicated concepts and/or inconsistent terminology and pointed out that 46 of the 47 studies chose the attributes without rigor to assess the walking environment. None of the above studies made the Service Level of users referred to as the "pedestrian network" (Nag et al., 2020). In Carvalho et al. (2021), the best route connecting points of Origin (Urban Terminal) to points of Destination of Campinas downtown was determined by the PROMETHEE multi-attribute method (BRANS,1984).

This study aims to expand Carvalho et al. (2021) work by considering the establishment of the best route as a multi-objective optimization problem considering the security, environment, and comfort indicators.

2.2 Walkability Performance Indicators and Measurement

A measurement is a mapping from the real world in numerical form (MIDGLEY AND DOWLING, 1978). Each dimension or aspect of the process observed can be represented by a measure. A performance measurement system is a brief and precise set of measures (social, economic, environmental) that supports the decision-making process of an organization by collecting, processing, and analyzing quantified data of performance information (GIMBERT, 2010). To be effective, performance measurement systems should utilize both qualitative and quantitative data analysis through indicators, which are variables that show the state and characteristics of the system.

Dizdaroglu (2015) highlights the importance of using indicators to measure efficiency and effectiveness within organizations revealing the performance of evaluated processes. Indicators evaluate all processes, whether by employees, executives, or clients. According to Gimbert (2010), indicators involve endogenous and exogenous variables. Performance indicators are the key components that enable management, improvement, and decision-making in various areas of system evaluation. They analyze processes, classify solutions, and support decisions related to processes, people, and organizations. In practical applications, many questions arise, such as: "What is the optimal number of indicators to use for representing a given process?" "Is there an ideal set of indicators?" and "How can we determine whether the indicators used adequately represent the system under investigation?"

To simplify the analysis of a system, it is necessary to reduce the set of indicators to an index that aggregates multiple sub-indicators. This index provides a coherent and multidimensional view of the system, allowing for easy comparison of organizational and sector results with the surrounding environment.

2.3 Multi-Objective Optimization

The solution to real problems often involves situations in which the goal is to minimize and/or maximize an objective function with several and usually conflicting functions. To reduce the complexity, traditional schemes convert the objective functions into a single-objective problem making use of a weight vector that specifies the relative importance of each objective. However, the weight vector is not simple to specify by the city manager (decision maker) what can be conducted in unappropriated results. Then, the decision-making process undergoes solving a multi-criteria problem in which multiple objective functions must be optimized simultaneously. A special case is multi-objective linear programming, where multiple linear functions are simultaneously optimized subject to a set of linear constraints. Mathematically, the problem can be expressed as a vector of objectives that must be traded off in some manner (AWARD AND KHANNA, 2015).

$$F(x) = \mathrm{Max}\ [\ f1(x),\ f2(x), \ldots, fm(x)\ |\ x \in X\ ],$$

Where X is a set of n decision vectors that represent parameters for the values selected to satisfy constraints and optimize a vector function,

$$X = [\ x_1,\ x_2,\ x_3,\ \ldots\ldots, x_n]^T$$

$$X^{min}_i < X_i < X^{max}_i \quad I = 1, 2, \ldots, n$$

F(x) is a vector, composed of competing objective functions. Different solutions exist for each fj(x). Solving multiobjective optimization does not typically produce an optimally unique solution. Instead, it generates a Pareto optimal solution, in which one objective cannot be improved without degrading at least one of the other objectives.

3. MATERIALS AND METHODS

The research is structured in ten steps starting from the area delimitation to determine the origin-destination points. The methodological process is detailed below:

Step 1: **Area specification**.

The urban area to be researched must be specified and the origin and destination points inside this area identified. The study area is a cut of the central region of a city with high commercial activity, and public and non-public service providers, including urban transport terminals.

Step 2: **Indicators Definition**

An Indicator is a qualitative or quantitative measure, which is used to capture and represent important information about elements that are objects under observation. It is a synthesis and simplification of a complex set of data that allows analyzing the aspects of the object in the study. The indicators selection for this study was based on the work of Bivina and Parida (2019), and Nag et al. (2020) and are structured as three macro indicators, subdivided into 12 sub-indicators, as shown in Table 1.

Table 1 - Indicatos

Indicator	Code	Description
Ambiance	I1	Sidewalk width (average)
	I2	Sidewalk surface quality
	I3	Accessibility for people with reduced mobility
	I4	Participation in Routes
	I5	Access to Public Transport
	I6	Distance
Safety	I7	Street lighting
	I8	Number of Crossing
	I9	Street width
	I10	Accident occurrence
Comfort	I11	Attractiveness
	I12	Weather protection

Source: authors 2023

Step 3: **Data collection and processing**

Data survey for the study can be obtained from Geographic Information System (GIS) and collected from secondary data on websites of public agencies such as the City Hall, Transit Department, etc.

Step 4 Segment-Indicator Matrix (SIM)

The Segment-Indicator Matrix (SIM) is formed with the value assumed by the indicators as in Table 2. The lines specify the segments, while columns show the valor of the indicator associated with the corresponding segment. For example, A(2,1) is the value for indicator I1, segment 2. A(3,3) is the value assigned for indicator 3 associated with segment 3. This procedure is performed for all segments.

Table 2: Segment-Indicator Matrix (SIM)

Segment Number	I1	I2	I3	I4	I12
S1	A(1,1)	A(1,2)	A(1,3)	A(14)	A(1,12)
S2	A(2,1)	A(2,2)	A(2,3)	A(2,4)	
S3	A(3,1)	A(3,2)	A(3,3)	A(3,4)	
Sm	A(m,1)	A(m,2)	A(m,3)	A(m,4)	

Source: authors 2023

Step 5 - Origin-Destination Matrix (ODM)

Each Origin-Destination route, Table 3, is composed of a set of segments, Figure 1. The line of Origin-Destination Matrix identifies the route (route 1; route 2; route n) and in the columns identifies the segments that belong to that route, as in Figure 1.

Figure 1 Origin – Destination routes

Table 3 – Origin – Destination Matrix for Figure 1

Rote number	**Segment**			
Rote 1	S1	S2	S3	S10
Rote 2	S4	S5	S6	S10
Rote 3	S7	S8	S9	
Rote 4	S6	S5	S11	

Source: authors 2023

Step 6: Routes Performance Matrix (RPM)

The performance average AIR(1,1), for route 1 and indicator 1, is determined from the composition of the first line of the Origin-Destination Matrix and the first column of the Segment-Indicator Matrix as, Eq.1.

$$AIR_{11} = \frac{A_{1,1}+A_{2,1}+A_{3,1}+A_{10,1}}{4} \qquad \text{Eq.1}$$

And average indicator 2 for route 1, Eq.2

$$AIR_{1,2} = \frac{A_{1,2}+A_{2,2}+A_{3,2}+A_{10,2}}{4} \qquad \text{Eq.2}$$

An example of consolidated indicators is presented in Route Performance Matrix, Table 4, where Ai,j represents the value for route i associated with segment j.

Table 4: Route Performance Matrix

	I1	I 2	Ii	……	I10
Route 1		AIR_{12}	0		AIR_{110}
Route 2					
………					
Route m		AIR_{m1}	AIRmi		AIR_{m10}

Source: authors 2023

Step 7: **Best Routes Determination**

Solve the shortest walking path problem for each of the objectives (Ambience, security, and comfort).

Step 8: **Solution of the Multiobjective Problem**

Restate the objectives as goals using the optimal objective values identified in Step 7 as the target value and create a deviation function that measures the amount by which any given solution fails to meet the goal.

Step 9: Formulate and solve the MINIMAX problem

Each of the deviation functions creates a constraint that requires the value of the deviation function to be less than the minimax variable Q. Solve the minimax Q.

The steps from 7 through 10 is referred to Ragsdale's (2004) book on page 338.

4. CASE STUDY

4.1 Area Delimitation

Campinas is the third largest city in the state of São Paulo, following Guarulhos (2nd) and the capital São Paulo (1st), and the 14th largest city in Brazil. The municipality of Campinas is divided into six regions, with the center identified by the red color, located approximately in the middle of Figure 2. It serves citizens from five different regions who are seeking to access various public service agencies, including the National Institute of Social Security, the city hall, the Municipal Market, the Mail Agency, the Central Post Office, the Palace of Justice, traditional churches, temples, and religious institutions.

Figure 2 Campinas municipality

Souce: https://paisagemtriangular.wordpress.com/2015/12/02/reconhecimento-da-zona-oeste/

This paper focuses on studying the central region, which is of high commercial importance and houses public offices including the National Institute of Social Security (INSS). To conduct the study, two large urban public terminals, namely the Central Terminal (OP1) and Market Terminal (OP2), are taken as the starting points. Additionally, four destination points (DP1, DP2, DP3, and DP4) related to public offices requiring attention regarding mobility issues in the region are considered, in Figure 3.

The Central Terminal (PO1) is the largest and main terminal of the city, serving around 70 thousand passengers a day, and receiving 32 bus lines. The Mercado Terminal (PO2), inaugurated in the late 70's, was the first point in the city to be structured as a bus terminal. Currently it serves about 20 thousand passengers a day, receiving 28 bus lines, Figure 3.

Figure 3 Area of Study

Souce: Adapted GOOGLE-EARTH, (2024)

4.2 Specification of Points of Study

The study considers two points for origin of trips (PO) and four points for destination of trips (PD), as identified in Figure 3. The yellow button represents the bus's central terminal, point of origin 1(PO1). The green button represents Mercado Terminal, Point of Origin (PO2). The red buttons represent the destination points, as specified in Table 5.

Table 5: Specification of points of study

Points	Characterization
Origin – PO1 Central Terminal	Largest and main terminal in the city of Campinas. Serves 32 bus lines.
Origin PO2 Market Terminal	Next to the Municipal Market of Campinas, known as Terminal Mercado. Receives 28 bus lines.
Destination 1 PD1 Post office	It is located about 700 meters from Terminal Central and 750 meters from Terminal Mercado.
Destination - PD2 Palace of Justice	It is located about 850 meters from Terminal Central and 400 meters from Terminal Mercado.
Destination PD3 INSS	It is located about 1,400 meters from the Central Terminal and 700 meters from the Market Terminal.
Destination PD4 City Hall	I am located about 1,400 meters from the Central Terminal and 700 meters from the Market Terminal.

Source: authors 2023

4.3 Best routes identification.

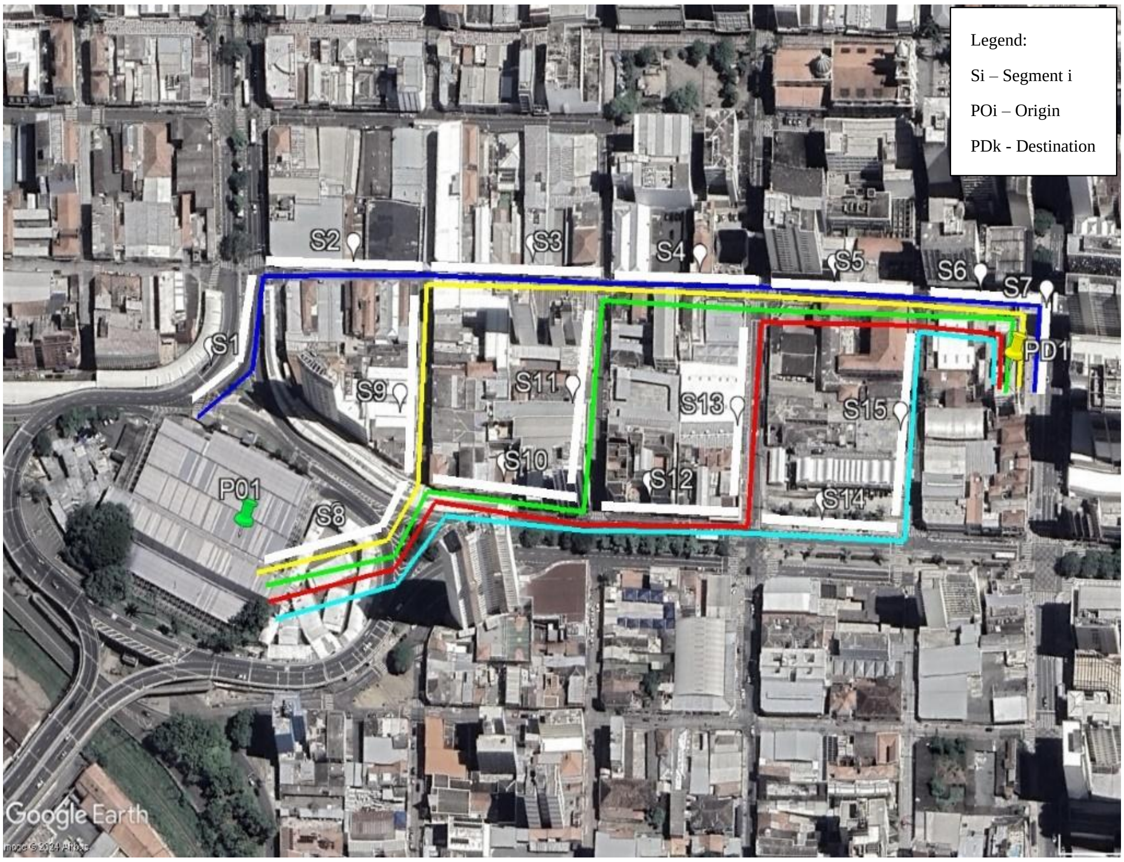
The study examines five potential routes, as illustrated in Figure 4. The Origin-Destination Matrix is shown in Table 6, with each row representing a specific route, and each column indicating the segment that bellows to that route. Route 1 covers segments 1 through 7, while Route 2 includes segments 8 and 9, along with segments 3 through 7.

Table 6 - Segment-Indicator Normalized Matrix

Central Terminal (P01) Post Office (PD1)	SEGMENTS							
ROTE 1	0	1	2	3	4	5	6	7
ROTE 2	0	8	9	3	4	5	6	7
ROTE 3	0	8	10	11	4	5	6	7
ROTE 4	0	8	10	12	13	5	6	7
ROTE 5	0	8	10	12	14	15	6	7

Source: Authors 2023

Figure 4 Routes from PO1 to PD1.



Source: authors 2023

4.4 Indicator Selection

Twelve indicators were associated with each segment. The indicator I1, sidewalk width is measured in meters. Indicator I2, sidewalk surface quality is rated from 1 to 5, with five being good. Indicator I3 denotes accessibility for people with reduced mobility. It is assigned a value of one if there are access ramps for such individuals while exiting a crossing; otherwise, its value is zero. On the other hand, the importance of a segment is indicated by the total number of times it is used for different routes, which is represented by Indicator I4. The higher the number of times the segment is used in different routes, the more significant this segment is. Indicator I5 now reflects the presence of public transport (1) in a segment and its absence (0) otherwise.

Indicator I6 is classified from one to five based on distance, with a higher number indicating a worse classification. Indicator I7, street lighting, defined from one to five with five being good; Indicator I8, number of crossings, the bigger number of crossing the worst; Indicator I9, street width, is measured in meters; Indicator I10, number of accidents (Standard Severity Unit); Indicator I11, attractiveness, from one to five, five being the best; Indicator I12, weather protection, one when exists and zero otherwise.

4.5 Definition of the Weight of Indicators

Table 7 displays the indicators specified in Table 1, some of which maximum value is better while others minimum valor is better. The weight for each indicator was determined by the evaluation of three experts using the Likert scale.

Table 7: Weight Vector

	Indicator											
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12
MIN/MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MIN	MIN	MAX	MAX
Weight	0,09	0,09	0,09	0,08	0,07	0,09	0,07	0,11	0,05	0,1	0,1	0,06

Source: authors 2023

4.6 Segment-Indicator Weight Matrix

The data for each segment indicator was sourced from various places like Google Earth Pro, Google Street View, and Municipality Official Sites. Fifteen segments were selected for evaluation of the PO1 - PD1 routes. The Segment-Indicator Matrix assigns values to each indicator, which can be quantitative or qualitative measures, such as meters and attractiveness. The data in Table 8 is presented in a normalized form based on either maximization or minimization criteria.

Fifteen segments were selected for evaluation in the OP1 - DP1 route selection process, Table 8. Each segment was associated with a set of indicators, which can represent quantitative or qualitative measures such as distance and attractiveness. Table 8 presents normalized data based on either maximization or minimization criteria.

Table 8. Normalized Segment-Indicator Matrix

	Indicadores											
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12
Segment	Ambience						Safety				Comfort	
1	0,08	0,07	0,00	0,03	0,00	0,06	0,06	0,07	0,07		0,03	0,00
2	0,03	0,07	0,00	0,03	0,00	0,07	0,06	0,02	0,09		0,03	0,00
3	0,03	0,07	0,00	0,06	0,00	0,07	0,04	0,04	0,09		0,05	0,14
4	0,03	0,07	0,00	0,09	0,00	0,06	0,04	0,04	0,09		0,05	0,00
5	0,03	0,07	0,00	0,11	0,00	0,06	0,06	0,04	0,09		0,05	0,00
6	0,03	0,07	0,00	0,14	0,00	0,05	0,06	0,09	0,09		0,05	0,00
7	0,08	0,07	0,00	0,14	0,50	0,03	0,06	0,11	0,04		0,05	0,00
8	0,17	0,07	0,50	0,11	0,00	0,08	0,09	0,11	0,00		0,14	0,14
9	0,17	0,07	0,50	0,03	0,00	0,08	0,09	0,11	0,00		0,14	0,14
10	0,08	0,07	0,00	0,09	0,00	0,07	0,09	0,07	0,07		0,14	0,14
11	0,03	0,07	0,00	0,03	0,00	0,09	0,06	0,04	0,09		0,05	0,00
12	0,08	0,07	0,00	0,06	0,00	0,06	0,06	0,07	0,07		0,05	0,14
13	0,06	0,07	0,00	0,03	0,00	0,09	0,06	0,04	0,06		0,05	0,14
14	0,08	0,07	0,00	0,03	0,50	0,06	0,09	0,09	0,07		0,08	0,14
15	0,03	0,07	0,00	0,03	0,00	0,09	0,06	0,04	0,09		0,03	0,00

Source: authors 2023

4.7 Mean Value for Macro-Indicators.

The mean value for the Macro indicators of Ambiance (Am), Safety (Sa), and Comfort (Co) of each segment can be determined from Table 8. For example, the mean value for Macro indicator ambiance of segment four is equal to (0,027+0,067+0,086+0,06)/6 = 0,040, while the mean value for the macro-indicator comfort is 0,054/2= 0,027. Table 9 presents the Mean Indicator Segment Matrix.

Table 9. Mean Indicator Segment Matrix

	Segments														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Am	0,04	0,03	0,04	0,04	0,05	0,05	0,14	0,15	0,14	0,05	0,04	0,04	0,04	0,12	0,04
Se	0,06	0,04	0,08	0,04	0,05	0,07	0,05	0,05	0,05	0,20	0,09	0,05	0,04	0,07	0,05
Co	0,01	0,01	0,10	0,03	0,03	0,03	0,03	0,14	0,14	0,14	0,03	0,10	0,10	0,11	0,01

Source: authors 2023

4.8 Routes identification from Central Terminal (PO1) to Post Office (PD1)

4.8.1 Route Matrix.

To determine the shortest path for each macro indicator, Table 9, and the incidence matrix generated were constructed from Table 6. For ambiance indicators, the shortest path consists of segments 6, 7, 8, 10, 12, 14, and 15 with an "ambiance cost" of 0.59 units. The shortest path for safety indicators includes segments 1, 2, 3, 4, 5, 6, and 7, with a "safety cost" of 0.40 units. Similarly, the shortest path for comfort indicators is the same as that for safety indicators, with 0.23 units of "comfort cost".

Table 10 – Shortest path for each indicator

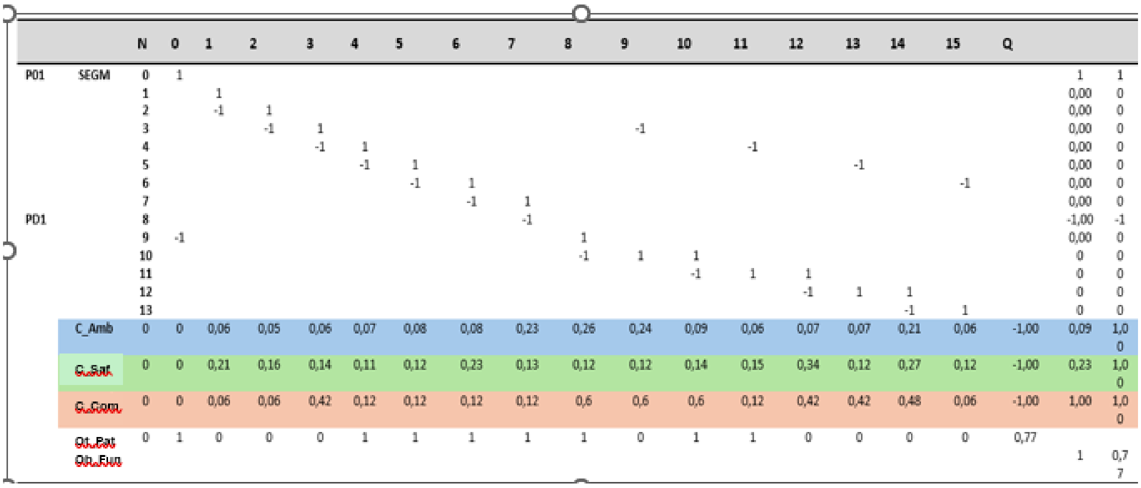
	Segments														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**OPS**
Amb	0	0	0	0	0	1	1	1	0	1	0	1	0	1	1	0,6
Saf	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0,4
Com	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0,2

Source: authors 2023

4.8.2 Multiobjective Optimization Model

The multi-objective optimization (Ambience-Safety-Comfort) model for determining the shortest path from Origen 1 (PO1) to Destination 1 (PD1) is presented in Table 11. According to the model, the shortest path from PO1 to PD1 is through segments 4, 5, 6, 7, 8, 10, and 11. The cost of this path is 0.7656, which is higher than the ambiance cost path.

Table 11 – Multi-objective model for path PO1-PD1



		N	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Q		
P01	SEGM	0	1																	1	1
		1		1																0,00	0
		2		-1	1															0,00	0
		3			-1	1						-1								0,00	0
		4				-1	1							-1						0,00	0
		5					-1	1								-1				0,00	0
		6						-1	1									-1		0,00	0
		7							-1	1										0,00	0
PD1		8								-1										-1,00	-1
		9	-1								1									0,00	0
		10									-1	1	1							0	0
		11											-1	1	1					0	0
		12													-1	1	1			0	0
		13															-1	1		0	0
	C_Amb	0	0	0,06	0,05	0,06	0,07	0,08	0,08	0,23	0,26	0,24	0,09	0,06	0,07	0,07	0,21	0,06	-1,00	0,09	1,00
	C_Saf	0	0	0,21	0,16	0,14	0,11	0,12	0,23	0,13	0,12	0,12	0,14	0,15	0,34	0,12	0,27	0,12	-1,00	0,23	1,00
	C_Com	0	0	0,06	0,06	0,42	0,12	0,12	0,12	0,12	0,6	0,6	0,6	0,12	0,42	0,42	0,48	0,06	-1,00	1,00	1,00
	Ot_Pat	0	1	0	0	0	1	1	1	1	1	0	1	1	0	0	0	0	0,77		
	Ob_Fun																			1	0,77

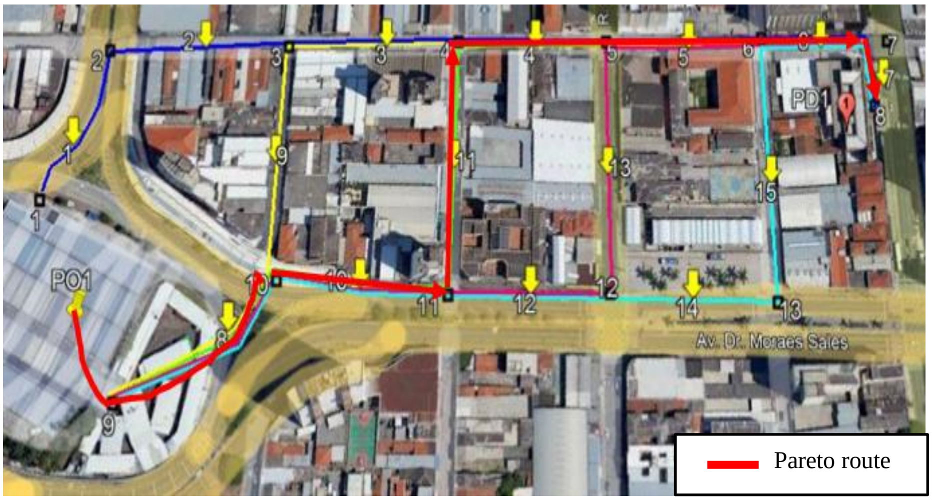
Source: Authors 2023

The route generated by the Mimimax objective is Pareto optimal. That is, given any solution generated by this approach it is certain that no other feasible solution allows an increase in any objective without decreasing at least one other objective. The red line in Figure 5 represents the Pareto optimal path from PO1 to PD1.

6 CONCLUSIONS

The integration of public transport with walking is a beneficial approach to the health of the citizens and a means of raising social issues in an urban environment, especially in a developing country like Brazil. However, people who walk have different perceptions and agility abilities associated with sex, age, and physical limitations. Efforts are required to incentivize downtown walkability to meet pedestrian expectations.

Figure 5 Pareto optimal Route from PO1 to PD1.



Source: authors 2023

Recognizing the importance of actions, public policymakers must develop actions to provide adequate infrastructure for safe and comfortable walking.

The contribution of this work is to propose a methodology to connect urban public terminals to points of essential public services by determining routes that consider the characteristics of the environment, comfort, and walking safety through which the pedestrian will travel. The choice of the best among all possible routes, connecting an origin and destination, was formulated as a multi-objective optimization problem.

The adoption of the solutions suggested here depends on the support of the public administration, which must evaluate and implement them, and at the same time develop actions that contribute to a smooth transit, improve crossing, and pedestrian traffic, avoid inappropriate use of public space with occupancy by stalls, parking on the sidewalks, etc. The proposition of this methodology can be applied to evaluate the impact of other measures such as the implementation of new boardwalks and the concept of shared streets. Thus, as a continuation of this work, it is proposed the interference of government in the current environment with the implementation of shared spaces between pedestrians, bicycles, and motor vehicles as a means of making the urban center a sustainable environment.

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