sustainability

MDPI

Article

Resilience and Vulnerability of Public Transportation Fare Systems: The Case of the City of Rio De Janeiro, Brazil

Tálita Santos [1,2,*], Marcelino Aurélio Silva [1], Vicente Aprigliano Fernandes [3] and Greg Marsden [4]

1 Transportation Engineering Program, Federal University of Rio de Janeiro, Av. Horácio Macedo 2030, Rio de Janeiro 21941-914, Brazil; marcelino@pet.coppe.ufrj.br
2 Department of Production Engineering, Federal University of Piaui, Av. Universitária, Teresina 64049-550, Brazil
3 Instituto de Geografia, Pontificia Universidad Católica de Valparaíso, Av. Brasil 2241, Valparaíso 2362807, Chile; vicente.aprigliano@pucv.cl
4 Institute for Transport Studies, University of Leeds, 34-40 University Road, Leeds LS2 9JT, UK; G.R.Marsden@its.leeds.ac.uk
* Correspondence: talitafloriano@pet.coppe.ufrj.br

Received: 6 December 2019; Accepted: 10 January 2020; Published: 16 January 2020

Abstract: Resilience is the ability of a system to adapt, persist, and transform as a reaction to threats, which may be external or internal to the system, while vulnerability is the state of being susceptible to harm from exposure to stresses associated with environmental and social change and from the inability to adapt. Based on a study of the threats that can affect urban mobility, we identified a gap regarding the analysis of the levels of resilience and vulnerability in the face of subsidy threats that can severely affect developing countries. This article measures the level of resilience and vulnerability due to the absence of public transport fare subsidies. For this purpose, we developed an approach based on fuzzy logic and applied it in 33 administrative regions (ARs) of the city of Rio de Janeiro, Brazil. We obtained four matrices of the levels of vulnerability and resilience of each of the regions as an origin and destination. The results show that areas nearest to the downtown region and those with high-capacity transportation available (commuter train and/or subway, systems with many transfer points) are more resilient, while a high level of vulnerability is associated with low income, negative socioeconomic indicators, and the predominance of road transportation to reach jobs. The contribution of this paper is the method applied to analyse the levels of vulnerability and resilience of public transport, which includes a threat that can cause a rupture that impacts routines and job accessibility in a region.

Keywords: resilience; vulnerability; public transport; fuzzy logic

1. Introduction

Policies and strategies should aim to optimise both the u-rbanisation process and urban functions and infrastructure in order to achieve sustainable development, maximise urbanisation's benefits, and reduce urbanisation's negative impacts [1]. As a way of promoting sustainable development, city planners need to create strategies to promote land use in line with public transport strategies. However, public transport faces threats that can disrupt its operation, making it necessary to discuss the concepts of resilience and vulnerability.

In this context, resilience-based strategies provide a holistic approach, considering both predictable and unpredictable threats [2]. The concept of resilience allows identifying the capacity of a city or region to respond to global threats such as climate change, oil price spikes, and land use challenges. It can be defined as the capacity of a system to adapt, change, and recover from and/or absorb internal or external threats and thus persist [3,4]. The concept can be used to evaluate complex systems, in which dynamic interactions exist between different scales and factors—as is the case with urban spaces [5].

Although resilience is mainly associated with climatic or environmental risks, society is gradually becoming more vulnerable to economic changes [6], as mentioned in the literature [7–9], so urban systems must be prepared to adapt to unexpected and unprecedented changes [10]. The most discussed threats in the literature on the resilience and sustainable development of cities are climate change and natural disasters [7,8,11–14], which are becoming increasingly frequent with more intense weather events, putting years of progress in emerging countries at risk [15].

These threats can bring a series of complications that may affect the dynamism of cities and, consequently, urban mobility: these threats include a rise in sea level [16–18], floods [16,17,19–21], earthquakes [19,20,22–25], a scarcity of natural resources, such as fossil fuels [5,26–29], electricity shortages [8,17,26,30], and the destruction of biodiversity [7]. Other works present the concept of vulnerability as being related to disruption but focused on railway systems [31–33]. These threats are important, but there is a gap in quantifying resilience and vulnerability oriented to urban mobility. Although there are studies analysing resilience in the context of urban mobility, they focus on the scarcity of fossil fuels [29,34], and thus some economic changes are yet to be analysed. Based on such studies, we identified a gap regarding the analysis of the levels of resilience and vulnerability in face of subsidy threats that can severely affect developing countries.

As an emerging country, Brazil is more susceptible to economic changes that interfere in the pattern of mobility. Access to job opportunities through public transport can have different impacts on individuals' lives, especially in developing countries where opportunities are limited, job informality rates are high, and socioeconomic characteristic gaps are big [35]. Providing efficient public transport in terms of accessibility is one of the main objectives of policymakers and planners in metropolitan areas throughout the world [36]. Such initiatives are capable of promoting the sustainable growth of a metropolis.

One of the initiatives that can be used is the fare integration, which allows users to pay a lower single fare for trips requiring transfers. In Rio de Janeiro, each mode of transport (bus, subway, train, Bus Rapid Transit, and ferry) is managed by a transportation agent, and the amount paid to use each mode is different. If users need more than one mode of transport (bus and BRT, for example) to reach their destination, fare subsidies allow them to pay only for the first ticket. These conditions are crucial to promote accessibility given the particular features of Brazilian urban space.

Data from the "Bilhete Único RJ" (the system responsible for electronic ticketing in Rio de Janeiro) show that in just 2 days the total subsidy was US$ 503,052.79. The number of citizens that benefit from this was 295,175, with the number of subsidized trips totalling 1,268,375 and therefore an average allowance per citizen of US$ 1.70 [37]. The motivation of this work is to understand which would be the most vulnerable and the most resilient areas if the subsidised fare integration program ceased to exist.

This article examines the following questions regarding this problem: What would the most vulnerable areas be if the fare subsidy ceased to exist? What are the most resilient areas? If an area is vulnerable, does this mean it is not resilient? Do regions with mass transit (train, subway) have better resilience indexes? To answer these questions, here we propose a method to measure the level of resilience and vulnerability based on fuzzy logic and apply it to a real situation through a case study of the subsidy, specifically of fare integration, for public transportation in the city of Rio de Janeiro, Brazil, from the standpoint of job access

This paper is structured into six sections. After this introduction, Section 2 summarizes the latest research about resilience and threats that affect urban mobility. Section 3 presents fuzzy system modelling, followed by a method characterization in Section 4. The case study about resilience and vulnerability levels is presented in Section 5. Finally, Section 6 presents the conclusions and implications of our findings.

2. Literature Review

2.1. Resilience and Vulnerability Concepts

Resilience refers to the capacity of a system or its components, in time and space, to maintain or quickly return to the desired functions when faced with a threat, to adapt to changes or to undergo rapid transformations [13,16], and/or to maintain the level of services offered through adequate conditions for persistence, allowing the system and its mode of organization to be prepared for a new situation [20].

The main goal of resilience is to reduce the impacts resulting from a disturbance or a concept transversal to various research areas with very similar definitions [38]. Therefore, the concept can be associated with changes, disturbances, uncertainties, and adaptations [10].

Many views on the resilience concept have been presented in the literature. For Ribeiro et al. (2019), four basic pillars of urban resilience are considered: resisting (maintaining functions and structures), recovering (protecting the life, propriety, and economy), adapting (preventing and mitigating vulnerabilities), and transforming (providing benefits to urban systems) [38]. Bruneau et al. (2013) claimed that resilience for both physical and social systems can be further defined as consisting of four properties: robustness (the ability of elements to withstand a given level of stress without suffering degradation); redundancy (the ability to satisfy functional requirements); resourcefulness (the capacity to identify problems, establish priorities, and mobilize resources); and finally, rapidity (the capacity to meet priorities and achieve goals) [39].

The topic has attracted the interest of academics and politicians with regard to local and community development [23], which can be seen from a socio-ecological perspective as involving attributes related to persistence, change, unpredictability, and multiple equilibria [22], in which disturbances to the system have the potential to create opportunities to develop new solutions incorporating the ideas of adaptation, learning, and self-organization [40].

Unlike the concept of resilience, vulnerability does not have a convergent definition. Vulnerability can be defined as the exposure of a city to shocks in terms of magnitude and frequency [7], the susceptibility to incidents that can in some way affect the system [41], or as the state of being susceptible to harm from the exposure to stresses associated with environmental and social change and from the absence of the capacity to adapt [42]. In this paper, we consider vulnerability as the susceptibility of a system to a determined threat.

The importance of recognizing areas of high vulnerability and improving their resilience by mitigating risks has attracted the interest, regarding local and community development, of academic and political circles [23]. The reason is that resilience not only involves persistence, but also the opportunities that threats bring in terms of the recombination of structures and processes, renovation of systems, and emerging trajectories [40].

2.2. Urban Resilience

Holling (1973) is considered a seminal paper on the concept of resilience. The author discussed the concept from ecological systems, addressing the characteristics of persistence and adaptation, and the transformation of these systems, arguing that the traditional view of natural systems may not reflect the reality experienced by a given species [43]. This is analogous to urban planning: the traditional view does not consider the threats and possible impacts they may have on citizens' lives and the dynamics of cities.

The socio-ecological system approach aims to develop an integrated framework that includes studies that often seem fragmented [9] in the context of urban resilience. The resilience of urban mobility is complex and interdependent, with parameters involving persistence, adaptation, and transformation, as presented by [43], who stated that the resilience determines the persistence of relationships within a system and is a measure of the capacity of the system to absorb changes and thus persist.

In the context of this study, we used the urban resilience concept. Urban areas in general, as ecosystems, are increasingly more vulnerable to shocks due to environmental, economic or social disturbances [29], so it is important to identify the threats that can affect mobility since public transport networks are essential to mobility in urban areas [44]. Urban resilience can be defined as the ability of the system to respond and recover after an extreme event [4,45].

A framework was proposed by Fernandes et al. (2017) [5] that adapted the concepts proposed by Folke et al. (2010) [46]. Fernandes et al. (2017) studied urban resilience by focusing on urban mobility. The role of public transport is significant for the resilience of urban mobility because, depending on its configuration and characteristics, this service may be vulnerable to risks, whether technical, human, or natural, and thus will affect urban mobility to some extent. Thus, resilience is classified as persistent, adaptable, or transformable.

Persistent resilience relates to the potential of individuals or groups to keep their mobility patterns without compromising their current quality of life. Adaptability is part of resilience and represents the capacity to adjust responses to changes in external factors and internal processes, and thus allow for development along the current trajectory, on which it is necessary to change the current state of the system to adjust it to a new situation [46,47].

Transformability is the ability to create a new situation of stability, i.e., to create novel responses to develop a new way of living when the existing ecological, economic or social structures become unsustainable [46,47]. Furthermore, transformability involves the potential to create new conditions for the adaptability and persistence in response to threats [5].

Martins, Silva, and Pinto [29] considered the possibility of trips made in motorized modes being transferred to active modes in the event of a disruption of the mobility system. The analysis assumed that people could walk or cycle up to a certain distance. In this way, they classified the trips as: exceptional, persistent, adaptable and transformable.

In another quantitative approach to the resilience of urban mobility, Fernandes et al. (2019) used data on transportation systems and infrastructure, transportation price, the average slope levels of each district, accessibility by bicycle to a train or metro station, wages, the matrix of expenditure, job positions, origins and destinations, and electric mobility projects. The authors classified the level of resilience as persistent, adaptable, or transformable. The classification is based especially on the change that would occur in the users' expense matrix if fossil fuels were to double in price [34].

According to [48], researchers should keep a watchful eye on the stability and diversification of urban economic structures to cope with unknown risks and pressures, highlighting the importance of developing a better understanding of how people react with respect to their mobility [49].

Resilience assessment tools should be able to produce a set of improvements to the conditions of the system and identify challenges and opportunities that result from mitigation and prevention measures or the possibility of changing the functioning of the systems themselves [38]. Resilience has a conceptual fuzziness that is beneficial by enabling it to function as a "boundary object" [13]. Therefore, the model proposed in this paper is based on fuzzy logic.

3. Fuzzy System Modelling

Fuzzy logic is a powerful tool, used to solve complex problems, due to its ability to infer conclusions and produce answers based on vague, ambiguous, and/or qualitatively incomplete or inaccurate information [50,51]. As such, it is a useful tool for dealing with decisions in which the phenomenon is imprecise and vague [52]. It has been associated with sustainable transport [53,54], transportation networks [55], and urban resilience [56,57]. Using fuzzy concepts, evaluators can use linguistic terms to assess indicators in a natural language expression, where each linguistic term is associated with a membership function [52]. The necessary concepts of fuzzy system modelling is described as follows [53,58–60].

Definition 1. *Fuzzy set and membership function. The characteristic function μA of a crisp set $A \subseteq X$ assigns a value of either 0 or 1 to each member in X, since crisp sets only allow full membership ($\mu_A(x) = 1$) or non-membership ($\mu_A(x) = 0$). This function can be generalized to a function μ_A* such that the value assigned to the element of the universal set X falls within a specified range, i.e., μ_A: X → [0, 1]. The assigned value indicates the membership grade of the element in set A. The function μ_A *is called the membership function and the set $A = (x,\ \mu_A(x))$, where $x \in X$, defined by $\mu_A(x)$ for each $x \in X$,* is called a fuzzy set.

Definition 2. *Triangular fuzzy number. A fuzzy set Ã, defined on the universal set of real numbers $\Re$, is said to be a triangular fuzzy number $A(a, m, b)$ if its membership function has the following form (1):*

$$\mu_A(x,a,m,b) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{m-a}, & a \le x \le m \\ 1, & x = m \\ \dfrac{b-x}{b-m}, & m \le x \le b \\ 0, & x \ge a \end{cases} \tag{1}$$

And the following characteristics (2) and (3):

$$x_1,\ x_2 \in [a,b] x_2 > x_1 \ \Rightarrow \mu_A(x_2) > \mu_A(x_1) \tag{2}$$

$$x_1,\ x_2 \in [b,c] x_2 > x_1 \ \Rightarrow \mu_A(x_2) > \mu_A(x_1) \tag{3}$$

Definition 3. *Trapezoidal fuzzy number. A fuzzy set Ã, defined on the universal set of real numbers $\Re$, is said to be a trapezoidal fuzzy number, such as $A(x, a, b, c, d)$, if its membership function has the following form:*

$$\mu_A(x,a,b,c,d) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases} \tag{4}$$

Definition 4. *Symbolically, Ã is denoted by $\mu_A(x,\ a,\ b, c, d)$. The generalized trapezoidal fuzzy number $\tilde{A} = (x,\ a,\ b, c, d)$ divides into three parts: the left part, middle part, and right part.*

Definition 5. *Gaussian fuzzy number. A fuzzy set Ã, defined on the universal set of real numbers $\Re$, is said to be a Gaussian fuzzy number, such as $A(x, c, s, m)$, if its membership function has the following form:*

$$\mu_A(x,\ c, s, m) = exp\left[-\frac{1}{2}\left|\frac{x-c}{s}\right|^m\right] \tag{5}$$

where c is the centre, s is width, and m is the fuzzification factor.

Definition 6. *The rule base. The rule base consists of logical rules determining causal relationships that exist in the system between fuzzy sets of its inputs and its output.*

Definition 7. *The fuzzy rule. The single fuzzy rule can be based on a modus ponens. The reasoning process uses logical connectives IF-THEN, OR, and AND.*

Definition 8. *A typical fuzzy model employs rules based on "IF-THEN". More formally, the process used to determine the output for a given input is called fuzzy inference. Based on this inference, the output is called the pertinence degree, with values ranging from 0 to 1, and is determined by:*

$$E_i(y) = T(\tau_i B_i(y)) \tag{6}$$

where E_i is a fuzzy subset., τ_i is the degree of the function, and B_i is the fuzzy subset of linguistic concepts defined in space y.

Definition 9. *For the method considering the "AND" rules of a set of variables (for example, IF employment in the destination is high AND the population of the origin is high, THEN the potential use of transportation is high), then:*

$$T(\ \tau_i B_i(y)) = \tau_i \hat{} B_i(y) \qquad (\hat{} = min) \tag{7}$$

$$T(\tau_i B_i(y)) = \tau_i B_i(y) \qquad (output) \tag{8}$$

Besides this, the operator $S(E_1(y), E_2(y), \ldots, E_n(y))$, for the method that considers the union of rules with "OR", involves Equations (9) and (10).

$$S(E_1(y), E_2(y), \ldots., E_n(y)) = Max\ _i(E_i(y)) \tag{9}$$

$$S(E_1(y), E_2(y), \ldots., E_n(y)) = 1 - \prod(1 - E_i(y)) \tag{10}$$

Definition 10. *To obtain a crisp output, it is necessary to defuzzify the result denoted by y*, according to the centroid method, as given by Equation (11).*

$$y^* = \frac{\sum_y E(y)y}{\sum_y E(y)} \tag{11}$$

4. Method Characterization

The approach proposed is presented in Figure 1 and contains eight steps.

Step 1. *Initial Definitions.* Initially, based on articles and government reports, we analysed the threats that can affect the use of public transport. Then, we defined one of them to analyse the levels of vulnerability and resilience.

Step 2. *Study Area and Zoning.* Based on the threat chosen, we defined the study area, whose mobility would be affected if the threat occurs, and its zoning.

Step 3. *Gathering Data.* We then identified the necessary data available in governmental databases, as well as real-time data (such as from Google API), for use in defining the levels of vulnerability and resilience.

Step 4. *Logical Architecture of the Problem of Using Fuzzy Logic*. In this step, we constructed a decision tree and applied fuzzy logic to represent the logical architecture of the problem. In formulating this tree, each node corresponds to a base of fuzzy logic rules called an inference block (IB), in which the linguistic variables are computed, by aggregation and composition, to produce an inferred result, also in the form of a linguistic variable.

We used three fuzzy subsets: trapezoidal, triangular, and Gaussian. The application was carried out employing the fuzzy function of MATLAB 2017®, considering the Mamdani model, with the following implications: AND method (minimum), OR method (maximum), implication (minimum), aggregation (maximum), and defuzzification (centroid). All concepts required for the fuzzy model are presented in Section 2.

Step 5. *Levels of Vulnerability and Resilience*. The previous step resulted in four matrices with the levels of vulnerability and resilience for origin and destination. We classified vulnerability into three levels: non-existent, low, and high. The "non-existent" situation implies that the threat does not occur for that origin-destination pair, so there is no vulnerability. The criteria adopted to classify the level of resilience were divided into three levels: persistence, adaptation, and transformation.

Step 6. *Vulnerability and Resilience Criteria*. The pertinence function of the level of vulnerability, $f(v)$, can be classified into three levels (non-existent, low, and high) according to Equation (12):

$$f(v) = \begin{cases} \text{non} - \text{existent}, & \text{x} = 0 \\ \text{low}, & \text{x} < 0.5 \\ \text{high}, & \text{x} \geq 0.5 \end{cases} \quad (12)$$

The pertinence function of the level of resilience, $f(r)$, can also be classified into three levels (persistence, adaptation, and transformation) according to Equation (13):

$$f(r) = \begin{cases} \text{persistence}, & \text{x} \geq 0.625 \\ \text{adaptation}, & 0.3 \leq \text{x} \leq 0.625 \\ \text{transformation}, & \text{x} \leq 0.3 \end{cases} \quad (13)$$

We classified vulnerability as "low" when the values of the pertinence functions obtained in the vulnerability matrix were lower than 0.5 and were as "high" when the values were greater than 0.5. Then, we counted the number of regions with non-existent, low, or high vulnerability.

The criteria adopted to classify the level of resilience were divided into persistence, adaptation, and transformation. "Persistence" occurs when the level of resilience is greater than 0.625, "adaptation" occurs when the level is between 0.3 and 0.625, and "transformation" occurs when the level of resilience is lower than 0.3. These values were obtained from the intersection of the Gaussian curves of the pertinence functions.

Step 7. *Vulnerability and Resilience Codes.* In this step, we prepared codes for vulnerability and resilience. These are values in terms of the percentage of connections where vulnerability was classified as non-existent, low, or high for each region. Analogously, we formulated the code for resilience, consisting of the percentages that are persistent, adaptable and transformable. The codes for vulnerability and resilience were analysed from the standpoint of origin and destination.

Step 8. *Vulnerability and Resilience Maps.* Finally, we prepared vulnerability and resilience maps. The first type represents the percentage of origin-destination connections with high vulnerability in each Rio de Janeiro Administrative Region (RJAR) as an origin and destination, while the second represents the percentage of persistent and adaptable connections for each RJAR as an origin and destination.

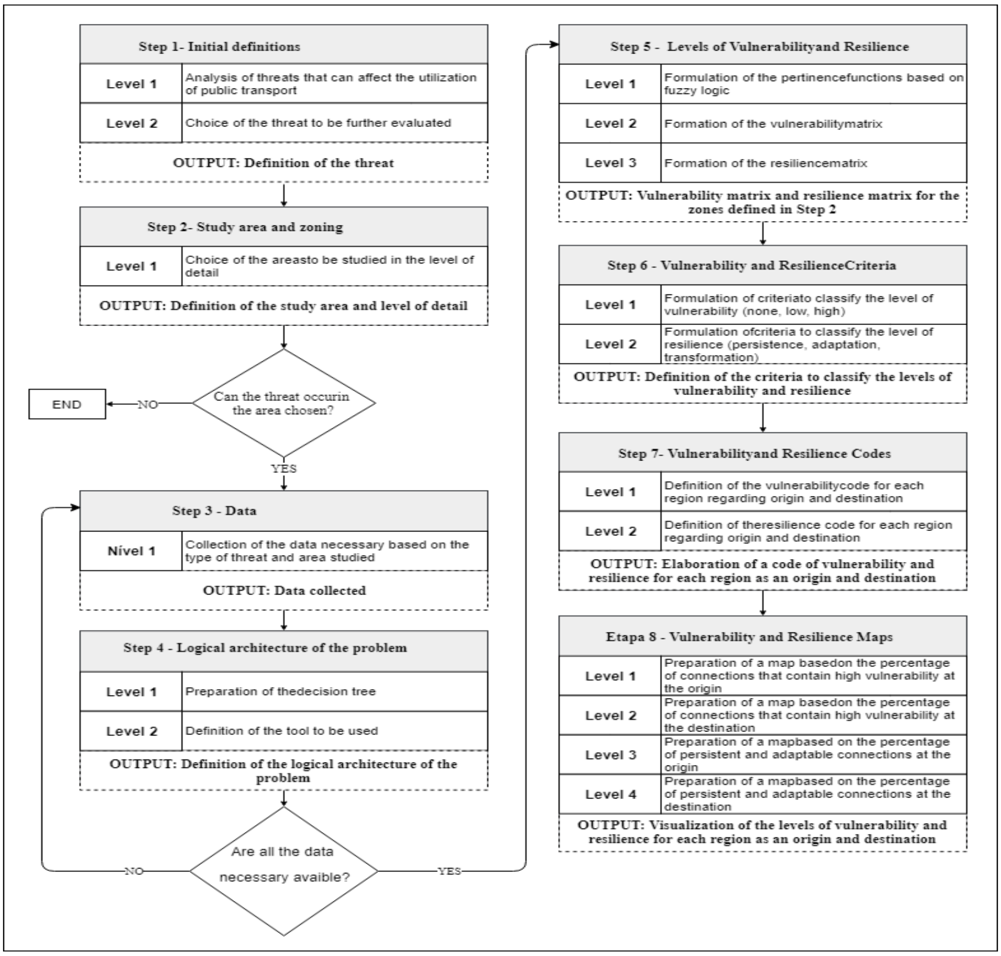

Figure 1. Methodological procedures.

5. Study Case

5.1. Initial Definitions

Based on the analysis of the threats that can impair urban mobility (obtained from articles and government reports), we defined an economic threat, namely the absence of fare subsidies, and its effects on job access.

5.2. Study Area and Zoning

The area studied was the city of Rio de Janeiro, located in south-eastern Brazil. The zoning was based on the municipal government's division of the city into 33 administrative regions (RJARs). The city of Rio de Janeiro is the capital of the state with the same name. It has more than 6 million inhabitants, and like all large Brazilian cities, suffers from large social inequalities, measured by job access, education, health and leisure services. Besides this, there is an unequal distribution of technologies, in particular, transportation technology, meaning inhabitants are unable to realize activities [61]. Figure 2 depicts the 33 administrative regions of Rio de Janeiro.

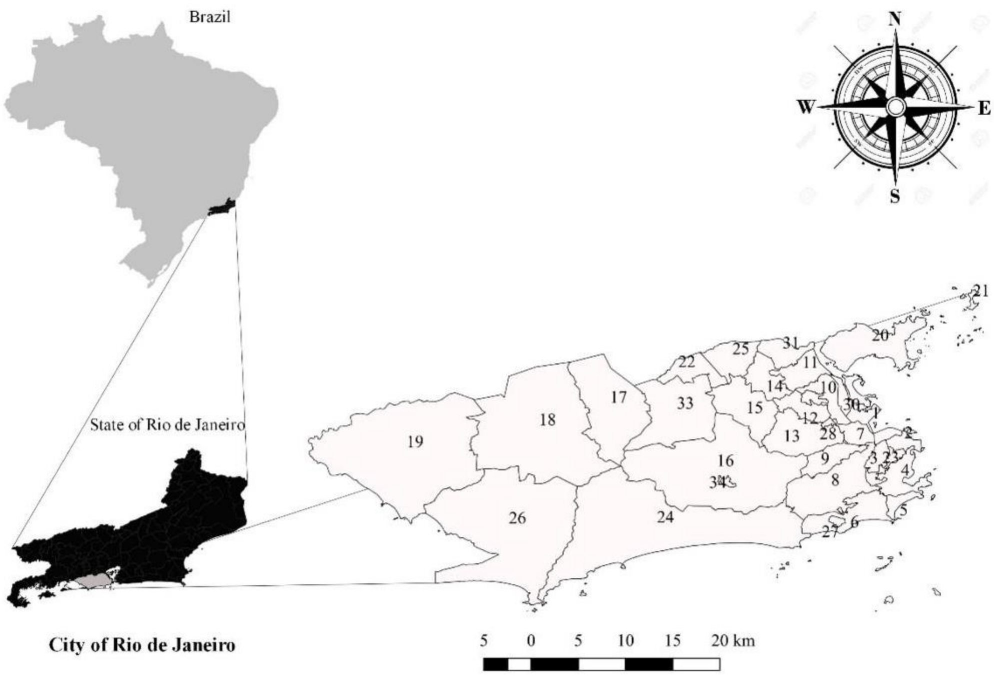

Figure 2. Administrative regions of the city of Rio de Janeiro (see Table 1 for legend).

Table 1. Administrative region codes and information.

CodRA	Administrative Region	Population	Jobs	Average Nominal Income (US$) [1]	Income Ranking	Social Development Indicator (SDI)	Income SDI
1	Portuária	48,664	30,936	138	27	0.561	24
2	Centro	41,142	626,936	363	7	0.643	7
3	Rio Comprido	78,975	56,991	242	14	0.596	14
4	Botafogo	239,729	143,160	827	2	0.735	2
5	Copacabana	161,191	50,434	807	4	0.73	3
6	Lagoa	167,774	84,681	1161	1	0.764	1
7	São Cristóvão	84,908	84,445	195	20	0.582	19
8	Tijuca	181,810	88,205	606	5	0.697	4
9	Vila Isabel	189,310	51,904	502	6	0.679	5
10	Ramos	153,177	110,011	211	16	0.591	15
11	Penha	185,716	46,255	201	18	0.591	16
12	Inhaúma	134,349	23,865	208	17	0.588	18
13	Méier	397,782	114,515	318	9	0.629	8
14	Irajá	202,952	25,814	250	13	0.61	11
15	Madureira	372,555	56,087	213	15	0.59	17
16	Jacarepaguá	572,030	112,836	302	11	0.6	13
17	Bangu	412,868	38,027	158	23	0.568	22
18	Campo Grande	542,084	150,255	184	21	0.562	23
19	Santa Cruz	368,534	34,945	132	29	0.528	32
20	Ilha do Governador	212,574	59,189	331	8	0.627	9
21	Paquetá	3361	184	297	12	0.608	12
22	Anchieta	158,318	9382	177	22	0.575	21
23	Santa Teresa	40,926	2297	311	10	0.624	10
24	Barra da Tijuca	300,823	164,863	811	3	0.676	6
25	Pavuna	208,813	32,528	142	26	0.553	27
26	Guaratiba	123,114	5512	143	25	0.493	33
27	Rocinha	69,356	1	122	30	0.533	30
28	Jacarezinho	37,839	0	103	33	0.534	29
29	Complexo do Alemão	69,143	0	108	32	0.532	31
30	Complexo da Maré	129,770	1802	118	31	0.547	28
31	Vigário Geral	136,171	32,048	146	24	0.559	25
32	Realengo	243,006	24,122	198	19	0.578	20
33	Cidade de Deus	36,515	773	133	28	0.559	26

[1] The official minimum wage in 2010 was US$128 per month. Conversion used: R$ 4 = US$ 1.

5.3. Gathering Data

The downtown region ("Centro") has the largest number of jobs: 27.7% of those in the city have jobs, which causes a strong attraction of trips. The region with the second largest proportion of jobs is Barra da Tijuca (164,863), followed by Campo Grande (150,255) and Botafogo (143,160). These four administrative regions together account for 48% of the city's jobs.

On the other hand, the population is well distributed. The regions with the largest populations are Jacarepaguá (572,030), Campo Grande (542,084), Bangu (412,868), Méier (397,782), and Madureira (372,555), while those with the highest average nominal monthly income levels (including people without income) are Lagoa (US$ 1161), Botafogo (US$ 827), Barra da Tijuca (US$ 3811), Copacabana (US$ 807), and Tijuca (US$ 606). For comparison, in 2010 (the year of these census numbers), the minimum monthly wage was US$ 128.

The social development indicator (SDI) is used for measuring the degree of social development in a geographic area in comparison to others of the same nature. It takes into consideration, among other factors, the percentages of illiteracy, households with a per capita income under the minimum wage, and households with a per capita income greater than five times the minimum. The regions with the highest SDI, in decreasing order, are Lagoa, Botafogo, Barra da Tijuca, Copacabana, and Tijuca. This indicator helps to identify regions with greater vulnerability. Chart 2 identifies the administrative regions' population, employment, nominal income and SDI.

The jobs counted in this chart are only in the formal sector, characterized as registered employees, self-employed individuals contributing to social security, or small business owners contributing to social security [35]. This explains the fact that the regions of Jacarezinho and Complexo do Alemão do not have any employment and Rocinha only has 1 job on record—they are all slum areas (*favelas*) where the local economy is overwhelmingly informal.

For the purpose of this study, we used the following basic variables: origin-destination travel time, population, average per capita income, SDI, employment, and the transportation fare. The travel times from each RJAR to reach the others were obtained through the Google Maps Distance Matrix API, using the centroid of each region, considering the shortest travel time using public transportation at 07:00 on weekdays (considered to be peak rush hour according to the 2013 Urban Transport Master Plan for Rio de Janeiro).

The data on population, income, and the social development indicator were obtained from the population census for 2010 conducted by the Brazilian Institute of Geography and Statistics (IBGE, 2010) for each region. The employment variable was the number of formal jobs, defined as the number of registered employees, self-employed individuals contributing to social security, or small business owners contributing to social security [35].

The fare data were obtained from Google Maps, considering how much users pay to travel to a destination. However, Google Maps only provides information on the full fare, i.e., without considering integration. Therefore, we used data from Riocard (supplier of magnetic fare cards), the subway operator and ferry operator, referring to 2018.

5.4. Logical Architecture of the Problem Using Fuzzy Logic

We considered the data obtained in the previous steps and used the following variables referring to the RJARs: origin population, origin employment, destination employment, the number of jobs within 60 min (using public transport) of a region, the number of jobs that can be reached by paying one fare, intervening opportunities provided by a region until reaching a destination, travel time, fare difference, the social development indicator (SDI), and income. The description of each variable used is described in Table 2.

Table 2. Description of variables.

Variables	Description	Source
Population (origin)	Referring to population in administrative region of origin	Census Data (2010) [1]
Employment (destination)	Referring to jobs in administrative region of destination	Census Data (2010) [2]
Potential use	Measures O-D link that can be used based on population and employment variables	Inference block 1 (Fuzzy logic)
Intervening opportunities	Number of jobs that can be reached until destination	Census Data (Jobs) and Google API (time)
Trip time	Time required to reach destination	Google API
Impedance	Measures the opposition to movement	Inference block 2
Flow rate	Measures O-D link flow considering impedance and potential use	Inference block 3
Jobs (60 min)	Number of jobs that can achieve 60 min using public transport	Google API
Jobs (one fare)	Number of jobs that can be reached paying one fare	Google API
Accessibility	Measures facility to reach a destination	Inference block 4
Fare difference	Difference between the fare paid with and without subsidy	Google API and Rio Card
Income (origin)	Average nominal income	Census Data (2010)
Fare subsidy effect	Calculates the importance of fare subsidies for the trip to happen	Inference block 5
Employment (Origin)	Referring to jobs in administrative region of origin	Census Data (2010)
SDI	Social Development Indicator	Census Data (2010)
Social economic factor	Measures the social and economic development of an administrative region	Inference block 6
Vulnerability level	Measures the vulnerability level based on fare subsidies effect and social economic factor	Inference block 7
Resilience level	Measures the level of resilience based on the lowest value between flow rate and vulnerability level (inference block 8) and accessibility or vulnerability level (inference block 9)	Lowest value between inference block 8 and 9

[1], see http://ibge.gov.br for details on the Census (2010); [2], see http://rais.gov.br for details on the Census (Jobs).

Each inference block had a set of rules considering linguistic values. We created 266 rules represented by trapezoidal, triangular, and Gaussian functions, where each rule had a weighting factor called the certainty factor (CF), in the interval from 0 to 1, indicating the degree of importance of each rule in the fuzzy rule base. In inference block 1, the potential use considers the population of origin with employment in the destination.

For example, if the population is high and employment (destination) is high, then the potential for use is high. Inference block 2, among other rules, considers the impedance to be high if intervening opportunities are high, until reaching the destination, and time is high. The flow level is the relationship between potential use and impedance: if the potential use is high and the impedance is low, then the flow level is high. An example of fuzzy logic rules is presented in Table 3.

Table 3. Fuzzy rules base for inference block 1 for "Very Low" employment.

IF		THEN	
Employment Destination	**Population Origin**	**Potential Use**	**Certainty Factor**
Very Low	Very Low	Very Low	1
Very Low	Low	Very Low	0.95
Very Low	Medium	Low	0.85
Very Low	High	Medium	0.7
Very Low	Very High	Medium	0.8

With these, we formulated nine inference blocks, as depicted in Figure 3.

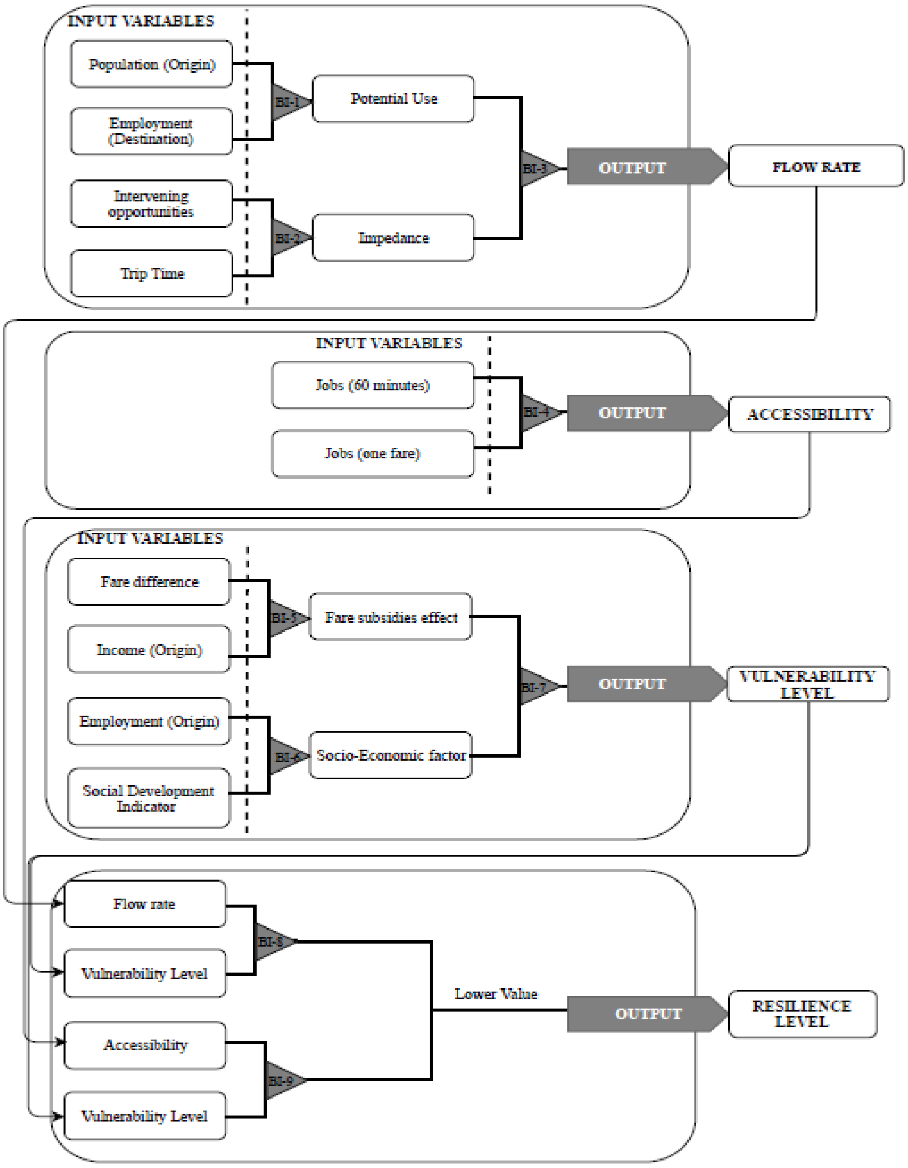

Figure 3. Architecture of the problem based on fuzzy logic.

5.5. Levels of Vulnerability and Resilience

Considering the decision tree based on IF-THEN connections in the previous step, we formulated the pertinence functions, which indicate that the levels of vulnerability and resilience, in the interval from 0 to 1. From these, we obtained matrices with levels of vulnerability and resilience, each one for an origin and a destination, for a total of four matrices. Table 4 reports the levels of vulnerability and resilience adopted.

Table 4. Levels of vulnerability and resilience.

	Level	What Means
Vulnerability	Non-existent	No fare subsidies are necessary to make the trip
	Low	Connection little vulnerable to threat
	High	Connection very vulnerable to threat
Resilience	Persistence	The potential of individuals or groups to maintain their standards of mobility without compromising their quality of life
	Adaptation	Need to change a routine for a trip to continue happening
	Transformation	Need a social and economic change due to the absence of fare integration that has a negative impact on the routine for making trips

5.6. Vulnerability and Resilience Criteria

These counts were used to compute the percentages of each RJAR, for each origin-destination pair. The classification of the level of vulnerability: when $f(v)$ is non-existent, it means that, even if the threat occurs, the O-D connection will not be affected, i.e., no fare subsidies are necessary to make that trip. A low level of vulnerability occurs when the pertinence function is less than 0.5, while vulnerability is high when the function has a value greater than or equal to 0.5.

The pertinence function of the level of resilience, $f(r)$, can also be classified into three levels (persistence, adaptation, and transformation). For a given level of resilience, the persistence metric is related to the potential of individuals or groups to maintain their standards of mobility without compromising their quality of life, even after the restrictions. Adaptability corresponds to the need to change a routine for a trip to continue happening, such as a change in route, a change of bus line, or an increased travel time. Finally, transformation refers to a social and economic changes that occur due to the absence of fare integration, which has a negative impact on the routine for making trips.

5.7. Vulnerability and Resilience Codes

Based on the criteria adopted to classify the levels of vulnerability and resilience, we formulated the vulnerability and resilience codes for the RJARs, considering the percentage values of each region in the mentioned classification, as shown in Table 5.

Table 5. Resilience and vulnerability Code.

Administrative Region	Resilience Code						Vulnerability Code					
	Origin			*Destination*			*Origin*			*Destination*		
	Transformation	**Adaptation**	**Persistence**	**Transformation**	**Adaptation**	**Persistence**	**Nonexist**	**Low**	**High**	**Nonexist**	**Low**	**High**
1	0.30	0.12	0.58	0.12	0.03	0.85	0.58	0.00	0.42	0.85	0.00	0.15
2	0.00	0.42	0.58	0.42	0.09	0.48	0.39	0.21	0.39	0.48	0.09	0.42
3	0.09	0.61	0.30	0.39	0.21	0.39	0.30	0.00	0.70	0.36	0.06	0.58
4	0.00	0.21	0.79	0.42	0.21	0.36	0.33	0.64	0.03	0.36	0.09	0.55
5	0.00	0.18	0.82	0.24	0.36	0.39	0.24	0.76	0.00	0.36	0.09	0.55
6	0.00	0.15	0.85	0.15	0.12	0.73	0.58	0.42	0.00	0.70	0.09	0.21
7	0.03	0.27	0.70	0.24	0.12	0.64	0.67	0.03	0.30	0.64	0.09	0.27
8	0.00	0.12	0.88	0.45	0.15	0.39	0.36	0.61	0.03	0.39	0.09	0.52
9	0.12	0.39	0.48	0.30	0.18	0.52	0.48	0.00	0.52	0.52	0.09	0.39
10	0.00	0.52	0.48	0.21	0.09	0.70	0.45	0.15	0.39	0.61	0.12	0.27
11	0.03	0.48	0.48	0.27	0.15	0.58	0.48	0.00	0.52	0.48	0.12	0.39
12	0.36	0.27	0.36	0.36	0.24	0.39	0.36	0.00	0.64	0.39	0.06	0.55
13	0.06	0.18	0.76	0.21	0.18	0.61	0.67	0.15	0.18	0.55	0.12	0.33
14	0.42	0.12	0.45	0.18	0.18	0.64	0.45	0.00	0.55	0.58	0.09	0.33
15	0.06	0.24	0.70	0.15	0.06	0.79	0.70	0.00	0.30	0.67	0.12	0.21
16	0.39	0.36	0.24	0.27	0.30	0.42	0.24	0.00	0.76	0.39	0.12	0.48
17	0.30	0.06	0.64	0.15	0.12	0.73	0.64	0.00	0.36	0.61	0.12	0.27
18	0.09	0.18	0.73	0.12	0.15	0.73	0.73	0.00	0.27	0.64	0.09	0.27
19	0.58	0.00	0.42	0.33	0.18	0.48	0.42	0.00	0.58	0.36	0.12	0.52
20	0.06	0.73	0.21	0.36	0.27	0.36	0.21	0.00	0.79	0.21	0.15	0.64
21	0.97	0.00	0.03	0.48	0.24	0.27	0.03	0.00	0.97	0.03	0.24	0.73
22	0.24	0.06	0.70	0.15	0.09	0.76	0.70	0.00	0.30	0.67	0.09	0.24
23	0.33	0.09	0.58	0.18	0.09	0.73	0.58	0.00	0.42	0.64	0.09	0.27
24	0.00	0.39	0.61	0.30	0.30	0.39	0.42	0.55	0.03	0.39	0.12	0.48
25	0.58	0.09	0.33	0.24	0.12	0.64	0.33	0.00	0.67	0.58	0.09	0.33
26	0.52	0.00	0.48	0.42	0.15	0.42	0.48	0.00	0.52	0.30	0.12	0.58
27	0.55	0.18	0.27	0.48	0.39	0.12	0.27	0.00	0.73	0.06	0.12	0.82
28	0.15	0.00	0.85	0.18	0.00	0.82	0.85	0.00	0.15	0.76	0.06	0.18
29	0.33	0.00	0.67	0.15	0.15	0.70	0.67	0.00	0.33	0.58	0.12	0.30
30	0.24	0.12	0.64	0.30	0.18	0.52	0.64	0.00	0.36	0.39	0.15	0.45
31	0.33	0.00	0.67	0.18	0.12	0.70	0.67	0.00	0.33	0.55	0.15	0.30
32	0.18	0.15	0.67	0.12	0.15	0.73	0.67	0.00	0.33	0.61	0.15	0.24
33	0.64	0.15	0.21	0.42	0.39	0.18	0.21	0.00	0.79	0.12	0.06	0.82

Table 5 presents the vulnerability and resilience codes of the RJARs. The fact that some of the connections have non-existent vulnerability means they are not susceptible to the threat of the absence of fare subsidies, i.e., no subsidies are necessary to travel between points A and B.

For example, in Portuária (AR 1), 58% of the origin connections are classified as persistent (i.e., pertinence function values are higher than 0.625), while in the destination analysis, 85% of the connections are persistent. This means that, as an origin, 58% of the connections manage to maintain the standards of mobility, but to access the region (destination perspective), 85% of the connections manage to access it even without fare subsidies.

The coding of resilience and vulnerability allows one to analyse each of the regions from the perspective of an origin and a destination. The resilience code shows that the higher the percentage of persistent and adaptive connections at a source, the better this region will be able to handle the absence of subsidies.

On the other hand, the vulnerability code can indicate which regions are most susceptible to this threat. This means that when the vulnerability does not exist, public transport users only need to use one mode of transport to reach their destination.

5.8. Vulnerability and Resilience Maps

With Table 5, we prepared maps of vulnerability and resilience. The vulnerability maps considered the percentage of connections with vulnerability classified as "high". By this measure, the five regions with the highest vulnerability levels as origins are Paquetá (AR 21), Ilha do Governador (AR 20), Cidade de Deus (AR 33), Jacarepaguá (AR 16), and Rocinha (AR 27).

In the Paquetá region, for example, 97% of the connections have high vulnerability, requiring fare integration to access 32 of the 33 regions (except itself). Because it is an island in the bay without any bridge to the mainland, it depends exclusively on transportation, specifically on ferry boats, which do not have fare integration with other modes. Ilha do Governador, Cidade de Deus, Jacarepaguá and Rocinha need fare integration in over 70% of their connections.

On the other hand, Botafogo (AR 4), Tijuca (AR 8), Barra da Tijuca (AR 24), Copacabana (AR 5), and Lagoa (AR 6) have the lowest vulnerability levels considering origin. Botafogo, Tijuca and Barra da Tijuca, each have only one connection with high vulnerability.

The five regions with the highest levels of vulnerability as destinations are Rocinha (AR 27), Cidade de Deus (33), Paquetá (21), Ilha do Governador (20), and Rio Comprido (AR 3), meaning they strongly depend on fare integration for their residents to access jobs in other regions of the city. On the other hand, the regions with the lowest vulnerability levels as destinations are Anchieta (AR 22), Lagoa (AR 6), Madureira (AR 15), Jacarezinho (AR 28), and Portuária (AR 1), meaning they are relatively impervious to the lack of fare integration.

It can be noted that the coastal regions and those near downtown (Centro) are the least vulnerable as origins, with favourable characteristics in terms of employment and SDI. About vulnerability as destinations, the least vulnerable ones are those with access to transport modes with greater capacity, namely subway and commuter train. Table 6 summarizes the vulnerability information, considering regions with highest and lowest indexes, and also indicates the income and SDI rankings.

It should be mentioned that the reason for the difference in vulnerability as an origin and destination is that the total fare to travel from point A to B is not necessarily the same as that required to travel from B to A. This means that fare integration is often needed more to go from point A to B than in the opposite direction. Besides this, vulnerability considers variables, such as income and SDI. In other words, a region with high income will be less vulnerable as an origin due to the lack of fare subsidy. Figure 4 presents a map of the vulnerability levels of all of the administrative regions of Rio de Janeiro.

Table 6. Vulnerability level summary.

	HIGHTEST	Ranking of Income and SDI	LOWEST	Ranking of Income and SDI
Origin	Paquetá (AR 21)	12th both	Botafogo (AR 4)	2nd and 2nd
	Ilha do Governador (AR 20)	8th and 9th	Tijuca (AR 8)	5th and 4th
	Cidade de Deus (AR 33)	28th and 26th	Barra da Tijuca (AR 24)	3rd and 6th
	Jacarepaguá (AR 16)	11th and 13th	Copacabana (AR 5)	4th and 3rd
	Rocinha (AR 27)	30th both	Lagoa (AR 6)	1st both
Destination	Rocinha (AR 27)	30th both	Anchieta (AR 22)	22nd and 21st
	Cidade de Deus (AR 33)	28th and 26th	Lagoa (AR 6)	1st both
	Paquetá (AR 21)	12th both	Madureira (AR 15)	15th and 17th
	Ilha do Governador (AR 20)	8th and 9th	Jacarezinho (AR 28)	33rd and 29th
	Rio comprido (AR 3)	14th both	Portuária (AR 1)	27th and 24th

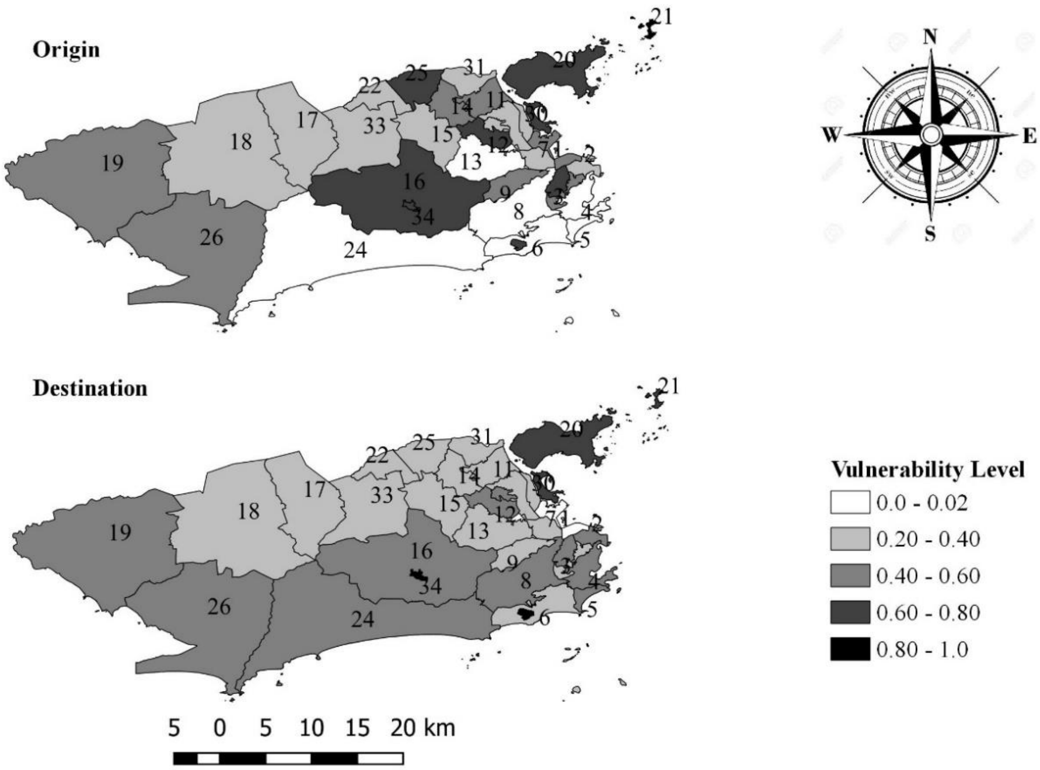

Figure 4. Vulnerability map of the (administrative regions) RJARs.

We considered the more resilient regions to be those with more persistent and adaptable connections, with a separate analysis for the origin and destination. The five regions with the highest levels of resilience as origins are Tijuca, Lagoa, Copacabana, Botafogo, and Barra da Tijuca. In all of them, all of the connections are persistent and adaptable. This means that riders who start their trips in this region manage to maintain their standards of mobility to access jobs in other parts of the city even without fare integration.

The five regions with the highest levels of transformation as origins, i.e., if the threat occurs, they will need to create alternatives to make home–work trips and would be affected socioeconomically, are Paquetá (97%), Cidade de Deus (79%), Rocinha (73%), Pavuna (61%), and Santa Cruz (58%). In other words, without fare integration these regions would need social and economic alterations, so there would be an impact on the trip routine.

The administrative regions with the highest levels of persistence and adaptation in relation to destination, i.e., those that are the most resilient to the absence of fare integration, are (in decreasing order) Portuária, Anchieta, Campo Grande, Complexo de Alemão, and Realengo. On the other hand, the five regions with the highest transformation levels, i.e., the worst resilience levels as destinations, are Ilha do Governador, Rocinha, Centro, Botafogo, and Tijuca. Table 7 summarizes the resilience information, considering regions with more persistent and adaptable connections and more transformation connections, also indicating the income and SDI rankings.

Table 7. Resilience Level Summary.

	More Persistent and Adaptable Connections	Ranking of Income and SDI	More Transformation Connections	Ranking of Income and SDI
Origin	Tijuca (AR 8)	5th and 4th	Paquetá (AR 21)	12th both
	Lagoa (AR 6)	1st both	Cidade de Deus (AR 33)	28th and 26th
	Copacabana (AR 5)	4th and 3rd	Rocinha (AR 27)	30th both
	Botafogo (AR 4)	2nd and 2nd	Pavuna (AR 25)	26th and 27th
	Barra da Tijuca (AR 24)	3rd and 6th	Santa Cruz (AR 19)	29th and 32th
Destination	Portuária (AR 1)	27th and 24th	Ilha Governador (AR 20)	8th and 9th
	Anchieta (AR 22)	22nd and 21st	Rocinha (AR 27)	30th both
	Campo Grande (AR 18)	21st and 23rd	Centro (AR 2)	7th both
	Complexo do Alemão (AR 29)	32nd and 31st	Botafogo (AR 4)	2nd and 2nd
	Realengo (AR 32)	19th and 20th	Tijuca (AR 8)	5th and 4th

The difference in the analysis for origin and destination can be explained by the number of jobs available in a particular region or nearby regions (those that are possible to access within 60 min using public transport). For example, Table 5 shows that in region 24 (Barra da Tijuca), 100% of the connections are classified as persistent and adaptable as an origin, while for destination only 69% are so classified. Barra da Tijuca is the region with the second largest number of jobs in the city (only behind Centro), making it highly resilient to the absence of fare integration for users who want to access jobs (origin perspective), but it is not as resilient for users who want to come there to access jobs (destination perspective). Figure 5 geographically presents the results.

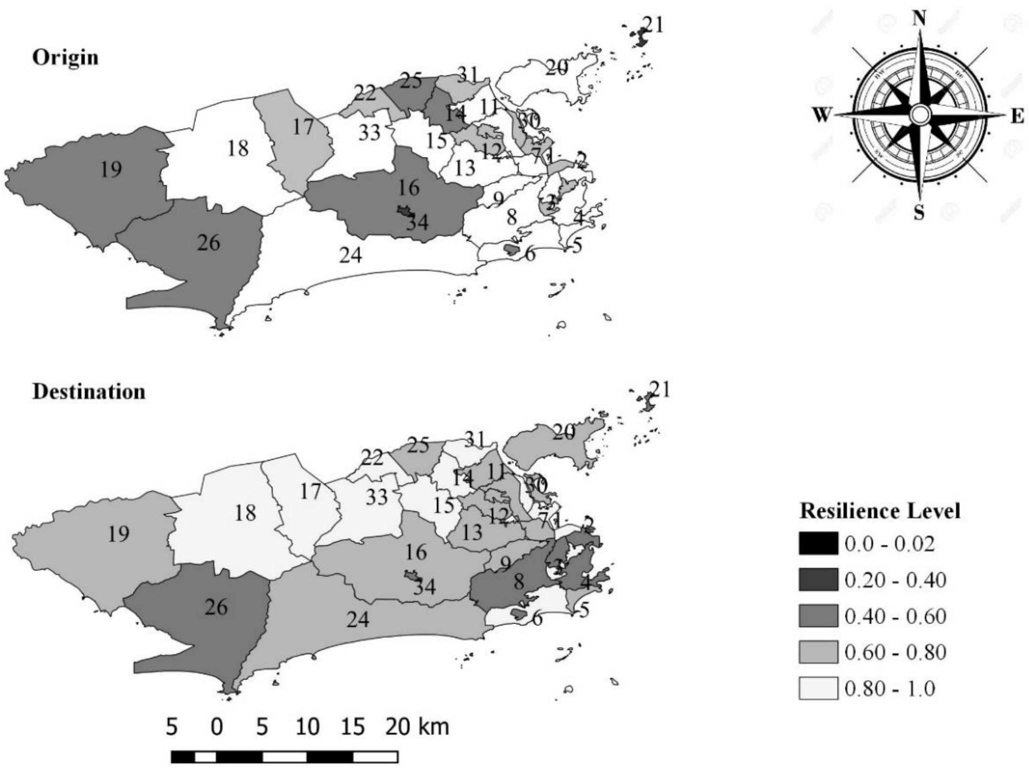

Figure 5. Resilience map of the RJARs.

5.9. Analysis

Rocinha (6), Cidade de Deus (34), and Paquetá (21) are the worst regions in the overall analysis. They have the lowest levels of resilience and the highest levels of vulnerability, both as origins and destinations. These three regions do not have high-capacity ground transportation available, causing an increase in trip time, and many connections need fare integration to occur. Also, since formal jobs in these regions are scarce, users need to access other regions for jobs.

Rocinha and Cidade de Deus are slum communities (*favelas*), marked by precarious levels of income, social development, and formal jobs. In turn, Paquetá is an island only linked to the rest of the city by ferry boats, and although it does not have precarious income and social development indexes, it is mainly a residential community, so it does not have a large number of jobs, formal or informal.

Ilha do Governador (AR 20), which depends solely on buses and does not have fare integration with all the other modes, is vulnerable as both an origin and a destination. But because it has a large number of jobs (59,185) and better socioeconomic factors than Cidade de Deus, Rocinha, and Paquetá, it is a resilient region both as an origin and a destination.

Lagoa (AR 6) was considered the best region in the overall analysis, with the highest levels of resilience as origin and of vulnerability as origin and destination. It has the highest average nominal income and SDI. Besides this, it is served by the subway system and is near downtown (Centro). This means that travel times to access jobs are short and fare integration is, relatively speaking, less important, both because of the relatively high income level and because most other regions with large numbers of jobs, such as Centro, can be reached without the need for transfers.

Tijuca (AR 8), Copacabana (AR 5), and Barra da Tijuca (AR 24) were considered to have the highest levels of resilience and the lowest levels of vulnerability as origins. The three regions are served by the subway system and Tijuca also is served by commuter trains. Tijuca and Copacabana are both near Centro, so their residents can access a large number of jobs with short trip times. These three regions are also among the five best in terms of income and SDI.

Portuária (AR 1) and Anchieta (AR 22) were considered to have high resilience and low vulnerability as destinations. Portuária does not have high-capacity transport available, but it is contiguous to Centro. On the other hand, Anchieta is served by trains, so its residents can access jobs in nearby regions, such as Campo Grande (AR 18), which has the third highest number of jobs in the city.

The separate analysis of the regions as origins and destinations showed some relevant differences from this perspective. For example, Tijuca is resilient as an origin: those who live in Tijuca and need to access other regions have the ability to do so even without fare integration. On the other hand, people from other regions who need to access Tijuca (destination) would need other alternatives to access the region in the absence of fare integration.

This implies that these regions as destinations would be impaired with the occurrence of the threat. This demonstrates that the lack of ability to deal with the threat of the absence of integration should be analysed both from the perspective of an origin and a destination. For instance, Botafogo and Tijuca were considered to have high resilience as origins but not as destinations, meaning that those who live in one of these two regions have good ability to withstand the threat, while those who need to access the two regions do not.

Some regions served by mass transit still presented low resilience, either as an origin (Santa Cruz and Pavuna) or as a destination (Centro, Botafogo and Tijuca). This can possibly be explained by the time needed to reach other regions, high impedance, and the need for fare integration to reach destinations with a huge number of jobs, such as Centro.

6. Conclusions and Implications

6.1. Conclusions

With resilience defined as the ability of a system to continue functioning even after a rupture, an analysis of this concept from the perspective of the need to reach jobs reveals that threats can occur in various forms. The threats most commonly examined in the literature are related to natural disasters, such as floods, earthquakes, and more recently, fossil fuel price spikes. There has been little discussion about the possible impacts related to economic changes that can affect transportation systems, especially in developing countries like Brazil.

Although the concept of resilience is widely discussed in the literature, there is a gap regarding the way to measure this concept when dealing with economic and social threats. Thus, here we proposed a way to measure resilience. Specifically, we determined the resilience of each of the administrative regions of Rio de Janeiro to the absence of fare integration, applying a tool that allows one to analyse problems holistically. The tool used was fuzzy logic, because it permits analysing complex problems using linguistic variables without resorting to multicriteria methods or measures that can imply offsetting values. Besides this, the level of resilience was measured for each origin-destination pair, resulting in 1089 links.

The results of this study serve as a reflection on sustainability and resilience policies. Although mass transit systems, such as commuter trains and subways, have a positive long-range impact in terms of the reduced consumption of fossil fuels and the emission of greenhouse gases, in the short run they may not be able to respond to spontaneous and immediate stresses of an economic nature, especially when there is no fare integration with other modes of transport.

In addition, this paper indicates deficient conditions which are related to the dichotomic relationship between economic growth and the sustainable development of cities nowadays, especially the continuous geographical expansion of cities in developing countries. In this context, land values tend to rise near coastal areas and cities' central business districts, generating socio-spatial inequality. In cities such as Rio de Janeiro, challenges are not only related to reducing travel time for people living in the suburbs through the available technological advancements of transportation systems; they are also related to transportation costs for those considered political minorities and vulnerable socioeconomic groups that are exposed to and affected by costly mobility conditions, which lead to reduced accessibility of urban opportunities in terms of jobs, leisure, education and basic services.

6.2. Implications

The method proposed here can be applied in other cities and to examine the potential effects on urban mobility of other threats, considering the particularities of each city. Therefore, this method can provide complementary support to the measurement of sustainability indicators, and vice versa, in the sense of developing and implementing policies to balance the maintenance and improvement of the environment to preserve the life quality of future generations (sustainability) and to create resilience for the present generation, which would enable people to respond and adapt to conditions of economic stress that can adversely affect urban mobility, such as policies for decentralization of jobs and reduction of socioeconomic inequality.

Besides proposing a way to measure the level of resilience, the method can be replicated in other Brazilian cities, without the need for O-D analysis, by using census data and Google API information.

6.3. Limitations and Future Work

The analysis of resilience and vulnerability considered in this paper assumes an absence of subsidies for the use of more than one mode of public transportation in the city of Rio de Janeiro. This is just one aspect that can be seen from the perspective of economic threats in emerging countries.

For future works, we recommend a deeper study in terms of geographic scale (reducing the size of regions to neighbourhoods and expanding the scope to other cities) and in terms of social and urban variables, which are significant for developing countries, can influence the urban mobility conditions, and would require exhaustive work to collect primary data due to the lack of information available, for example, the distribution of informal jobs and transportation systems that are not legalized by the government (informal transportation systems).

Author Contributions: Formal analysis, M.A.S. and V.A.F.; Methodology, T.S.; Software, M.A.S.; Writing—review and editing, T.S.; Visualization, G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (process 201575/2018-3)—Brazil.

Acknowledgments: We gratefully acknowledge the three anonymous reviewers for their constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, X.Q. The trends, promises and challenges of urbanisation in the world. *Habitat Int.* **2016**, *54*, 241–252. [CrossRef]
2. Lomba-fern, C.; Hernantes, J.; Labaka, L. Guide for Climate-Resilient Cities: An Urban Critical Infrastructures Approach. *Sustainability* **2019**, *11*, 4727. [CrossRef]
3. Marchese, D.; Reynolds, E.; Bates, M.E.; Morgan, H.; Clark, S.S.; Linkov, I. Resilience and sustainability: Similarities and differences in environmental management applications. *Sci. Total Environ.* **2018**, *613*, 1275–1283. [CrossRef]
4. Gaitanidou, E.; Tsami, M.; Bekiaris, E. A review of resilience management application tools in the transport sector. *Transp. Res. Procedia* **2017**, *24*, 235–240. [CrossRef]
5. Fernandes, V.A.; Rothfuss, R.; Hochschild, V.; Ribeiro, W. Resiliência da mobilidade urbana: Uma proposta conceitual e de sistematização. *Transportes* **2017**, *25*, 1–15. [CrossRef]
6. Ajibade, I. Can a future city enhance urban resilience and sustainability? A political ecology analysis of Eko Atlantic city, Nigeria. *Int. J. Disaster Risk Reduct.* **2017**, *26*, 85–92. [CrossRef]
7. Boschetti, F.; Gaffier, C.; Moglia, M.; Walke, I.; Price, J. Citizens' perception of the resilience of Australian cities. *Sustain. Sci.* **2017**, *12*, 345–364. [CrossRef]
8. Sellberg, M.M.; Wilkinson, C.; Peterson, G.D. Resilience assessment: A useful approach to navigate urban sustainability challenges. *Ecol. Soc.* **2015**, *20*, 43. [CrossRef]
9. Sharifi, A.; Yamagata, Y. Principles and criteria for assessing urban energy resilience: A literature review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1654–1677. [CrossRef]
10. Ahern, J. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landsc. Urban Plan.* **2011**, *100*, 341–343. [CrossRef]
11. Jaroszweski, D.; Hooper, E.; Chapman, L. The impact of climate change on urban transport resilience in a changing world. *Prog. Phys. Geogr.* **2014**, *38*, 448–463. [CrossRef]
12. Leichenko, R. Climate change and urban resilience. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 164–168. [CrossRef]
13. Meerow, S.; Newell, J.P.; Stults, M. Defining urban resilience: A review. *Landsc. Urban Plan.* **2016**, *147*, 38–49. [CrossRef]
14. Tromeur, E.; Ménard, R.; Bailly, J.-B.; Soulié, C. Urban vulnerability and resilience within the context of climate change. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 1811–1821. [CrossRef]
15. Gallagher, D.; Cruickshank, H. Planning under new extremes: Resilience and the most vulnerable. *Proc. Inst. Civ. Eng. Munic. Eng.* **2016**, *169*, 127–137. [CrossRef]
16. Abdrabo, M.A.; Hassaan, M.A. An integrated framework for urban resilience to climate change—Case study: Sea level rise impacts on the Nile Delta coastal urban areas. *Urban Clim.* **2015**, *14 Pt 4*, 554–565. [CrossRef]
17. Coaffee, J. Risk, resilience and environmentally sustainable cities. *Energy Policy* **2008**, *36*, 4633–4638. [CrossRef]
18. Zhao, P.; Chapman, R.; Randal, E.; Howden-Chapman, P. Understanding resilient urban futures: A systemic modelling approach. *Sustainability* **2013**, *5*, 3202–3223. [CrossRef]
19. Chen, L.; Miller-Hooks, E. Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport. *Transp. Sci.* **2012**, *46*, 109–123. [CrossRef]
20. Spaans, M.; Waterhout, B. Building up resilience in cities worldwide—Rotterdam as participant in the 100 Resilient Cities Programme. *Cities* **2017**, *61*, 109–116. [CrossRef]
21. Gil, J.; Steinbach, P. From flood risk to indirect flood impact: Evaluation of street network performance for effective management, response and repair. *WIT Trans. Ecol. Environ.* **2008**, *118*, 335–344.
22. Reggiani, A.; Nijkamp, P.; Lanzi, D. Transport resilience and vulnerability: The role of connectivity. *Transp. Res. Part A Policy Pract.* **2015**, *81*, 4–15. [CrossRef]

23. Wang, C.-H.; Chen, N.; Chan, S.-L. A gravity model integrating high-speed rail and seismic-hazard mitigation through land-use planning: Application to California development. *Habitat Int.* **2017**, *62*, 51–61. [CrossRef]
24. McDaniels, T.; Chang, S.; Cole, D.; Mikawoz, J.; Longstaff, H. Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Glob. Environ. Chang.* **2008**, *18*, 310–318. [CrossRef]
25. Ilbeigi, M. Statistical process control for analyzing resilience of transportation networks. *Int. J. Disaster Risk Reduct.* **2019**, *33*, 155–161. [CrossRef]
26. O'Brien, G. Vulnerability and resilience in the european energy system. *Energy Environ.* **2009**, *20*, 399–410. [CrossRef]
27. Leung, A.; Burke, M.; Cui, J. The tale of two (very different) cities—Mapping the urban transport oil vulnerability of Brisbane and Hong Kong. *Transp. Res. Part D Transp. Environ.* **2017**, *65*, 796–816. [CrossRef]
28. Leung, A.; Burke, M.; Perl, A.; Cui, J. The peak oil and oil vulnerability discourse in urban transport policy: A comparative discourse analysis of Hong Kong and Brisbane. *Transp. Policy* **2018**, *65*, 5–18. [CrossRef]
29. Da Mata Martins, M.C.; Silva, A.N.R.; Pinto, N. An indicator-based methodology for assessing resilience in urban mobility. *Transp. Res. Part D* **2019**, *77*, 352–363. [CrossRef]
30. Rendall, S.; Page, S.; Reitsma, F.; Van Houten, E.; Krumdieck, S. Quantifying transport energy resilience: Active mode accessibility. *Transp. Res. Rec.* **2011**, *2242*, 72–80. [CrossRef]
31. Esposito Amideo, A.; Starita, S.; Scaparra, M.P. Assessing Protection Strategies for Urban Rail Transit Systems: A Case-Study on the Central London Underground. *Sustainability* **2019**, *11*, 6322. [CrossRef]
32. Binder, S.; Maknoon, Y.; Bierlaire, M. The multi-objective railway timetable rescheduling problem. *Transp. Res. Part C Emerg. Technol.* **2017**, *78*, 78–94. [CrossRef]
33. D'Acierno, L.; Gallo, M.; Montella, B.; Placido, A. The definition of a model framework for managing rail systems in the case of breakdowns. In Proceedings of the 16th International IEEE Conference on Intelligent Transportation Systems (ITSC), The Hague, The Netherlands, 6–9 October 2013; pp. 1059–1064.
34. Fernandes, V.A.; Rothfuss, R.; Hochschild, V.; Silva, M.A.V.; Silva, W.R.; Steiniger, S.; Santos, T.F. Urban resilience in the face of fossil fuel dependency: The case of Rio de Janeiro's urban mobility. *Urbe Rev. Bras. Gestão Urbana* **2019**, *11*, e20180160. [CrossRef]
35. Boisjoly, G.; Moreno-Monroy, A.I.; El-Geneidy, A. Informality and accessibility to jobs by public transit: Evidence from the São Paulo Metropolitan Region. *J. Transp. Geogr.* **2017**, *64*, 89–96. [CrossRef]
36. Saghapour, T.; Moridpour, S.; Thompson, R.G. Public transport accessibility in metropolitan areas: A new approach incorporating population density. *J. Transp. Geogr.* **2016**, *54*, 273–285. [CrossRef]
37. RiodeJaneiro. Available online: https://site.riobilheteunico.com.br/ (accessed on 11 January 2020).
38. Ribeiro, P.J.G.; Pena Jardim Gonçalves, L.A. Urban resilience: A conceptual framework. *Sustain. Cities Soc.* **2019**, 101625. [CrossRef]
39. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; Von Winterfeldt, D. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
40. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Chang.* **2006**, *16*, 253–267. [CrossRef]
41. Berdica, K. An introduction to road vulnerability: What has been done, is done and should be done. *Transp. Policy* **2002**, *9*, 117–127. [CrossRef]
42. Adger, W.N. Vulnerability. *Glob. Environ. Chang.* **2006**, *16*, 268–281. [CrossRef]
43. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
44. Rodríguez-Núñez, E.; García-Palomares, J.C. Measuring the vulnerability of public transport networks. *J. Transp. Geogr.* **2014**, *35*, 50–63. [CrossRef]
45. *Brasil Planmob: Caderno de Referência para Elaboração de Plano de Mobilidade Urbana*; Ministério das Cidades: Brasilia, Brazil, 2015; pp. 1–238.
46. Folke, C.; Carpenter, S.R.; Walker, B.; Scheffer, M.; Chapin, T.; Rockström, J. Resilience thinking: integrating resilience, adaptability and transformability. *Ecol. Soc.* **2010**, *15*, 20. [CrossRef]
47. Walker, B.; Holling, C.S.; Carpenter, S.R.; Kinzig, A. Resilience, Adaptability and Transformability in Social–ecological Systems. *Ecol. Soc.* **2004**, *9*, 5. [CrossRef]
48. Zhang, X.; Li, H. Urban resilience and urban sustainability: What we know and what do not know? *Cities* **2018**, *72*, 141–148. [CrossRef]

49. Wang, Q.; Taylor, J.E. Patterns and limitations of urban human mobility resilience under the influence of multiple types of natural disaster. *PLoS ONE* **2016**, *11*, e0147299. [CrossRef]
50. Cosenza, C.; Sandres, G.; Junior, P.S.; Siggete, E. CRFM: An application of the fuzzy logic in APELL programme. *Int. J. Saf. Secur. Eng.* **2016**, *6*, 63–72. [CrossRef]
51. Adjetey-Bahun, K.; Birregah, B.; Châtelet, E.; Planchet, J.-L. A model to quantify the resilience of mass railway transportation systems. *Reliab. Eng. Syst. Saf.* **2016**, *153*, 1–14. [CrossRef]
52. Vinodh, S.; Devadasan, S.R. Twenty criteria based agility assessment using fuzzy logic approach. *Int. J. Adv. Manuf. Technol.* **2011**, *54*, 1219–1231. [CrossRef]
53. Sałabun, W.; Palczewski, K.; Wątróbski, J. Multicriteria Approach to Sustainable Transport Evaluation under Incomplete Knowledge: Electric Bikes Case Study. *Sustainability* **2019**, *11*, 3314. [CrossRef]
54. Rajak, S.; Parthiban, P.; Dhanalakshmi, R. Sustainable transportation systems performance evaluation using fuzzy logic. *Ecol. Indic.* **2016**, *71*, 503–513. [CrossRef]
55. Freckleton, D.; Heaslip, K.; Louisell, W.; Collura, J. Evaluation of resiliency of transportation networks after disasters. *Transp. Res. Rec.* **2012**, 109–116. [CrossRef]
56. Olazabal, M.; Pascual, U. Use of fuzzy cognitive maps to study urban resilience and transformation. *Environ. Innov. Soc. Transit.* **2016**, *18*, 18–40. [CrossRef]
57. Bozza, A.; Asprone, D.; Manfredi, G. Developing an integrated framework to quantify resilience of urban systems against disasters. *Nat. Hazards* **2015**, *78*, 1729–1748. [CrossRef]
58. Yager, R.R. Simultaneous solution of fuzzy models: An application to economic equilibrium analysis. *Fuzzy Sets Syst.* **2000**, *115*, 339–349. [CrossRef]
59. Sałabun, W. Reduction in the Number of Comparisons Required to Create Matrix of Expert Judgment in the Comet Method. *Manag. Prod. Eng. Rev.* **2014**, *5*, 62–69. [CrossRef]
60. Faizi, S.; Rashid, T.; Sałabun, W.; Zafar, S.; Wątróbski, J. Decision Making with Uncertainty Using Hesitant Fuzzy Sets. *Int. J. Fuzzy Syst.* **2018**, *20*, 93–103. [CrossRef]
61. Fernandes, V.A.; Henríquez, C.; Soto, C.L. Cidade para Viver ou Trabalhar? Contradições da Distribuição de Atividades, Transporte e Condições Sociais: Estudo de Caso da Cidade do Rio de Janeiro A City to Live or Work In? Contradictions Present in the Spatial Distribution of Economic Activities. *Espaço Aberto* **2017**, *7*, 157–179. [CrossRef]