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Research article

Enhancing sidewalk accessibility assessment for wheelchair users: An adaptive weighting fuzzy-based approach

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ABSTRACT

To reach a destination within the community, it is crucial that wheelchair users possess the ability to plan, execute, and acquire knowledge of routes in a safe and efficient manner. While numerous methods have been introduced for assessing the accessibility of sidewalks, existing studies often overlook the variations in the perception of the accessibility of long segments based on each wheelchair user's capabilities. Extended distances may lead to increased fatigue, impacting the ability of individuals with mobility disabilities to navigate sidewalks comfortably and independently. In this paper, we propose an adaptive weighting method, effectively addressing the accessibility assessment of sidewalks by considering more specifically the impact of sidewalk length. The results underscore the significant impact of sidewalk length on mobility, delineating varying accessibility indices in long sidewalk segments, and offering a more realistic evaluation of accessibility based on wheelchair users' perceptions. For validation purposes, the proposed model was implemented in a personalized routing tool called MobiliSIG and compared with the conventional fuzzy model provided by the tool for accessibility assessment through a case study in Quebec City. The results demonstrated improved routing outcomes compared to previous methods, showcasing the effectiveness of our model in enhancing sidewalk accessibility assessment.

1. Introduction

Wheeling is a significant active transportation mode for individuals with mobility impairments [1–6]. Therefore, there is a necessity for equal access to the physical environment, irrespective of individuals' abilities [7]. However, wheelchair users may face various social and physical obstacles that hinder their mobility and social participation. These obstacles might be static or dynamic such as narrow sidewalks, challenging riding surfaces, inadequate or excessively steep ramps, inappropriate curb cuts, obstructed

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sidewalks, and unfavorable weather conditions [8–13].

According to the Disability Creation Process model (DCP), disability is not solely determined by an individual's impairments. It is the result of the interaction between personal and environmental factors that can either facilitate or impede an individual's participation in society. Social and physical barriers could limit wheelchair users' daily activities, and lead to their isolation and exclusion from society [14]. Following this model, the accessibility of a sidewalk depends on the wheelchair user's personal factors (identity, organic systems, and capabilities) and their interactions with the physical factors of sidewalks. Assessing the accessibility of a sidewalk for a wheelchair user therefore requires taking this interaction into account.

According to Tyler [15], the capability model provides a valuable framework for understanding what is at stake in the user-environment interaction underlying the accessibility. This model maps the interaction between the individual and the environment. The individual decides whether to undertake an activity in an environment based on his own capabilities, called provided capabilities. The provided capabilities are what an individual brings to a given task within a specific environment, at a specific moment. Each activity needs a set of the wheelchair user's capabilities in order to be completed successfully which are called required capabilities [15]. To perform an activity, the capabilities a wheelchair user estimates to be able to provide must therefore be at least equal or more to the capabilities required by the environment. In other words, assessing the accessibility of a sidewalk relies on an evaluation of the provided and required capabilities. Environmental factors such as steep slopes, narrow sidewalks, or inadequate pavement (texture) might enhance the required capabilities of wheelchair users to wheel along a sidewalk segment. The length of a sidewalk segment, in particular, can intensify the impact of a slope, uneven surface, or other features on the required capabilities. Therefore, on long sidewalks, as the distance of the pathway increases, one's abilities can be reduced gradually, so that his provided capabilities are less than the required capabilities.

This is further heightened by the associated fatigue. Fatigue is a significant factor to consider, as the energy needed to complete a series of actions differs from that required for an individual action. Notably, there is a distinction in the body's performance when undertaking a single step compared to the more complex task of climbing a hundred steps. Individuals using wheelchairs might choose to traverse a short path characterized by a steep incline. However, they would refuse to wheel through a lengthier path with a steep slope [16]. While fatigue sets in, one's capabilities to be provided for an action might be reduced, and in some cases, this may even lead to health issues.

Consequently, careful consideration of the impact of the length of a sidewalk segment in the assessment of its accessibility is of utmost importance as it could help wheelchair users decide whether to choose a path considering their capacities, fatigue, and health issues. So, it is important to establish a clear understanding of the relationship between the wheelchair user's confidences to move on a sidewalk in the presence of an environmental factor of which its impact on accessibility might be increased by the sidewalk length.

While the environmental factors such as the slope and quality are measurable, the capabilities an individual could provide to perform an activity in an environment are too complex to be measured. An alternative solution to measure wheelchair users' capabilities is to ask them to express their confidence in confronting different factors of the environment. Thus, some of the research works evaluate wheelchair users' confidence in being able to provide the capabilities the environment requires rather than the capabilities themselves [17,18]. Our work stands on this line itself.

The above mentioned studies dealing with sidewalk accessibility assessment, although helpful, have some limitations in considering the role of sidewalk length as they did not consider the changes in the perception of the wheelchair users on the accessibility of a sidewalk considering its length (ex. a long sidewalk with a steep slope or bad quality).

This article presents a new approach that uses an extended fuzzy-based method with an adaptive weighting system for evaluating pedestrian network accessibility by considering the length of segments, their characteristics, and their impact on the overall accessibility of a given itinerary. The proposed method is a confidence-based approach for a more accurate accessibility assessment of a sidewalk by considering the effects of the length on required capabilities by each environmental factor. The remainder of this paper is organized as follows: Section 2 presents a review of previous research on the accessibility of pedestrian networks for wheelchair users considering environmental and personal factors. Section 3 outlines the proposed method for assessing accessibility. Section 4 elaborates on a case study experiment conducted according to this new method and its implementation. Section 5 provides an analysis of the results, and Section 6 discusses the obtained results for a manual wheelchair user, as well as the benefits of this method in presenting personalized accessible routes. Finally, Section 7 presents the conclusions and perspectives of this study.

2. Related works

Several methods and tools (such as AccesSIG and MobiliSIG) [12,16,17,19,20], were proposed and used for accessibility assessment of a given itinerary in the presence of diverse environmental factors (e.g., slope, quality of the surface, sidewalk length, presence of people, etc.). One of the factors that could affect the perception of sidewalk accessibility is the length of the segments. For instance, let us consider two sidewalk segments within an urban environment, both characterized by the same surface quality, slope, and other physical features relevant to accessibility assessment. However, segment A spans a shorter distance, while segment B extends over a more considerable length. In this scenario, individuals with mobility impairments may face distinct challenges when navigating segment B compared to segment A, despite similar characteristics. The prolonged distance of segment B could result in increased fatigue and exertion for those with limited mobility, potentially affecting their ability to traverse the sidewalk comfortably and independently.

Some researchers considered the length of each segment as an effective factor in the accessibility assessment of sidewalks for people with mobility impairment [16,19,20,21,22,23,24,25,26,27,28,29].

Gharebaghi et al. [17] proposed a personalized routing approach that uses the Fuzzy Technique for Order of Preference by

Similarity to Ideal Solution (FTOPSIS) to assess sidewalk accessibility for people with motor disabilities, incorporating user confidence and employing the Dijkstra algorithm to determine accessible paths. Their method effectively captures key physical characteristics of sidewalk segments, such as length, slope, width, surface quality, and elevation changes, offering an insightful framework for evaluating accessibility. However, while this approach is comprehensive in its analysis of physical attributes, it fails to account for variations in user confidence as individuals encounter different sidewalk features in a long and continuous route. Therefore, the model may not fully represent the real-world experience of navigating extensive sidewalks, where evolving user perceptions are crucial to understanding overall accessibility.

Yaaqoubi et al. [20], proposed a theoretical framework for assessing the accessibility of urban environments for people with mobility impairments. Their approach emphasizes the importance of user perception and accounts for the heterogeneity of user profiles. By employing a questionnaire and drawing on the experiences of wheelchair users, the researchers gained valuable insights into how individuals perceive barriers relative to their personal characteristics. The study considers length as an independent factor, providing a useful perspective on physical dimensions of sidewalks. However, this framework does not address how user perceptions might evolve over the course of traversing long sidewalks. In reality, a user's experience and perception of various sidewalk features can shift significantly depending on the length and sustained exposure to environmental factors. This oversight may limit the framework's effectiveness in capturing the dynamic nature of user interactions with extended sidewalk segments.

Hashemi and Karimi [16], introduced a collaborative and personalized way-finding method. Their approach involved collecting data from wheelchair users and incorporating it into optimal route recommendations. Length was utilized as an intensifying factor in each segment, potentially reducing the accessibility of that segment [16]. However, this method not only consistently risks diminishing accessibility, a premise that is not always applicable, but also overlooks the factors influenced by length.Tajgardoon and Karimi [19] assessed the accessibility of sidewalks in the urban environment for wheelchair users based on six important parameters (slope, stairs, length, intersection, width, type, and conditions of the surface). By assigning different weights to these parameters using a linear model, different scenarios are recommended for routing. Finally, the sidewalk network, in each scenario, is classified into four accessible, relatively accessible, poorly accessible, and not accessible. Results are presented as a map. Scenario selection is based on the importance of the wheelchair user parameters. Length has been used as an independent physical factor in this research [19]. This linear method cannot accurately account for the effects of length on sidewalk accessibility, which may lead to an oversimplification of the factors influencing user experience and mobility.

In these studies, with the exception of one [16], length was generally treated as an independent factor rather than an enhancer of other factors. However, length can be considered an amplifying element, capable of magnifying the impact of other factors in accessibility assessments of sidewalks for wheelchair users. To effectively consider length as an intensifier, it is crucial to identify which factors and to what extent are affected by length for each segment, as these can influence the segment's accessibility. According to the literature, two key factors are significantly influenced by segment length, which, in turn, affects the accessibility of sidewalks for wheelchair users. Research suggests that wheelchair users generally prefer shorter routes with steep slopes over longer routes with similar slopes [16]. Slope significantly impacts energy expenditure and physical strain, making it crucial to account for both the slope angle and the length over which it extends. Furthermore, gradual slopes over long distances may still pose substantial physical challenges, impacting a wheelchair user's endurance and safety, particularly on routes with variable topography [30–32]. While slope plays an essential role in the accessibility of long sidewalks, its impact varies across different scenarios and must be analysed with precision.

Sidewalk texture is the second critical factor influencing accessibility on longer sidewalks. While smoother surfaces reduce rolling resistance and increase ease of travel, rougher textures can significantly heighten the difficulty of propulsion, especially over long segments. This increased difficulty not only slows travel but can also lead to fatigue and increased risk of discomfort or injury for wheelchair users [33,34,35,36]. Although the relationship between texture, propulsion distance, and exposure time for wheelchair users has been well studied, texture's specific impact on the accessibility of long sidewalks remains largely unexplored.

While these research articles discuss the role of slope and surface texture in long sidewalks, they do not quantify the effects of these two parameters on the accessibility of sidewalks for wheelchair users. To effectively account for length as an intensifier, it is essential to determine, based on user perception, how and to what extent these two factors—slope and texture—are affected by length for each segment, as they directly influence segment accessibility for wheelchair users. Additionally, prior studies tended to assign a single accessibility rating to the entire long segment, overlooking accessibility variations within a segment. This oversight suggests they did not consider how a user's capabilities and perceptions might differ from the beginning to the end of a long segment, potentially altering the overall accessibility rating.

In light of these insights, this research investigates the effect of segment length on sidewalk accessibility, considering these crucial factors and the perceived accessibility from a user's perspective. We propose a novel framework for a confidence-based method for measuring accessibility using fuzzy set theory. Our goal is to define a more realistic assessment of long sidewalk accessibility for individuals using manual wheelchairs through an adaptive weighting method that incorporates user perceptions of slope and texture.

3. An adaptive weighting Fuzzy-TOPSIS method for accessibility assessment of sidewalks

Our method for personal accessibility assessment of sidewalks is based on the Disability Creation Process model where mobility is considered as the result of the interaction between personal and environmental factors [14]. Hence, accessibility has been defined as the function of environmental factors and human factors (Equation (1)) [37].

$$\text{Accessibility} = f\,(e, h) \tag{1}$$

While “e” is the set of environmental factors and “h”, is the set of human factors. This interaction is very important and must be considered carefully, especially for wheelchair users. The proposed approach is to evaluate the accessibility of sidewalks, considering users’ confidence to move on the sidewalk in the presence of different environmental factors such as steep slopes and bad surface quality. In fact, we need to explore users’ perceptions of their own capabilities while encountering each physical factor on a sidewalk. This perception could be well defined by expressing their confidence when facing different physical factors. By doing so, we will be able to provide a personalized accessible route.

Segment length has been considered as an independent physical factor in most of the previous research. However here in this paper, we argue that the segment length must be considered as an intensifier that might increase or decrease the confidence of a user to move on that segment and hence affect its accessibility. Such a consideration allows a more accurate estimation of the accessibility of a sidewalk. This necessitates evaluating the effects of length on the accessibility of each segment along a sidewalk in the presence of other factors. As mentioned before, assessing accessibility depends on a set of environmental factors (slope, width, texture, etc.). Thus, listing the environmental factors that may be affected by length is a prerequisite.

To compute the accessibility of a sidewalk, we need to combine these factors which is a challenging task due to the complex interactions between personal and environmental factors. In such a context, a multi-criteria decision-making (MCDM) method is essential. There are various MCDM methods, and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is one of these methods [38]. TOPSIS is advantageous in that it considers both the best and worst alternatives, providing a comprehensive view of the decision space. Additionally, it accounts for the relative importance of criteria, making it a robust tool for evaluating the accessibility of sidewalks [18]. While TOPSIS has been used by Gharebaghi et al., for accessibility modeling of sidewalks [17] and also in our previous article for accessibility assessment of sidewalks in the presence of crowd as a dynamic factor [39], it has shown limitations in considering the length factor. To address this, we propose an adaptive Fuzzy-TOPSIS method specifically tailored to overcome these limitations. This enhanced approach aims to provide a more comprehensive evaluation of accessibility, particularly regarding sidewalk length.

In the proposed adaptive FTOPSIS method, we consider both environmental factors and user confidence. Environmental factors are quantified by measurement (for example, a slope of 5 %); however, user confidence is expressed by more qualitative terms such as « steep slope». Hence, we employ an Adaptive FTOPSIS method for the integration of those factors for the assessment of accessibility.

As illustrated in Fig. 1, the adaptive FTOPSIS method for the assessment of sidewalk accessibility considers the segment’s length and its effects are composed of several steps including 1) identifying sidewalk physical factors that are affected by length, 2) fuzzification of those factors, 3) assigning user’s confidence to each physical factor, 4) computing accessibility index by the proposed Adaptive FTOPSIS approach. While this method uses the similar steps which has been used in FTOPSIS presented by Gharebaghi et al., and Jahromi et al. [18,39], Adaptive FTOPSIS method is quite different in normalization and also calculating the weighted Euclidean distance. In the following subsections, we will present these steps in more detail.

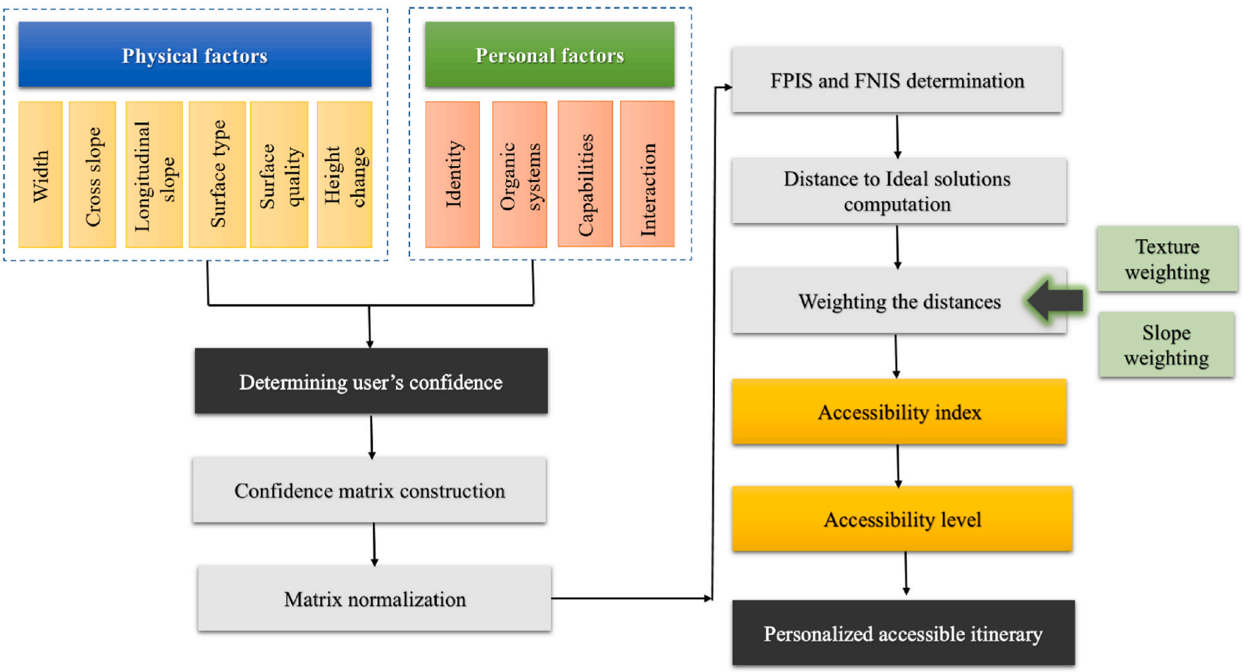

Fig. 1. Overview of the proposed method.

3.1. Identification of effective sidewalks' physical factor on the mobility of wheelchair users

The design of sidewalks may differ from one part of the city to another due to local topographic characteristics and other constraints such as urban density and architecture. The assessment of sidewalk accessibility necessitates the identification of key physical factors that impact the mobility of wheelchair users during their daily trips. Different studies addressed the most important physical factors that affect the mobility of wheelchair users [14,18,22,40,41,42,43,44]. These factors include width, length, slope, surface quality, texture, and height changes, which are classified as static physical factors across sidewalks.

To establish the range of values for each physical factor (Table 1), Iranian standards for urban planning and architecture for individuals with mobility impairments were employed, followed by the categorization of these values into distinct criteria through consultation with experts and utilization of the aforementioned standard [45].

3.2. Fuzzifying physical factors

People use a qualitative approach to describe and characterize objects in reality [46]. For instance, they would talk about a steep slope and not a slope of 20 % or 15°. In fact, quantitative values may not be used by wheelchair users in real-world situations. Hence, to qualify the physical factors that impact the mobility of individuals with mobility impairments, we need to use a qualitative value to describe a given factor (ex. narrow sidewalk or steep slope). To address this challenge, fuzzy logic is used to transform crisp values into non-crisp values, a process known as fuzzification. To achieve this, membership functions are established, which are mathematical functions that convert a given value into a range of values between 0 and 1 [46]. For each factor, such as width, slope, surface type, surface quality, and height change, a membership function is defined.

The process of fuzzification of these factors can be expressed mathematically. In this context, a fuzzy set A within universe X is defined by a membership function $\mu_A(x_i)$, where the domain of X is in the range of [0, 1]. The membership value of xi in set A, denoted as $\mu_A(x_i)$, is calculated using (2), which is based on the seminal work of Zadeh et al. [46]. Here, set A is a trapezoidal fuzzy number denoted as A = (a,b,c,d), and x_i is a criterion belonging to the set $X = [x_1, x_2, \dots x_n]$ as depicted in (Equation (2)).

$$\mu_A(x_i) = \begin{Bmatrix} 0, & x_i \le a \\ \frac{x_i - a}{b - a}, & a \le x_i \le b \\ 1, & b \le x_i \le c \\ \frac{d - x_i}{d - c}, & c \le x_i \le d \\ 0, & d \le x_i \end{Bmatrix} \tag{2}$$

For each factor, membership values are calculated based on the above equation. For example, a ramp with a slope of 3 %, belongs to the fuzzy set gentle with the membership value of 0.82 and fuzzy set moderate with the membership value of 0.18 respectively (Fig. 2).

3.3. Assigning user's confidence

As we mentioned before, the role of wheelchair users' confidence in the computation of accessibility is significant for personal routing. The presence of each physical factor along a sidewalk can change its perceived accessibility for a given user. To better understand this, we organized a semi-structured interview and asked the participants to express their level of confidence in carrying out their mobility in the presence of each physical factor described in Table 1, while watching recorded videos and photos of sidewalks. The participants were asked to choose a qualitative value (very low, low, medium, high, and very high) to indicate their confidence level to move on the sidewalks. To illustrate these different levels of confidence, we utilized a membership function suggested by Malczewski [47], which is depicted in Fig. 3 alongside the corresponding fuzzy sets and values (Table 2).

To follow our previous example, a ramp with a slope of 3 %, belongs to the fuzzy set gentle (Fig. 2). According to the interview with a wheelchair user, a confidence level very high is assigned to this ramp while the user is going up the ramp.

Table 1
The criteria, value ranges, and subsets of sidewalk physical factors.

Physical factor	Range of values	Subset
Width (m)	(0–3)	{Narrow, Moderate, Wide}
Cross slope (%)	(0–5)	{Gentle, Moderate, Steep}
Longitudinal slope (%)	(0–8)	{Gentle, Moderate, Steep}
Surface type	–	{Concrete, Asphalt, Brick, Gravel, Cobblestone, Granit, Marble}
Surface quality	(0-10)	{Good, Fair, Poor}
Height change (cm)	(0-20)	{Small, Moderate, Big}

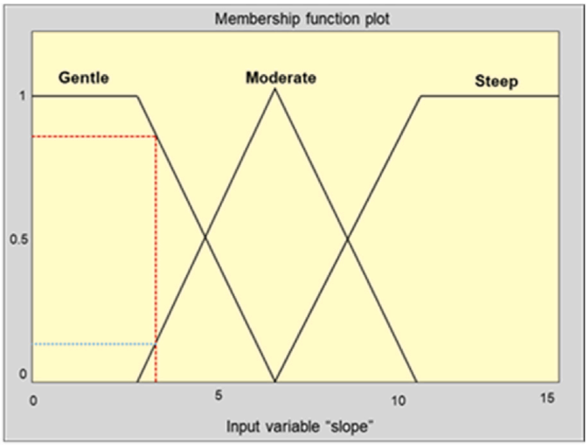

Fig. 2. Membership function of slope (ramp).

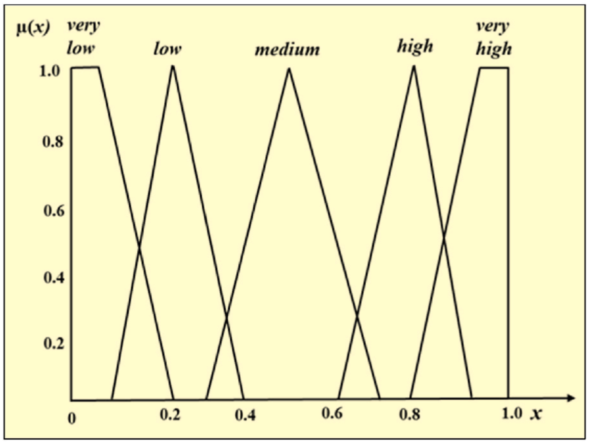

Fig. 3. Membership function of user's confidence.

Table 2
Fuzzy sets, and fuzzy values of user's confidence.

Fuzzy set	Fuzzy numbers
Very low	(0, 0, 0.1, 0.2)
Low	(0.1,0.25, 0.25, 0.4)
Medium	(0.3,0.5,0.5,0.7)
High	(0.6, 0.75, 0.75,0.9)
Very high	(0.8, 0.9, 1,1)

3.4. Computing accessibility indices using the proposed adaptive Fuzzy-TOPSIS method

In this investigation study, the degree of accessibility of each segment is established based on the confidence of users in confronting various physical factors while navigating through a segment, considering the segment's length. Based on this, the accessibility index has been computed for segments by aggregating the user's confidence regarding multiple factors of each segment, considering an adaptive weighting based on the length of the segment. Then, using the accessibility index, accessibility grades (not accessible, low accessible, moderate accessible, and highly accessible) are allocated to segments.

We demonstrated the importance of the length, and we are going to take the length as an intensifier, so we are proposing a method that is more adaptive. This method does not apply the effects of length continuously in a long segment but rather considers its effects on sub-segments.

In this developed FTOPSIS, an adaptive weighting system is applied to describe the effects of the segment's length on the accessibility considering different physical factors of sidewalk segments. The dynamic weighting system allows the variation of accessibility to be taken into consideration. The following are the important steps of the proposed Adaptive FTOPSIS method.

a) Fuzzification: The first step is fuzzification which is described in the previous section with details.
b) Normalization of Fuzzy Vectors: The objective of this step is to standardize the user's confidence ratings for physical factors into a uniform scale, which enables computation and comparison. This is achieved by generating normalized fuzzy vectors (r_i), where the normalized value for each factor is determined by dividing the user's confidence levels for one factor by their maximum confidence level for that factor (Equation (3)).

$$r_i = \left(\frac{(a\_con)_i}{(d\_con_i^*)}, \frac{(b\_con)_i}{(d\_con_i^*)}, \frac{(c\_con)_i}{(d\_con_i^*)}, \frac{(d\_con)_i}{(d\_con_i^*)} \right) \tag{3}$$

While $(d\_con)_i^* = \max (d\_con)_i$

However, the normalized value for cost factors is calculated differently, considering the minimum level of the user's confidence for one factor by the user's confidence levels for that factor (Equation (4)).

$$r_i = \left(\frac{(a\_con_i^-)}{(d\_con)_i}, \frac{(a\_con_i^-)}{(c\_con)_i}, \frac{(a\_con_i^-)}{(b\_con)_i}, \frac{(a\_con_i^-)}{(a\_con)_i} \right) \tag{4}$$

While $(a\_con)_i^- = \min (a\_con)_i$

In this context, (a_con, b_con, c_con, d_con) represent the user's confidence level for a criterion, ($d\_con_i^*$) denotes the user's highest and ($d\_con_i^-$) is the user's minimum confidence level for that particular criterion.

c) Determination of the fuzzy positive ideal solution and fuzzy negative ideal solution: identifying the highest and lowest levels of confidence for each factor, which are respectively referred to as FPIS and FNIS (Equation (5)).

$$FPIS = [r_1^*, r_2^*, \ldots r_5^*] \text{ Where } r_i^* = \max \{r_{i4}\} \tag{5}$$

$$FNIS = [r_1^*, r_2^*, \ldots r_5^*] \text{ Where } r_i^* = \min\{r_{i4}\}$$

d) Calculation of the weighted Euclidean distance between each normalized value and the FPIS and FNIS: In the context of decision-making, it is crucial to recognize that not all criteria carry equal significance, especially considering the specific demands of the application. To effectively consider the relative importance of distances from PIS and NIS, a straightforward method involves multiplying each distance by its corresponding weight. It becomes imperative to allocate higher weights to criteria that hold greater importance relative to others.

In this research, we considered different weights of PIS and NIS distances. In each segment, weight is considered for each factor based on the significance of the factor for the participant. In segments along which the accessibility levels of the segment are affected by the segment's length, a different scenario for weighting has been considered. Having the weights, the difference between the confidence level of each factor and the FPIS and FNIS has been determined (Equation (6)).

$$D_i^* = w_i \sqrt{\frac{1}{4} \sum (r_i - r_i^*)^2} \tag{6}$$

$$D_i^- = w_i \sqrt{\frac{1}{4} \sum (r_i - r_i^-)^2}$$

e) Determining the Accessibility index: For each physical factor, the Accessibility index is computed using Equation (7):

$$AI_i = \frac{\sum_{i=1}^{5} D_i^-}{\sum_{i=1}^{5} D_i^- + \sum_{i=1}^{5} D_i^*} \tag{7}$$

3.5. Adaptive weighting

Based on the literature [31–34,48–54], slope and texture are two critical parameters that can affect wheelchair users' mobility while considering the length impedance which might change the influence of the confidence of a wheelchair user on the accessibility of a segment.

a) Slope weighting

To comprehensively evaluate the impact of slopes on the accessibility index of sidewalk segments, considering the length, it is crucial to consider the dynamic changes in the user's speed and the user's weight [30,32,51]. This evaluation involves calculating the energy expenditure (Equation (8)) involved in altering the gravitational potential energy of the participant and the wheelchair according to Ref. [51].

$$\Delta Ei = mgh\nu \sin\theta \tag{8}$$

In this equation, ΔE represents the change of energy for the ith segment, m is the mass of the wheelchair user, g is gravitational acceleration which is equal to 9.8 m/s^2, ν is the person's speed and θ is the slope angle. ΔE is calculated for each segment considering its slope and the wheelchair user's speed.

A weight would be assigned to each sub-segment according to the amount of participant's energy for that sub-segment. The weights would be different for going up and down the slopes.

b) Texture weighting

Wheelchair users are often subjected to unhealthy levels of vibration exposure due to rough pathways [53]. The daily vibrations encountered during wheelchair movements have the potential to contribute to increased fatigue rates among users [54], and also pain in the back and neck (twice more than other people) [48], thereby limiting their engagement in community activities.

Understanding and minimizing the exposure to whole-body vibrations (WBVs) during pathway navigation is crucial due to the detrimental effects associated with such vibrations [35,55]. According to Duvall et al. [48], there is a direct correlation between whole-body vibrations experienced by wheelchair users and the surface WPRI (Wheelchair Pathway Roughness Index). Based on WPRI, a "healthy" propulsion distance and exposure time for wheelchair users for a surface floor with a WPRI higher than 100 mm/m [33,48] is 600 m with an exposure time shorter than 10 min (when the wheelchair speed is 1 m/s). Similarly, traveling for 2 h over a surface with a PRI of 50 mm/m would equate to reaching the vibration threshold after 7.2 km (4.5 miles).

So, for going along each sidewalk texture, a weights system has been considered based on the amount of surface WPRI, the healthy propulsion distance, and the corresponding exposure time. The other environmental factors listed in Table 1 are considered in the computation of the accessibility but are not weighted.

4. Case study

In this section, we will demonstrate the application of the proposed adaptive Fuzzy -TOPSIS method in the accessibility assessment of a sidewalk via a numerical example for a wheelchair user. As discussed in previous sections, our proposed framework aims to evaluate the accessibility of sidewalks by considering the participant's confidence regarding the physical factors they encounter on their routes, considering segment length. Specifically, we focused on how individuals with mobility impairments, particularly wheelchair users, perceive and navigate through environmental barriers while wheeling a long sidewalk.

To evaluate and illustrate the model, we will demonstrate the application of the method and adaptive weighting in the accessibility assessment of three sidewalk segments and a ramp. To illustrate the benefit of using the proposed method, these examples have been chosen since sidewalks and ramps have different lengths, slopes, and textures, and therefore, adaptive weighting is applicable. Each of them consists of one single long segment and has slope and texture as their attributes. The attributes of the sidewalk have been described in Table 3.

This demonstration underscores the necessity of carefully considering user-specific characteristics alongside environmental factors when assessing sidewalk accessibility for individuals with mobility impairments. The user characteristics in this research include the type of wheelchair (specifically, a manual wheelchair), age range (35–55 years), physical fitness level (defined as the user's ability to maneuver the wheelchair independently), and the user's confidence levels when encountering various physical features of sidewalks. The relevant sidewalk factors, described in detail in the previous section, encompass attributes such as length, width, slope, and the type and quality of pavement surface. The following section provides a comprehensive review of the data employed in this analysis.

4.1. Sidewalk data

Sidewalk data provided by Omran Zaveh, an engineering consulting firm contracted by the municipality of Tehran, were employed in this study. The data were collected through a combination of ground surveys and satellite imagery and include key attributes such as width, length, slope, surface type (categorized as slippery or non-slippery), height differences, and surface quality of each sidewalk. Additionally, other data such as the medium and low longitudinal slopes and cross slopes of the sidewalks were assessed. All collected

Table 3
Attribute of the segments.

	Length	Width	Long_Slope	Cross_Slope	Texture	Height change	Surface Quality
Sidewalk #1	298 m	140 cm	0%–0%	0%–0%	Cobblestone	0	10
Sidewalk #2	300 m	135 cm	2%–5%	0%–0%	Concrete	0	10
Sidewalk #3	288 m	142 cm	0 %	1%–3%	Concrete	0	10
Ramp	9 m	130 cm	5%–8%	0 %	Concrete	-	10

data are systematically stored in a dedicated database for analysis.

4.2. Wheelchair user's confidence levels

This step focuses on gathering wheelchair users' confidence levels in response to various physical factors encountered along different sidewalk routes. To achieve this, we utilized confidence data collected from our previous research [39], following a rigorously designed protocol. The study considered a range of routes, encompassing both steep and flat sidewalks, as well as varying surface types and lengths. Videos were recorded along these routes, emphasizing key physical barriers. Participants then viewed the videos and provided their confidence levels for each identified factor through a semi-structured interview. These confidence levels were measured using a five-point scale, ranging from very low to very high. The collected confidence data forms the profile of a wheelchair user, a key component of the analysis in this study.

4.3. Computing accessibility index using the proposed method

Due to the extensive nature of the calculation procedures involved in assessing the accessibility index for all four paths—three sidewalk segments and a ramp—this article will present a detailed step-by-step calculation for one selected segment. By focusing on this individual example, we aim to provide a comprehensive understanding of the methodology employed. Nevertheless, to ensure a complete representation of the study's outcomes, the resultant accessibility maps for all four paths will be included and discussed.

4.3.1. Fuzzifying physical factors of sidewalk

The physical factors of sidewalks then have been fuzzified as discussed in section 3.2. A membership function has been defined for each physical factor and the membership values have been determined according to Table 2. For example, the width of the segment is 140 cm, which belongs to the fuzzy set wide. The fuzzy set and fuzzy membership of the physical factors of the segment has been shown in Tables 4 and 5, respectively.

4.3.2. Assigning confidence levels to sidewalk physical factors

Then, the user's confidence levels are assigned to each physical factor. Table 6 shows the confidence levels of the user for the above segment. For example, the confidence of the user for passing through this segment with a width of 140 cm that belongs to the fuzzy set wide and has a fuzzy value of 1.0 is very good. So, a confidence level of very good has been assigned to the width 140 cm. But his confidence level for the texture, which is cobblestone, with a fuzzy value of 1.0 is medium. Therefore, a confidence level of medium has been assigned to this texture.

Then, a fuzzy vector has been assigned to each confidence level (Table 6) using the function suggested by Malczewski [47] (Table 7).

4.3.3. Normalizing the fuzzy vector based on FPIS and FNIS

For accessibility assessment of each segment using FTOPSIS, the vector is normalized based on the participant's maximum confidence level for each factor (FPIS and FNIS) while all factors are considered as benefit factors. But, in this research, considering the participant's fatigue while navigating a long segment, texture is considered as a cost factor and is normalized based on the participant's minimum confidence for that factor (Equation (4)). The maximum and minimum confidence levels for each physical factor have been obtained during the semi-structured interview and their corresponding fuzzy vectors have been demonstrated in Table 8.

The normalized fuzzy values have been calculated and are demonstrated in Table 9.

4.3.4. Calculating the distances from ideal solutions

These normalized values are then used to calculate the distance between these values and the fuzzy positive ideal solution and the fuzzy negative ideal solution. The results have been demonstrated in Table 10. The weight has been assigned to each factor based on the user's preferences, while the segment's length is less than 100 m. But for segments that are longer than 100 m, a different weight is applied. For a long segment, in each extra 100 m, we have a change in weights of the factors that are affected by segment length.

To incorporate slope weight into our analysis, we considered the frequency of users' energy variations, primarily influenced by their weight, wheeling speed, and the slope encountered. According to urban road design guidelines in Iran, increasing the sidewalk slope from 5 % to 10 % correlates with an approximate 12 % reduction in wheeling speed. Additionally, elevating the slope to 20 % results in a 25 % decrease in wheeling speed. To model these effects, considering the user's weight, we adopted a logarithmic weighting approach.

In our experiment, for lengthy steep segments, we subdivided them into shorter segments, each spanning 100 m (based on the standard of urban planning for wheelchair users), and calculated ΔE (energy change) for each sub-segment. Sub-segments with lower

Table 4
The fuzzy set of the physical factors of the segment.

	Length	Width	Slope	Texture	Height change	Surface Quality
Sidewalk#1	298 m	140 cm	0 %	Cobblestone	0 cm	10
Fuzzy set	–	Wide	Gentle	Cobblestone	Small	Good

Table 5
Fuzzy membership values of different factors of the 30th Tir sidewalk.

	Fuzzy set	Fuzzy numbers	Membership value
Length	Short	(0.5,0.6.0.8,1)	–
	Medium	(0.2.0.25,0.4,0.5)	–
	Long	(0.0, 0.0, 0.1,0.2)	1
Width	Narrow	(0.0, 0.0, 0.1,0.2)	–
	Medium	(0.5,0.6.0.8,0.9)	–
	Wide	(0.8,0.9,1.0,1.0)	1
Longitudinal slope	Low	(0.8,0.8,1.0,1.0)	1
	Medium	(0.5,0.6.0.8,0.9)	–
	High	(0.0, 0.0, 0.1,0.2)	–
Cross slope	Low	(0.8,0.9,1.0,1.0)	–
	Medium	(0.5,0.6.0.8,0.9)	–
	High	(0.0, 0.0, 0.1,0.2)	–
Surface Texture	Non-Slippery	(0.8,0.9,1.0,1.0)	1
	Slippery	(0.1,0.2,0.4,0.5)	–
Height change	Small	(0.5,0.6.0.8,1)	1
	Medium	(0.2.0.25,0.4,0.5)	–
	Big	(0.0, 0.0, 0.1,0.2)	–
Surface quality	Week	(0.1,0.2,0.4,0.5)	–
	Medium	(0.4,0.5,0.5,0.6)	–
	Good	(0.6,0.8,1.0,1.0)	1

Table 6
Confidence levels of the user for the physical factor of the segment.

	Width	Slope	Texture	Height change	Surface Quality
Sidewalk#1	Very high	Very high	Medium	Very high	Good

energy expenditure receive reduced weights on uphill slopes. Conversely, downhill slopes impact accessibility in diverse ways. Sub-segments with higher energy expenditure receive reduced weights on downhill slopes.

The procedure of calculating accessibility index for ramps is similar to sidewalks. We used the same method of weighting for calculating the accessibility of ramps. However, for a ramp, the distance interval of 3 m has been applied according to the standard of urban planning for people with mobility difficulties.

Considering the texture, Singra [34] argues that to minimize WPRI, while wheeling along a surface, the consecutive distances must be limited to 100 m or less. Therefore, for our experiment, a 100-m scale was used, and each sidewalk was split into 100 m segments. Then weighting is assigned to each segment according to the distance from the origin and the healthy propulsion distance for that texture. For our example, for cobblestone (which has been used mostly in historical touristic areas) with a WPRI of 112 mm/m, and an exposure time of less than 10 min, an ascending logarithmic weighting scheme will be used for sidewalk segments in each 100 m. So, going through this long segment, which is covered by cobblestone, the texture gains more weight in the length of 100–200 m in comparison to 0–100 m, as we discussed in section 3-5-2.

4.3.5. *Calculating the accessibility index*

The accessibility index has been calculated using Equation (7). This accessibility index then is categorized as “very low accessible”, “low accessible”, “medium accessible” and “very accessible” (Table 11).

5. Results

In light of the fact that human mobility is intricately influenced by the interactions between individuals and their surroundings [56], our approach places a strong emphasis on the assessment of human abilities when navigating diverse environmental conditions during the process of navigating prolonged sidewalks.

Here, we present the impact of the segment’s length on two components of a pedestrian route (sidewalks and ramps) in three different sidewalk segments and a ramp (Table 3). Within our methodology, we undertake the quantification of the accessibility level associated with distinct segments (represented as cost values) by incorporating a measure of confidence from individuals with mobility impairments in relation to their own mobility capabilities. Through this assessment, we generate an accessibility schematic map to demonstrate the resultant accessibility level.

According to the results, sidewalk length could affect the mobility of wheelchair users significantly. Accessibility can be affected by the topography and texture of sidewalks on prolonged sidewalks. Regarding this, our proposed method considered the role of length in the accessibility assessment by assigning an adaptive weighing to these factors while they are assumed as cost values in the algorithm.

In the first long sidewalk, we considered all factors with ideal attributes for the user (like wide width and without any crack, texture change, or height change), except for the texture which is cobblestone. Based on the result, for this sidewalk, accessibility is medium

Table 7
Fuzzy vector of the confidence levels.

	Width				Slope				Texture				Height Change				Surface Quality			
Sidewalk#1	0.8	0.9	1.0	1.0	0.8	0.8	0.9	1.0	0.3	0.5	0.5	0.7	0.8	0.8	0.9	1.0	0.8	0.9	0.9	1.0

Table 8
FPIS and FIS of physical factors.

	Width				Slope				Texture				Height Change				Surface Quality			
FPIS	Very High				Very High				Medium				Very High				Very High			
	0.80	0.90	1.0	1.0	0.80	0.80	0.89	1.00	0.3	0.5	0.5	0.70	0.8	0.8	0.89	1.0	0.8	0.8	0.89	1.0
FNIS	Very Low				Very Low				Low				Low				Very Low			
	0	0	0.1	0.2	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0	0	0.1	0.2

Table 9
Normalized Fuzzy vector of confidence levels matrix.

Type	Width				Slope				Texture				Height Change				Surface Quality			
Sidewalk#1	0.80	0.90	1.00	1.00	0.80	0.80	0.89	1.00	0.33	0.20	0.20	0.14	0.80	0.80	0.89	1.00	0.80	0.80	0.89	1.00

for the whole sidewalk according to the previous FTOPSIS models (Fig. 4a). But, considering the adaptive weighting, the accessibility would change along the sidewalk. According to the latest results, considering the wheelchair user speed of 0.5 m/s traversing rough textures, while the accessibility of the first part of the segment is medium, this accessibility would be low and very low for the second and third parts of the segment (Fig. 4b). This result is compatible with Duvall et al., 2016, as cobblestone with a WPRI of more than 100 is just traversable for 10 min. In fact, the body vibration induced by the cobblestone roughness prohibits the wheelchair user from traversing the sidewalk at the same speed as it causes the feeling of discomfort and fatigue, and finally, pain in the neck and back which is harmful to him. While cobblestone surfaces are considered the most difficult path to traverse, it must be noted that for getting the actual weights for other textures, the amount of WPRI for each texture must be identified through the available literature or a field-based study.

We evaluated the longitudinal slope along sidewalk 2 while its attributes are the same and ideal for all factors except for the slope. The accessibility of sidewalk 2 is evaluated for going up a medium slope. As you can see in Fig. 5a, the accessibility is high for the whole sidewalk using the common FTOPSIS method. But the application of the adaptive FTOPSIS while considering the user's weight and speed, the accessibility changes along the sidewalk. The accessibility is high for the first part of the segment, but it will change to medium and low for the second and third part of the segment, as his speed decreases, giving him the feeling of losing control, because of the gravity imposed to the wheelchair and increasing the sense of fatigue (Fig. 5b).

However, the result is not the same for the sidewalk while the wheelchair user is coming down the sidewalk with a medium slope. Its accessibility is high as the user's confidence in coming down the longitudinal slope is high (Fig. 5c). Applying the weighting, the accessibility is high for the first two parts of the segment, but the accessibility changes to low for the third part of the segment. The wheelchair user's speed increases due to the slope, giving him the feeling of losing control of his wheelchair while there is the risk of deviating to the side of the sidewalk (Fig. 5d).

The cross slope has been evaluated along sidewalk 3 while we have the ideal attributes for all factors except for the cross slope. The accessibility of the sidewalk is evaluated for going along a medium slope. According to the result, the accessibility is high for the whole sidewalk using the common FTOPSIS method (Fig. 6a). But using adaptive FTOPSIS, the accessibility is high for the first part of the segment, but it will change to medium and low for the second and third parts of the segment (Fig. 6b).

Finally, we evaluated the accessibility of the ramp. Our results for going up a ramp with a medium slope indicated that its accessibility is high in going up the slope using FTOPSIS (Fig. 7a), but using adaptive FTOPSIS, the accessibility will change to medium and very low in the second and third segments (Fig. 7b). A downhill slope boosts wheeling speed, but too much of a downhill slope can increase the speed in a dangerous way and increase the costs of accessibility. So, in coming down the ramp, the accessibility is medium for the first segment, and it will change to low for the second and third segments (Fig. 7c and d).

To assess and demonstrate the method in a real-world routing scenario, we implemented the proposed approach to three sidewalks of Tehran, The west sidewalk of Hijab Street with longitudinal slope, the sidewalk of Shamshiri Street with cross slope and the touristic 30th Tir street with cobblestone walkway. According to the result, this method has a better performance considering the segment's texture, slope and also the direction of movement. The adaptive weighting FTOPSIS method could outperform the FTOPSIS method and increase the accuracy of accessibility assessment by 20 %. It indicates that the suggested methodology could better evaluate the accessibility of the sidewalk according to the profile of the user compared to the previous approaches implemented in other research articles and the few dedicated applications dedicated to the wayfinding based on the accessibility assessment of sidewalks such as MobiliSIG. To compare the results, the adaptive FTOPSIS method has been implemented in MobiliSIG applications.

The MobiliSIG application for personalized routing [57] designed and developed by the team at Université Laval. For this study, a long sidewalk segment situated in the Montcalm district of Quebec City, Canada, was specifically chosen. This segment features a

Table 10
Weighted distance between each normalized value and the FPIS and FNIS.

Type	Segments	D*	D-
Sidewalk#1	Part#1	1.86	1.40
	Part#2	3.71	1.38
	Part#3	7.43	1.37

Table 11
Accessibility index.

Type	Segments	AI	**Accessibility Level**
Sidewalk #1	Part #1	0.43	Medium
	Part #2	0.27	Low
	Part #3	0.16	Very low

moderate longitudinal slope, providing a relevant setting for this research work. In accordance with MobiliSIG approach, which has been well described in Gharebaghi et al., 2017, the wheelchair user's confidence level for 12 predefined questions has been answered based on the user's profile, [18]. The accessibility level of the sidewalk utilizing the conventional method of MobiliSIG has been calculated and illustrated in Fig. 8a, c. Then, using our research approach, for each sub-segment, the wheelchair user's indicated confidence levels, available in his profile, have been assigned to each physical factor of that segment. The accessibility level has been calculated using the proposed adaptive weighting FTOPSIS method. The accessibility level of the sidewalk based on the Adaptive weighting FTOPSIS method has been demonstrated in Fig. 8b, d.

The calculated accessibility levels of the same route for two directions (while the wheelchair users go up and down the steep sidewalk segment) are comparable. While the accessibility level for going from A to B is very high using the conventional method in MobiliSIG, the accessibility level is different, especially in the last part of the segment according to the adaptive weighting FTOPSIS method. Moreover, the accessibility level is different based on the direction of the movement.

Based on the research findings and the validation outlined in this study, we can underscore the advantages of the proposed methods in assisting wheelchair users in their mobility and social participation. As it is obvious for both sidewalks and ramps, the accessibility index is different while using conventional methods in comparison to adaptive FTOPSIS. By assigning appropriate weights to factors such as slope and texture, with due consideration to the varying lengths of sidewalk segments, this method provides a more realistic sidewalk accessibility as perceived by wheelchair users. In addition to examining the impact of length on sidewalk accessibility for wheelchair users, the incorporation of an adaptive weighting system adds a valuable dimension to enhance the routing and navigation for wheelchair users.

6. Discussion

This study highlights the significant influence of sidewalk segment length on the accessibility of pedestrian routes, specifically focusing on wheelchair users. Our methodology quantifies accessibility levels associated with distinct segments by integrating measures of confidence from individuals with mobility impairments regarding their mobility capabilities. This approach is crucial, as it recognizes the subjective experiences of wheelchair users and provides a more comprehensive understanding of accessibility.

The results indicate that the length of a sidewalk can considerably impact the mobility of wheelchair users. For instance, our assessment of the first long sidewalk, which features ideal attributes except for a cobblestone texture, reveals a medium overall accessibility rating. However, by employing adaptive weighting in our evaluation, we observe that accessibility perceptions change along the length of the segment. This finding aligns with previous research by Duvall et al. (2016), which underscores the adverse effects of cobblestone surfaces on user mobility due to the vibrations and discomfort they cause. The significance of texture becomes particularly evident when considering the speed of wheelchair users, which diminishes as they encounter rough surfaces, ultimately leading to fatigue and discomfort.

Similarly, our analysis of the second sidewalk, characterized by a medium longitudinal slope, demonstrates that accessibility is rated high when using conventional methods. However, applying our adaptive FTOPSIS model reveals that accessibility diminishes for users as they ascend, due to increased fatigue and loss of control, emphasizing the dynamic nature of accessibility as it relates to user experience. In contrast, while descending the slope, users initially feel confident, but our findings indicate that this confidence can

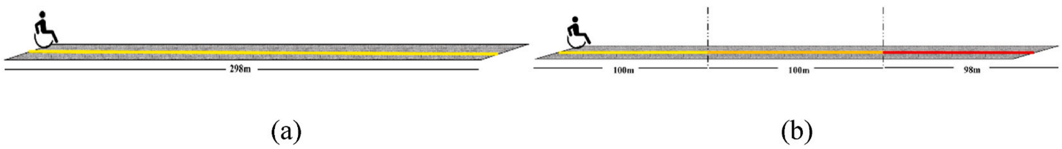

Fig. 4. Accessibility of cobblestone using, a) FTOPSIS model, b) dynamic weighting FTOPSIS model.

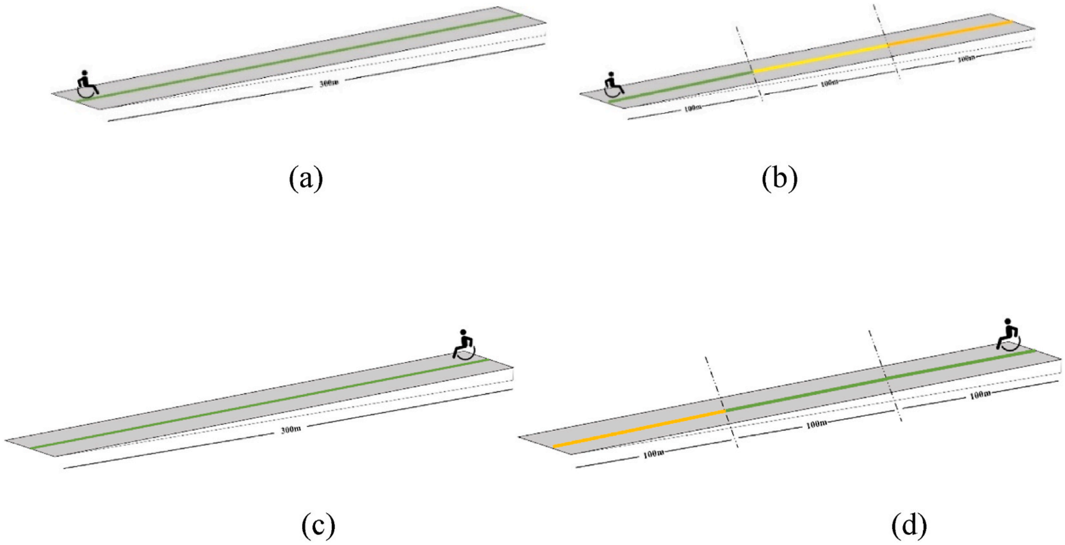

Fig. 5. Accessibility of going up a sidewalk with a longitudinal slope of 4 % using, a) FTOPSIS model, b) Adaptive FTOPSIS model, accessibility of coming down a sidewalk with a longitudinal slope of 4 % using, c) FTOPSIS model, d) Adaptive FTOPSIS model.

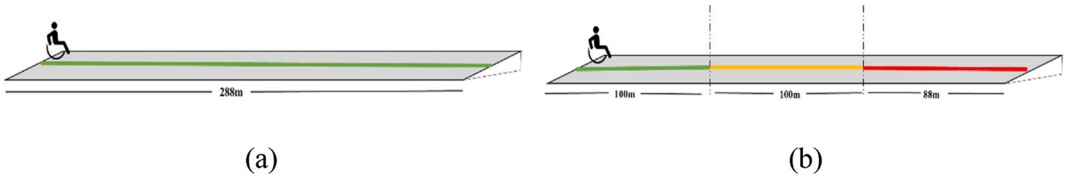

Fig. 6. Accessibility of traversing a sidewalk with a cross slope of 2 % using, a) FTOPSIS model, b) adaptive FTOPSIS model.

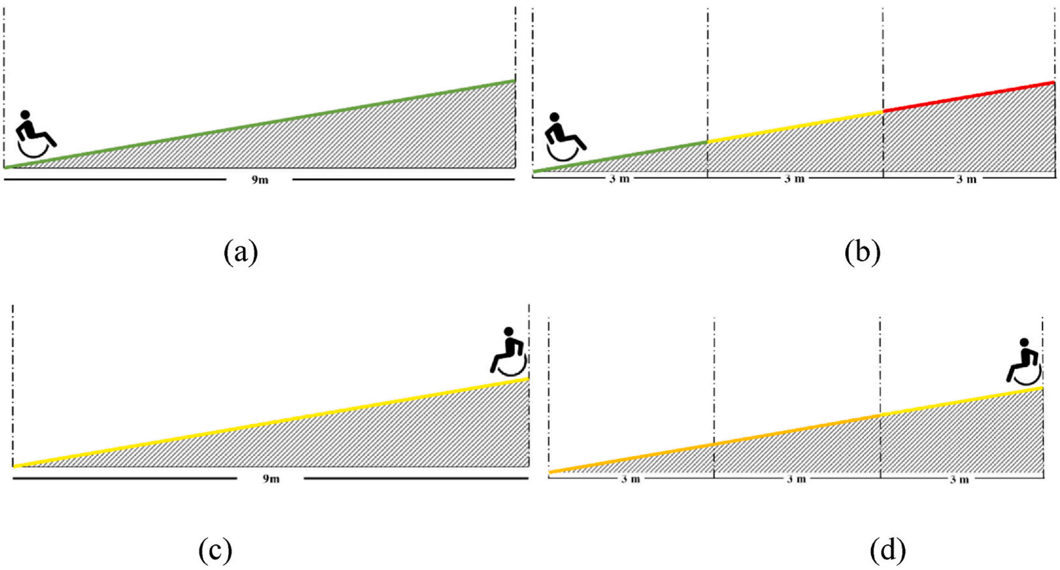

Fig. 7. Accessibility of going up a ramp with a slope of 7 % using, a) FTOPSIS model, b) adaptive FTOPSIS model, accessibility of coming down a ramp with a slope of 7 % using, c) FTOPSIS model, d) adaptive FTOPSIS model.

quickly diminish in steeper sections, illustrating the complex interplay between slope, user confidence, and accessibility.

The results from the third sidewalk, which examined cross slopes, further emphasize the importance of incorporating adaptive weighting into accessibility assessments. Our findings indicate that while conventional methods may categorize a segment as

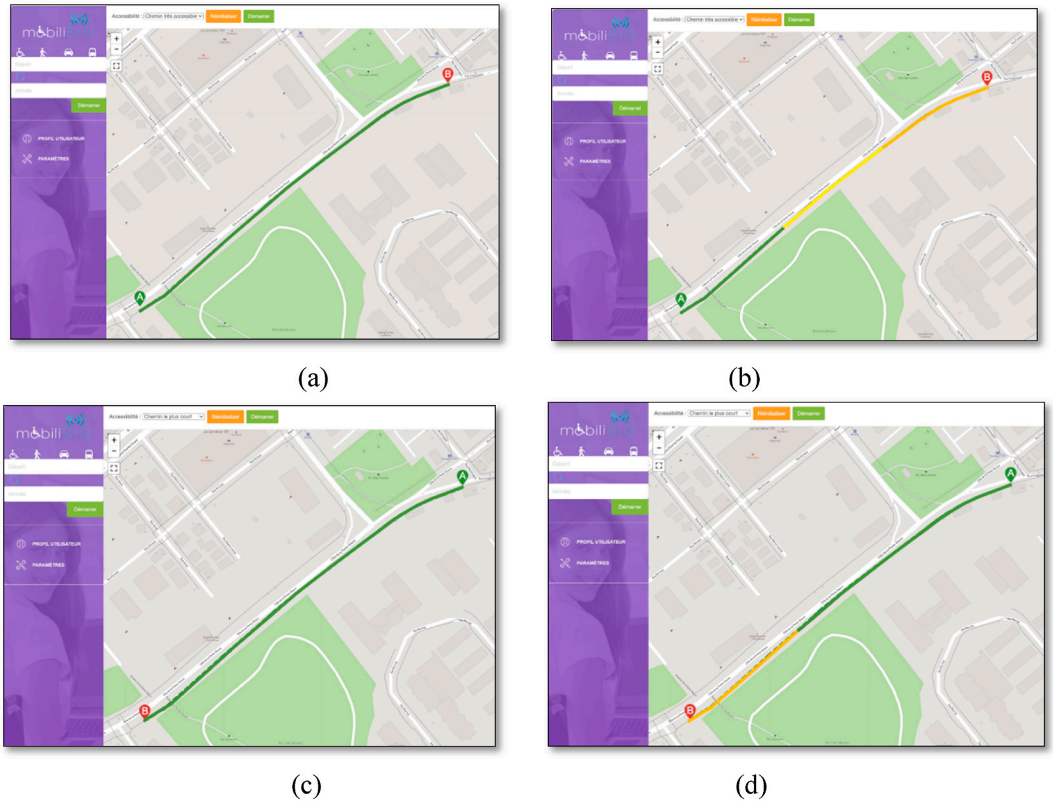

Fig. 8. Accessibility of going up a sidewalk with a moderate longitudinal slope using, a) conventional method in MobiliSIG, b) Adaptive FTOPSIS model; Accessibility of coming down a sidewalk with a moderate longitudinal slope using, c) conventional method in MobiliSIG, d) Adaptive FTOPSIS model.

universally accessible, the adaptive FTOPSIS model reveals significant variability in user experience, reinforcing the need for a more nuanced approach to accessibility evaluations.

When assessing the ramp's accessibility, we observe similar trends. The high accessibility rating during ascent using conventional methods does not account for the challenges users face at different segments of the ramp, highlighting the potential dangers associated with increased speed when descending. The analysis showcases the necessity of considering both physical attributes and user experiences in mobility assessments, further supporting the argument for adaptive methodologies.

In implementing our proposed approach in real-world scenarios, particularly in Tehran, we demonstrate its superior performance in assessing accessibility. The adaptive weighting FTOPSIS method outperformed conventional assessments, achieving a 20 % increase in accuracy. Additionally, we observed further promising improvements in accuracy when factoring in sidewalk texture, made possible by our access to detailed data on the WPRI and exposure time for each surface texture type.

This finding is significant as it underscores the importance of tailoring accessibility evaluations to reflect user profiles and real-world conditions, thereby enhancing mobility and social participation for wheelchair users. Moreover, the comparative analysis with the MobiliSIG application illustrates the effectiveness of our methodology in providing personalized routing solutions for wheelchair users. By integrating user confidence levels into accessibility evaluations, we showcase a more refined approach to understanding how various factors, including length and slope, affect mobility.

The significance of these findings extends beyond theoretical insights; they hold crucial implications for promoting travel among individuals with mobility impairments. By elucidating the accessibility challenges faced by wheelchair users in various sidewalk environments, these results can inform urban and transportation planners in designing more inclusive infrastructure. Specifically, the adaptive weighting FTOPSIS methodology emphasizes the importance of considering factors such as sidewalk length, slope, and surface texture in accessibility assessments. By integrating these findings into the planning process, policymakers can prioritize enhancements to pedestrian pathways and ramps that address the unique needs of people with disabilities. Such measures could include implementing smoother surfaces, optimizing slope gradients, ensuring consistent maintenance, and installing benches along longer inclines (sidewalks and ramps), ultimately fostering a more inclusive urban environment that encourages mobility and social participation for all individuals.

Additionally, these findings offer valuable insights for improving applications designed for wheelchair routing. By incorporating the modelling approach presented in this study, developers can create more accurate navigation tools that address the specific mobility challenges encountered on long sidewalks. This integration would provide more reliable guidance, enabling individuals with mobility impairments to navigate urban spaces with greater confidence. By addressing these considerations, policymakers and app developers can work together to create urban environments that are truly inclusive and supportive.

7. Conclusion

In this paper, we have considered the problem of perceived accessibility of sidewalks for wheelchair users based on their personal capability variation while navigating on a pedestrian network. For this purpose, we have proposed a FTOPSIS model with adaptive weights for different physical factors while considering their extended presence on sidewalks (ex. a long steep sidewalk vs. a short steep sidewalk). Our literature assessment allowed us to identify two factors including slope and texture that significantly affect the perception of accessibility of sidewalks based on their extended length. Hence, these two factors were considered more specifically in the development of our extended FTOPSIS model. Then different simple scenarios were generated to adjust and evaluate the proposed model. Finally, the model was implemented in the MobiliSIG application and tested in a district of Quebec City in Canada for personalized routing scenarios.

The results obtained for various sidewalk segments across different scenarios, as well as from MobiliSIG, reveal that the inclusion of each physical factor, with consideration for their extended presence, improves accessibility indices by approximately 20 % compared to the conventional fuzzy model previously implemented in the application. According to the results, ascending slopes in long sidewalks, resulted in lower accessibility scores, as wheelchair users generally encounter greater difficulty when moving uphill, a trend reflected in the adaptive FTOPSIS model. In contrast, descending long slopes initially showed high accessibility ratings in the conventional FTOPSIS method; however, our adaptive weighting approach more accurately adjusted these ratings to a medium level, better reflecting the real challenges faced by wheelchair users on long steep declines. Moreover, the results indicated that surface texture conditions, as captured by the WPRI and exposure time, directly impacted wheelchair users' ability to navigate long sidewalk segments. Specifically, this led to a very low accessibility level for sidewalks covered by cobblestones after just 10 min of exposure, highlighting the challenges posed by certain surface types for wheelchair users. These results imply that the assessed values of accessibility represent a more realistic evaluation of the perceived accessibility of sidewalks by wheelchair users. Despite the comparison presented in this paper, further investigations are necessary to validate the obtained results with the participation of wheelchair users in different locations with diverse characteristics in urban areas.

CRediT authorship contribution statement

Maryam Naghdizadegan Jahromi: Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation. **Najmeh Neysani Samany:** Writing – review & editing, Methodology, Conceptualization. **Meysam Argany:** Writing – review & editing, Validation, Supervision, Formal analysis. **Mir Abolfazl Mostafavi:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Ethics statement

This study was reviewed and approved by the research ethics committee of the faculty of Geograoghy, University of Tehran, with the approval number: ETHIC-202406-12, Dated 24 May 2020.

All participants provided written informed consent for their participation in the study and the publication of the analysis results derived from their data.

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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