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Review

Walkability Indices—The State of the Art and Future Directions: A Systematic Review

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Abstract: This systematic review aims to illustrate the state of the art of walkability indices and future research directions. A comprehensive search in the general Google database and Google Scholar identified a total of 45 records published between 2005 and 2023. Using a selection process based on the PRISMA model, 32 records were identified as meeting the inclusion criteria. These are organized incrementally, highlighting their novelty relative to preceding studies, and divided into sectors of prevalent application. The 5Ds theory provides a first contribution by identifying walkability metrics based on proximity to amenities, land use diversity, and density. Recent advancements, leveraging GIS systems and open data, have expanded such metrics to include green spaces, footpath design, and noise pollution. However, these developments remain largely tied to the *catchment area* logic and offer coarse descriptions of the built environment's morphological structure, often lacking justification for metric selection and weighting. To address these shortcomings, future research should use more detailed descriptions of urban form, balance metric comprehensiveness with data availability, employ robust methods for metric selection, and explore alternative weighting techniques based on cognitive and emotional responses to urban settings. These efforts are crucial for advancing the understanding and measurement of walkability in the context of the compact city and place-making paradigms.

Keywords: compact city; place-making; urban form; walkability index; sustainable futures

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1. Introduction

The world is undergoing a process of fast and unprecedented urbanization. Official reports estimate that 68% of the global population will live in cities by the end of 2050 [1]. This can be seen as a positive phenomenon as it brings advantages such as better living standards due to the agglomeration of economic activities and cheaper and better public services, including more efficient transport systems [2]. However, mass-scale urbanization also brings several disadvantages such as the exacerbation of socioeconomic inequalities [3,4] and environmental degradation [5], especially in more challenging contexts such as in developing countries.

These issues call for more sustainable forms of development and the retrofitting of existing places to ensure better and safer urban futures, generate more livable and equitable places for all, and minimize the environmental impact of urbanization at the local and global scales. These aims require efforts from a wide array of different disciplines, including environmental science, civil engineering, economics, transportation planning, and disaster management, to name a few. Urban design and planning also play a fundamental role in this as forms of urban settlements influence patterns of resource consumption.

Since the late 1980s, the concept of the compact city, i.e., a city organized as a tapestry of dense urban centers seamlessly interconnected to each other through a network of sociable public spaces, emerged as a part of the place-making approach to design sustainable cities [6,7]. Works by Newman and Kenworthy [6] in Australia; A. Jacobs and Appleyard [7], Moudon [8], and Calthorpe [9] in the US; and Ian Bentley et al. [10] and Frey [11] in the UK found an operational synthesis in two very influential manuals, published at the end of the 1990s: Towards an Urban Renaissance [12] and the Urban Design Compendium [13]. However, the *foundations* of the place-making movement in urban design can be drawn back to the 1960s and early 1970s, with Lynch [14], J. Jacobs [15], Alexander [16], Gehl [17], Newman [18], and Whyte [19].

In the place-making tradition, a *walkable* place is not simply characterized by high footfall, which can be triggered by occasional factors not necessarily connected to the built environment. Rather, walkability describes the *spatial quality of a place* that favors the presence of pedestrians in the public space. Such a quality can be broken down into a combination of mobility features, streetscape character, land-use, and urban form. The latter, in particular, concerns the physical characteristics and spatial arrangements of plots, buildings, and streets that constitute the morphological structure of cities and towns [20,21]. The assumption is that places that show a more walkable morphological structure, for example one characterized by a higher built-up density, would attract more pedestrians. However, although a place may possess this feature, it may still exhibit a limited footfall under particular circumstances, for example if it is a tourist destination and it is out of season, or experiencing an economic downturn, or the climate is just too harsh. Nevertheless, *everything else equal,* a street located in an area with a higher built-up density is more likely to have more pedestrians than one in a less dense area. In this sense, built-up density is one the morphological aspects of a place that contributes to *walkability.*

The emphasis on the quality that makes places sociable was a rather new acquisition for the times. Place-making emerged as a reaction against the abstract logic of theory-driven approaches introduced by the Congrès Internationaux d'Architecture Moderne (CIAM) in the 1930s [22]. In that period, traffic engineering became a driving factor of modern city planning. The idea of the city as a perfectly functional mechanism for the machine-age was predicated on the grounds of Corbusier's 7Vs concept [23], where each traffic component is served by distinct and rigorously separated infrastructural networks. Walkability was attributed, in that framework, a purely functional connotation: the pedestrian was conceived as a mobility component, subject to the same logic of cars, and therefore segregated in dedicated spaces. Paramount was the operational concept of the *catchment area*, i.e., the area defined by all destinations within a given distance from a given origin. Pedestrians, confined in their protected *precincts* [24], preferably in contact with nature, would have enjoyed a safe lifetime in their neighborhood [25–27]. This was physically defined at its borders by traffic thoroughfares. The neighborhood was understood, essentially, as a protected catchment area. The impact of this mobility model in the new city of the machine-age was profound, affecting both the traditional urban form structure [28] and centuries-long customary rules regarding the scale and configuration of streets, blocks, plots, and buildings, a departure radical enough to generate the first bifurcation in thousands of years of urban form evolution [29].

Diametrically opposed to this was the core message of place-making, where public spaces, and streets in particular, are considered not only mobility infrastructure, but also—and perhaps mainly—the theatre of public life. Suddenly, *people in the public space* came to center-stage, taking with them all forms of social relationships, including economic prosperity, wellbeing, health, community identity, etc. Immersed in such mesmerizing complexity, people were not reducible any longer to *pedestrians*. They were all-round social and cultural living beings in continuous relation with each other and the built environment. As cognitive, emotional, interpersonal, and quality-driven ecological considerations came back into the field of vision of planners and designers, *walkability* was to forever leave the domain of traffic modelling. *Accessibility* (to relevant destinations, such as shops, services, and jobs) was to give way to a more subtle and comprehensive notion, that of *attraction*, where the latter depends on a much larger array of morphological features (e.g., street width, plot size, built-up density) including but not limited to distance to destination. As a result, the emphasis of place-making on the pivotal role of public life in supporting the social, economic, and environmental sustainability of cities, put the morphological structure of places back to center stage.

These concepts still deeply inform today's policy and practice. Several recent reports and policy papers from UN-Habitat argue that the compact city model yields favorable outcomes in terms of resource efficiency, economic prosperity, public health, social cohesion, and cultural dynamics [30–32]. This is indeed backed up by previous urban design and planning studies (e.g., [6,33,34]) arguing that compactness contributes to sustainability by minimizing travel distances and commute duration, reducing car dependency, lowering individual energy consumption rates, restricting the use of building materials and infrastructure, addressing pollution, preserving the diversity of workplace options, service facilities, and social connections, and curbing the loss of green and natural spaces. This is supported by the emphasis of the compact city on intensifying development and activities through a dense and tightly knit urban fabric, establishing boundaries for urban expansion, promoting diversity in land use and social composition, and prioritizing active travel options, such as walking and cycling. In brief, the compact city capitalizes on the benefits of agglomeration and density, unlocking a wide range of environmental, economic, and social advantages. The recent COVID-19 pandemic and related movement restrictions brought the place-making and compact city concepts back to center-stage in the urban design debate. Moreno et al. [35] highlighted the importance of urban layouts in which residents can reach essential categories of amenities (i.e., living, working, commerce, healthcare, education, and entertainment) within a 15 min walking or cycling distance. Building on a long and important history of neighborhood planning theory [25–27], the authors maintain that these layouts would not only be more resilient in case of health emergencies, but also enhance the overall quality of life of city dwellers. This point is generally supported by other researchers, including Speck [36] and Florida [37]. The theory by Moreno et al. has been recently integrated in several reports by international organizations, including UN-Habitat [38] and the World Health Organization (WHO) [39], and operationalized to map pedestrian accessibility to amenities, for example, in Portland, OR (US) [40]. In the UK, the national government allocated £2 billion for the creation of an ad-hoc executive agency, i.e., Active Travel England (ATE), (https://www.gov.uk/government/organisations/active-travel-england, accessed on 15 February 2024) focusing on the promotion of more sustainable modes of transport, including walking and cycling, by providing advice to improve design schemes, acting as a statutory consultee for large-scale planning applications, evaluating funding applications, and annually publishing reports grading highway authorities on their active travel performance.

Accessibility to amenities within walking distance is endorsed nearly everywhere in the aforementioned cases. However, Shashank and Schuurman [39] highlight how ambiguities emerge when one questions the identity of the walkers and their needs [40] or why they are walking (e.g., for going to work, for leisure) [41]. These various facets related to walkability are expressed in indices using metric weights. For transportation purposes, for example, the importance of connectivity between work and home is emphasized, while for leisure or recreational purposes, proximity to parks and trails holds greater weight.

In conclusion, it is important to recognize that the emphasis on the comprehensive quality of the built environment for urban life, wellbeing, and prosperity, introduced by place-making in the 1980s and 1990s, permeates the narrative of current urban planning theory, policy, and practice, with walkability being a central component. However, when it comes to *operationalizing the narrative*, starting from what walkability is and how it should be measured, there seems to be a predominant reliance on the *catchment area* approach: walkability is about walking-distance to local amenities. Indeed, this is a reductive interpretation which draws back to the traffic engineering mindset that place-making set out to counter in the first place.

The aim of the literature review presented in this paper is not to provide a complete overview of studies on walkability, repeating what has already been undertaken by several researchers in the last two decades in the urban design, transport [42,43], and health domains [44,45], but rather to highlight gaps in the knowledge-base side of existing walkability indices and identify a way forward for future developments. In other words, to what degree do the existing indices of walkability go beyond the functional idea of the catchment area, to truly characterize the morphological dimension of walkable places?

To explore this question, we first present *pioneering* studies that did not define indices, but established a robust set of metrics to describe walkability by investigating the relationship between such metrics and different output variables. Second, we illustrate existing methodologies that created walkability indices for research, commercial, or public good purposes, inspired by these pioneering studies. Third, we highlight the main limitations of such indices, identify possible future work to address them, and offer concluding remarks.

2. Pioneering Quantitative Approaches

Quantitative research on walkability has been increasingly playing a role in the affirmation of the place-making agenda in urban design, for example in new urbanism [46], transit-oriented development (TOD) [47], and traditional town planning [48] schemes. This was generally undertaken using regression analysis with relevant metrics as independent variables and Vehicle Miles Traveled (VMT) or levels of physical activity as dependent ones, while controlling for socioeconomic aspects and household characteristics. The metrics considered in such models pertained to the so-called 3Ds (Density, Diversity, and Design) theory [49], later upgraded to the 5Ds, to include Destination accessibility and Distance to transit [42,50]. More specifically, Density is consistently calculated as the variable of interest (e.g., population, dwelling units, employment, or building floor area) per area unit. Diversity relates to the provision of different land uses within a specific area and their distribution across land, floor area, or employment. Entropy measures [51], where lower values represent areas with a single predominant use and higher values indicate more diverse land uses, are commonly used. Design encompasses characteristics of the street network such as block size, proportion of four-way intersections, and the number of intersections per unit area. Additionally, design is also occasionally described by factors such as sidewalk coverage, counts of pedestrian crossings, street trees, and other physical variables that distinguish pedestrian- from car-oriented environments. Destination accessibility assesses the convenience of reaching (local or regional) attractors. In certain investigations, regional accessibility is simply the distance to the central business district (CBD). In alternative approaches, it involves the count of jobs that can be reached within a specified travel time. On the other hand, local accessibility is usually defined as the distance from home to the nearest store. Distance to transit involves calculating the average of the shortest street route from residences or workplaces in a given area to the closest public transport stop (e.g., rail station or bus stop). Alternatively, the same can be assessed through metrics such as transit route density, the distance between transit stops, or the count of stations per unit area. Ewing and Handy [52] delved deeper into urban design aspects related to walkability by first identifying perceptual qualities highlighted in the literature, such as imageability, enclosure, and human scale, second, reporting previous attempts to operationalize these concepts and, finally, providing 27 operational definitions for each of such qualities. For example, they proposed the number of people on the same side of the street as a proxy for imageability, proportion of street wall on the same side of the street for enclosure, and number of long sight lines for human scale.

The 5Ds theory provides a first systematic approach to measure aspects of the physical world potentially associated with walkability. However, while this approach covers functional catchment areas to an array of different amenities and services through Diversity, Destination accessibility, and Distance to transit, morphological aspects are only partially accounted for, and in a relatively coarse manner: for example, through metrics of Density and Design such as dwelling units per area unit and block size. Ewing and Handy [52] proposed a more comprehensive set of metrics; however, only a few of them, like number of buildings with non-rectangular silhouettes, proportion of street walls, proportion of first floors with windows, building height, and number of buildings, are in fact morphological.

In the next sections, we first illustrate the methodology used to identify the relevant literature; second, we present walkability indices starting from the pioneering works mentioned above, with an eye at the degree to which these indices went beyond the functional catchment area idea, to include features of the built environment's morphological structure.

3. Review Methodology

3.1. Screening Process

The search strategy employed the general Google database and Google bibliographic database (i.e., Google Scholar) to ensure thorough coverage of pertinent literature, including grey literature. Titles and abstracts were filtered based on inclusion criteria, selecting articles and reports published from January 2005 to December 2023, written in English, and featured in peer-reviewed journals. The search was further narrowed using the following keywords: "walkability", "walkability index", "walkability indices", "quantitative walkability index", and "quantitative walkability indices". A total of 45 records were identified from the two databases mentioned above. Four different reviewers independently screened each record retrieved. Manual screening conducted on these records led to the exclusion of 13 records: 6 of such records proposed walkability metrics but not an overall index and 7 were literature reviews. Following the screening process presented in Figure 1 based on the PRISMA model (see Supplementary Materials) (https://www.prisma-statement.org/, accessed on 15 February 2024), 32 records were finally retained for review. The final selection criteria included only articles and reports directly defining a walkability index.

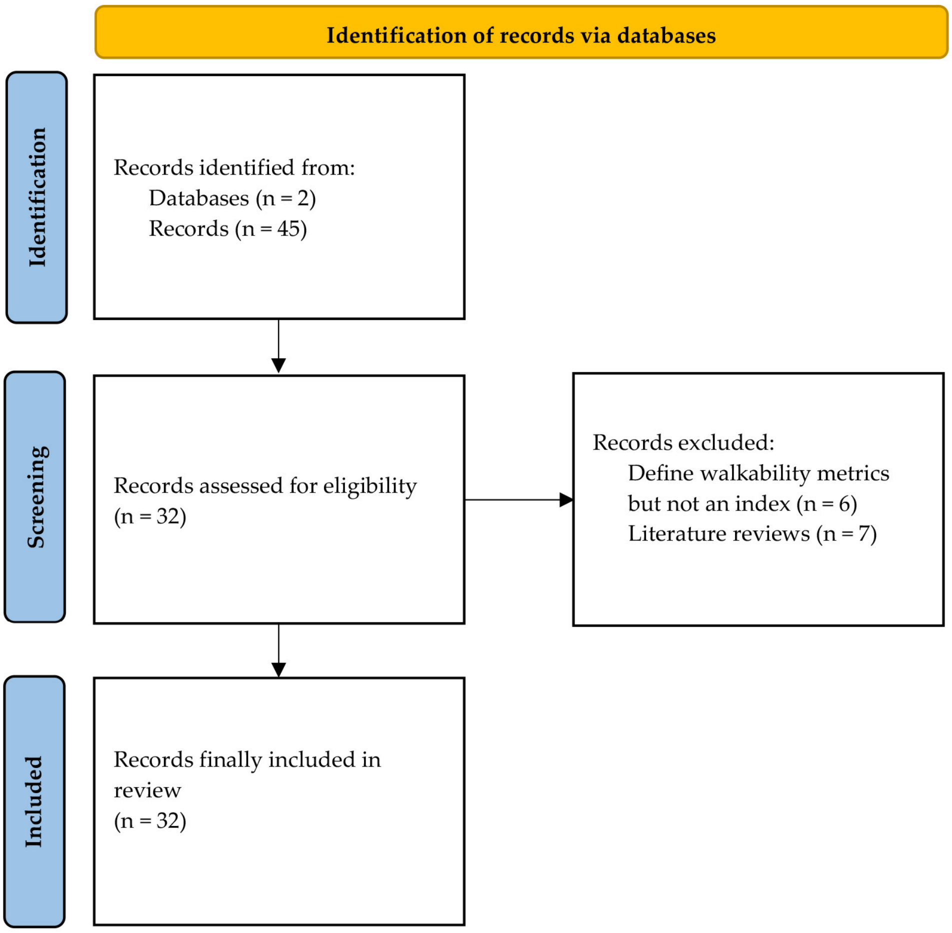

Figure 1. Overview of screening process based on the PRISMA model. Source: the authors.

3.2. Sectoral Division

Due to the large number of walkability indices, publications are divided into three subsections according to the sector (i.e., academic, commercial, and public) of prevalent application. This approach provides a multisectoral perspective of the state of the art in the field compared to review strategies focusing exclusively on academic production. Each of these sectors produced walkability indices aligned with their particular scopes and aims, and this largely influenced methodological choices. Academic indices tend to push research boundaries, for example, by adding previously overlooked metrics and implementing novel technologies and statistical techniques. Commercial indices are created to generate revenue, and they therefore tend to use existing input data and prefer replicability over specificity. Indices created in the public sector tend to account for existing planning policies and community engagement practices and may thus be more context specific. This subdivision not only provides a multisectoral perspective on existing walkability indices but can also help readers from different backgrounds and occupations to explore indices pertaining to their preferred sector. The studies referenced in each subsection are organized in an incremental fashion by identifying the novelty with respect to the theory presented above. The main methodological aspects of each of these studies are summarized in Table 1, while more detailed analysis and discussion are provided in the next section.

Table 1. Main methodological aspects of the walkability indices considered in this review.

		5Ds					Street Conditions	Greenery and Other Environmental Factors	Combination Technique
		Density	Diversity	Design	Destination Accessibility	Distance to Transit			
Academic sector	Frank et al. [53]	Dwelling density	Evenness of distribution of square footage of residential, commercial, and office development	Density of street intersections	-	-	-	-	Sum of standard scores of metrics with land-use mix x6
	Stockton et al. [54]	Dwelling density	Shannon index of land uses	Density of street intersections	-	-	-	-	Sum of decile-converted metrics
	Sundquist et al. [55]	Dwelling density	Herfindahl–Hirschman index of land uses	Density of street intersections	-	-	-	-	Sum of standard scores of metrics with density of street intersections x1.5
	Dobesova & Krivka [56]	Household density	Shannon index of land uses	Density of street intersections	Retail floor area ratio	-	-	-	Sum of standard scores of metrics with density of street intersections x2
	Leslie et al. [57]	Dwelling density	Shannon index of land uses	Density of street intersections	Retail floor area ratio	-	-	-	Sum of normalized (decile) metrics
	Coffee et al. [58]	Dwelling density	Shannon index of land uses	Density of street intersections	Retail floor area ratio	-	-	-	Sum of normalized (decile) metrics
	Frank et al. [59]	Dwelling density	Shannon index of land uses	Density of street intersections	Retail floor area ratio			-	Sum of standard scores of metrics with density of street intersections x 2
	Glazier et al. [60]	Population density, dwelling density	Shannon index of land uses	Count of intersections with 3 or more legs within a 720 meter network buffer from the census tract centroid	Number of locations (of different categories of amenities) within 10 min walk	-	-	-	Standard score obtained through Principal Component Analysis (PCA)
	Peiravian et al. [61]	Population density	Shannon index of land uses	Density of street intersections	Density of commercial establishments	-	-	-	Multiplication of normalized (0–1) metrics

Table 1. *Cont.*

	5Ds					Street Conditions	Greenery and Other Environmental Factors	Combination Technique
	Density	Diversity	Design	Destination Accessibility	Distance to Transit			
Lee et al. [62]	-	-	Local integration, global integration	Weighted distances to avenue-oriented, destination-oriented, and routine amenities	-	Pedestrian footfall	-	Sum of metrics weighted through Analytical Hierarchy Process (AHP)
Zaleckis et al. [63]	Population density	-	Reach-to-residents within a 15 min walk from each building, straightness-to-residents within a 15 min walk from each building	Weighted distance to amenities within 15 min walk	-	-	-	Sum of normalized (0–1) metrics
Neckerman et al. [64]	Population density	Shannon index of land uses	Density of street intersections	Ratio of retail building floor area to retail land area	Minimum distance along the street network to the nearest subway stop	-	-	Sum of standard scores of metrics
Tsiompras & Photis [65]	Population density	Shannon index of land uses	Density of street intersections	Weighted sum of number of destinations (including public transit stops) accessible within 400 m distance	Weighted sum of number of public transit stops accessible within 400 m distance	Percentage of pavements with a width smaller than 1 m per km^2, percentage of pavements of poor surface condition per km^2, percentage of pavements with obstacles per km^2	-	Survey-weighted standard scores of metrics

Table 1. *Cont.*

	5Ds					Street Conditions	Greenery and Other Environmental Factors	Combination Technique
	Density	Diversity	Design	Destination Accessibility	Distance to Transit			
Buck et al. [66]	Population density	Shannon index of land uses	Density of street intersections	Density of public playgrounds, sports facilities, public transit stops	Density of public transit stops	Density of pavement, density of cycleways	Density of parks/green spaces	Average score of standard scores of metrics
Alves et al. [67]	-	Land use mix (undefined)	Density of street intersections	-	-	Quality of pedestrian surfaces, presence of pavement, pavement width, presence of stairs, presence of obstacles, presence of urban furniture, street lighting quality, diversity of information signs	Presence of trees	Slope-weighted sum of binned metrics (1 to 3 classes)
Bonatto & Alves [68]	-	Land use mix (undefined)	Density of street intersections	-	-	Quality of pedestrian surfaces, presence of pavement, pavement width, presence of stairs, presence of obstacles, presence of urban furniture, street lighting quality, diversity of information signs	Presence of trees	Slope-weighted sum of binned metrics (1 to 3 classes)
Steiniger et al. [69]	-	-	-	Weighted walking distance to 11 different land uses	-	-	Weighted walking distance to parks	Sum of weighted metrics
Tijana et al. [70]	Population density	Survey-weighted diversity of reachable amenities	-	-	-	Quality-weighted length of pavements within a 15 min walk	-	Sum of metrics

Table 1. *Cont.*

	5Ds					Street Conditions	Greenery and Other Environmental Factors	Combination Technique
	Density	Diversity	Design	Destination Accessibility	Distance to Transit			
Trolese et al. [71]	Population density	-	Building heights	Number of activities, number of points of interest	-	Pavement width, number of signalized intersections and crosswalks, number of car lanes, presence of lighting, presence benches and fountains	Green areas in m^2	Survey-weighted normalized (min-max) metrics
Talavera-Garcia & Soria-Lara [72]	-	-	Density of street intersections	Density of shops	-	Traffic speed, number of car lanes, pavement width	Density of trees	Average score of survey-weighted and ranked metrics
Taleai & Yameqani [73]	-	Shannon index of land uses	-	-	-	Average land surface temperature for 30 m buffer around each street, street average slope	Density of pixels with NDVI values above 0.3 for 20 m buffers around each street	Metrics weighted through Spatial Multi-criteria Evaluation (SMCA) in a distance-based cost equation
Al Shammas & Escobar [74]	Population density	Shannon index of land uses	Density of street intersections	-	-	Sound levels, shade factor	-	Sum of survey-weighted metrics
Velázquez et al. [75]	Percentage of unit area occupied by residents	-	-	Percentage of unit area occupied by facilities and services	-	Percentage of unit area occupied by roads, sidewalks	Percentage of unit area occupied by green areas, percentage of unit area occupied by trees, average annual temperature, solar radiation, shading of slopes and urban features	Sum of metrics weighted through Analytical Hierarchy Process (AHP)

Table 1. *Cont.*

		5Ds					Street Conditions	Greenery and Other Environmental Factors	Combination Technique
		Density	Diversity	Design	Destination Accessibility	Distance to Transit			
Commercial sector	Walk Score	-	-	Density of street intersections, block length	Weighted walking distance to 9 land uses	-	-	-	Sum of weighted metrics
	WalkShed	-	-	-	Weighted walking distance to 9+ (?) land uses	-	-	-	(undefined)
	Walkonomics	-	-	Building quality	Presence of street activities (undefined)	-	Traffic speed, perceived fear of crime, presence of vandalism, presence of graffiti, presence of presence of police, street average slope, number of road accident, street type, street width, presence of physical barriers, presence of pedestrian crossings, presence and characteristics of pavements, presence of pedestrian signs, presence of lighting	Presence of greenery, noise levels	Average of metrics
	The Prince's Foundation [76]	-	-	Density of street intersections, block length	Number of everyday land uses within 5 min walk	Presence of public transit stops at walking distance	-	-	(undefined)

Table 1. *Cont.*

		5Ds							
		Density	**Diversity**	**Design**	**Destination Accessibility**	**Distance to Transit**	**Street Conditions**	**Greenery and Other Environmental Factors**	**Combination Technique**
	State of Place	Density of buildings	-	Ease of access within and across blocks, building height, attractiveness	Quantity and quality of proximal non-residential land uses, mixed use	-	Streetscape quality, features that facilitate pedestrian & bicyclist comfort, features that impact perceptions of safety, features that make walking and bicycling safer from motorist traffic, maintenance level	Presence, quality, and accessibility of parks and public spaces	Sum of standard scores of metrics
Public sector	Coalition for Healthy Streets and Active Travel [77]	-	-	-	Number of land uses within 500 m walk	-	-	-	Sum of weighted metrics
Public sector	Wagtendonk & Lakerveld [78]	Population density	Shannon index of land uses	Density of street intersections	Retail floor area ratio	-	-	Percentage of green space per 100 m^2	Sum of standard scores of metrics
Public sector	US Environmental Protection Agency [79]	-	Employment mix, employment and household mix	Density of street intersections	-	Distance from population centre to nearest transit stop in meters	-	-	Sum of ranked and weighted metrics
Public sector	Bureau of Planning and Sustainability (BPS) [40]	-	-	Density of street intersections	Distance to everyday land uses	Distance to public transit stops	Proportion of pavements, average slope	Distance to parks	Sum of binned metrics (one to three classes)

4. Walkability Indices

4.1. Academic Sector

The replicability of the 5Ds theory has been, until recently, hampered by the lack of appropriate computer-aided tools, computational power, and data. Indeed, most research presented above used field work to collect data and were thus geographically limited in their extents and scales (typically, the neighborhood). One of the first attempts to overcome these technical limitations and operationalize a replicable, GIS-based methodology was carried out by Frank et al. [53]. The authors considered three of the 5Ds by including residential units per residential acre, intersections per square kilometer, and uniformity in the allocation of square footage across residential, commercial, and office development (measured through the Shannon index [51]). These metrics were computed over a 1 km buffer (measured along the street network) from any specific address. The overall index was achieved by adding the *z*-scores (*Z*-scores are computed through the following formula: $Z = \frac{x-\mu}{\sigma}$, where x is the observed value, μ is the mean of the sample, and σ is the standard deviation of the sample; the computation of z-scores allows having the same value range for the metrics considered in order to directly compare and sum them) of the three metrics, with land use mix multiplied by six. Weights for each metric were decided through trial-and-error models with levels of physical activity as output variable.

This first index paved the way for many subsequent attempts in different geographic contexts [54,55], as well as attempts to advance the methodology by including the remaining Ds (i.e., Destination accessibility, Distance to transit). More specifically, several indices accounted for retail floor area ratio (i.e., the ratio of retail floor space to the overall retail-designated land) [56–59], number of locations of different categories of amenities within a 10 min walk [60], density of commercial establishments [61], or walking distances to avenue-oriented, destination-oriented, and routine amenities, representing, respectively, amenities that can induce impulsive buying, amenities specialized in specific products or services, and amenities that are neither one nor the other [62]. A distinctive aspect of this last index is that it considers three metrics of street network centrality derived from Space Syntax [80] rather than intersection and population density. These three metrics are integration, connectivity, and intelligibility, measuring, respectively, the accessibility to a particular intersection within the street network, the ease of movement between streets, and the degree of recognition of a smaller urban space within a larger urban context, and vice versa. A further interesting aspect of this work is that it uses both surveys and the Analytical Hierarchy Process (AHP) [81] to obtain metric weights. AHP is a decision-making method aimed at systematically evaluating and prioritizing criteria or alternatives. It involves breaking down complex decisions into a hierarchical structure, assigning numerical values based on relative importance, and using mathematical calculations to derive a priority scale. Space Syntax was also used by Zaleckis et al. [63] to create a walkability index. However, unlike Lee et al. [62], they implemented later developments of such an approach [82] on a 15 min walk radius by considering centrality of gravity applied to different amenity categories, reach-to-residents from each building, and straightness-to-residents from each building. One of the first attempts to introduce the fifth D (i.e., *Distance to transit*) in the calculation was achieved by Neckerman et al. [64], who proposed a walkability index based on all the metrics previously mentioned and the minimum distance along the street network to the nearest subway stop.

Thanks to the increased availability of different data and more efficient digital methods of data collection, recent walkability indices include metrics that quantify design and maintenance of streets and footpaths. Tsiompras and Photis [65] proposed an index that included metrics derived from the 5Ds theory (i.e., number of intersections with more than three links per km^2, entropy of land use categories, number of inhabitants per km^2, and the weighted sum of the number of destinations accessible within 400 m distance, including public transport stops), but also further metrics accounting for design and levels of maintenance of footpaths (i.e., percentage of footpaths with a width smaller than one meter per km^2, percentage of footpaths with poor surface condition per km^2, and percentage of footpaths with obstacles per km^2). Buck et al. [66] considered the aspects mentioned above and added greenery by applying a kernel density function [83] to point data representing parks, green spaces, and public playgrounds.

More recent studies at the scale of the street segment exhibit much more heterogeneous methodologies. While accounting for previously unmeasured aspects, they did not include (or only partially included) metrics derived from the 5Ds theory. Alves et al. [67] devised and applied a walkability index for the elderly, which was then replicated by Bonatto and Alves [68] in a different geographic context, which accounted for several design and maintenance aspects of footpaths and streets (i.e., presence and width of footpaths, footpath surface quality, presence of obstacles on footpaths, presence of street furniture, street lighting quality, diversity of information signs, presence of complex street intersections), greenery (although the specifics of the metric were not clarified), and steepness (i.e., presence of stairs and slope level). However, the index only incorporated one of the Ds (i.e., Diversity) through a metric of land use mix, where three or more land use categories scored the highest on a one to three scale. Similarly, Steiniger et al. [69] included a metric of greenery (i.e., walking distance to parks), however they only considered one of the Ds (i.e., Destination accessibility) by measuring walking distance to 11 categories of amenities. Tijana et al. [70] introduced a metric for simultaneously assessing the quality and quantity of the pedestrian infrastructure (i.e., weighted length of footpaths within a 15min walk), where different weights were assigned based on the results of a local survey. Only two of the original Ds (i.e., Density and Diversity) were included: population density and weighted diversity of reachable amenities, where weights were given in the same manner as described above. Trolese et al. [71] considered metrics for the same Ds, thus missing the other three, but accounted for green areas (in m^2) and several design and maintenance features of footpaths, i.e., sidewalk width, number of signalized intersections and crosswalks, number of car lanes, presence of lighting, benches, and fountains.

A growing concern for environmental issues, combined with a heightened understanding of the relationship between streets that are attractive, support wellbeing, and are environmentally sustainable, has given rise to several studies aiming at creating walkability indices which include metrics of thermal comfort, presence of greenery, and other environmental metrics. However, like the studies mentioned above, these did not fully account for metrics derived from the 5Ds theory. Talavera-Garcia and Soria-Lara [72], for example, included a metric of tree density and one of environmental comfort (i.e., speed limit) to account for road safety, but they only considered two of the original Ds (i.e., Design and Density) through the computation of number of intersections per street segment and number of shops per km^2. Taleai and Yameqani [73] considered average slope at the street level, density of maximum values of the Normalized Difference Vegetation Index (NDVI) (NDVI is a measure commonly used in remote sensing to quantify the amount of vegetation cover from satellite pictures) at the street level, and average land surface temperature. However, they only accounted for the entropy index of land use types at the street level as a measure of *Diversity*. Al Shammas and Escobar [74] not only included the entropy index of land use types, but also density of street intersections and net residential density, thus covering two more Ds. Furthermore, they added sound levels and shade factor at the street level to account for thermal and hearing comfort. Velázquez et al. [75] considered only two of the 5Ds (i.e., Destination accessibility and Density) by measuring percentage of area occupied by facilities and services and percentage of area occupied by residents, but also added metrics of greenery (i.e., percentage of area occupied by green areas, percentage of area occupied by trees), thermal comfort (i.e., mean annual temperature, solar radiation, shading of slopes, and urban features), and distribution of surfaces (i.e., percentage of area occupied by roads and sidewalks).

4.2. Commercial Sector

WalkScore® is the best-known walkability index in the commercial sector (https://www.walkscore.com/, accessed on 15 February 2024). Originally created in the US, it is now present in the UK, Canada, and Australia. The Walk Score® methodology integrates three factors: the minimum distance to a set of destinations (such as commercial and service areas, public transportation, dining establishments, shopping centers, parks and green spaces, and educational institutions), representing Destination accessibility, the length of blocks, and the density of intersections around an address, representing Design. The final score (0–100) is achieved by subtracting the sum of the second and third factors (penalties reflecting pedestrian friendliness) from the first factor [84]. Before 2010, Walk Score® used a one-mile Euclidean distance buffer but currently the buffer is calculated for addresses on the street network [85]. WalkShed® is a WalkScore® inspired index which claims to consider further destinations compared to the latter (https://walkshed.org/, accessed on 15 February 2024). However, no public information is provided on such added elements.

Walkonomics is a further commercial index using an automatic system (i.e., WalkoBot) to score the walkability of streets by interpreting public datasets (https://walkonomics.com/, accessed on 15 February 2024). More specifically, the tool includes a wide array of different metrics, i.e., traffic speed and volume, presence of greenery, crime statistics, fear of crime, vandalism, graffiti, presence of police, noise levels, street steepness, road accident statistics, street type, street width, physical barriers, provision of pedestrian crossings, presence and characteristics of pavements/sidewalks, pedestrian signs, lighting, and building quality. However, no information is disclosed as for how such metrics are combined and weighted to obtain the final score. An interesting aspect of Walkonomics is that users can input personal evaluations of specific street scenes in a dedicated app, which will then directly affect the overall score. In terms of the 5Ds theory, this tool only accounts for Destination accessibility but clearly provides a broader perspective on several other features of the urban environment and related phenomena.

A further commercial index of walkability has been developed by Space Syntax Limited and applied to UK cases (https://spacesyntax.com/project/walkability-index/, accessed on 15 February 2024). The methodology is seemingly based on a combination of three metrics computed at the street segment and building scale: location of bus and train stops at walking distance, connectedness of the street and pedestrian/cycle path network, and number of different everyday land uses [86], thus accounting for Distance to transit, Design, and Destination accessibility. However, more details on the methodology are currently unavailable.

State Of Place (SOP) is a further walkability index that capitalized on recent developments in Artificial Intelligence (AI) and Machine Learning (ML) (https://www.stateofplace.co/, accessed on 15 February 2024). It is based on extensive audits including questions (in Boolean or Lickert scale format) on more than 100 features of the urban environment (e.g., presence of specific house types, public institutions, graffiti, litter, signaling system, street attractiveness, perceived safety, number of street trees). Partial scores are then converted to z-scores and added together (even though a recent iteration of the methodology uses multiplication rather than addition) [87]. The final index is normalized into a score from 0 to 100. ML models are then trained on the audit outputs and scaled up to larger areas by using AI-based visual recognition techniques on street views to predict the walkability scores. Being completely raster based, it is difficult to ascertain what Ds SOP accounts for. However, by looking at the urban design dimensions presented by Koschinsky et al. [87], it is probably safe to state that it considers Design (but not street network connectivity), through metrics of streetscape quality, pedestrian and bicyclist comfort, and street attractiveness, among several others; Density, by measuring concentrations and height of buildings; and Destination accessibility, through a unspecified measure of quantity and quality of non-residential land uses and mixed-use. It does not seem to consider metrics of Diversity and Distance to transit.

4.3. Public Sector

In terms of walkability indices generated by public and civic institutions, the Coalition for Healthy Streets and Active Travel (CoHSAT) in Oxford (UK) has developed an index (ranging from one to five) based on accessibility to a selection of amenities, including doctor surgeries, schools, pubs, open spaces, supermarkets, for pedestrian isochrones and combined such metrics by adding the partial scores [77], thus covering Destination accessibility.

The Dutch government recently adopted a walkability score created by researchers at the Amsterdam Public Health Research Institute [78] covering Design, Diversity, and Density, through measures of density of intersections with three or more legs, the entropy index applied to five land use categories (i.e., residential, commercial, social-cultural services, offices and public services, greenspace and recreation), population density per km^2, and density of retail area floor. Furthermore, the percentage of green space per 100 m^2 and percentage of sidewalk area per 100 m^2 are also considered to add information on greenery and presence of infrastructures for pedestrians. The overall score is then obtained by adding the z-scores of each single metric. A distinctive aspect of this methodology is that data are aggregated for cells (of 25 m) rather than street segments or neighborhoods.

The US Environmental Protection Agency (EPA) has recently developed a National Walkability Index [79] which is based on four metrics: intersection density, proximity to transit stops, diversity of employment types, and diversity of employment types and occupied housing, thus accounting for Design, Distance to transit, and Diversity. Each metric is aggregated for official census areas (i.e., block groups) and scored from 1 to 20. Weights are derived from previous work [88] and computed by dividing the partial scores of the first two metrics by three and the partial scores of the last two metrics by six. The final index is obtained by adding the weighted scores. In terms of spatial granularity, the US index is coarser compared to the examples above as it is calculated for areas rather than addresses, street segments or smaller spatial units.

Still in a US context, the Bureau of Planning and Sustainability (BPS) of the city of Portland, OR (US), recently proposed a 20 min neighborhood index to map pedestrian accessibility [40]. The methodology considered three of the 5Ds by including metrics of *Design* (i.e., intersection density, street connectivity), Destination accessibility to grocery stores, retail, restaurants, parks, and elementary schools, Distance to transit, but also slope steepness. Each metric was computed for cells of 400 m, discretized on a one to three scale, and added together to calculate the final index.

5. Main Limitations of Existing Walkability Indices

Walkability indices developed in the three sectors considered in this paper tend to have similar shortcomings; that is, they do not fully include aspects that are relevant in the 5Ds theory and they are essentially tied to the functional concept of catchment area and offer rather limited descriptions of the morphological features of the built environment, which are crucial in place-making. As a consequence, they tend to reassert the traffic modelling perspective that conceptually, and in theory, they set out to challenge in the first place. There are, however, some exceptions. In the academic sector, for example, several non-recent indices [56–60,62–65,82] fulfill the 5Ds theory and consider previously unmeasured aspects, such as street centrality, maintenance levels of footpaths, and greenery. However, the morphological structure of places is still partially described, for example through rather coarse metrics like block size and street length. Furthermore, the use of very detailed spatial information like surface condition and presence of obstacles on the footpaths, hampers, to a certain extent, the replicability of such indices. Walkonomics and SOP stand out as they indirectly consider small scale elements of urban form by using automatic interpreters on public databases and image recognition techniques on street views. However, the fact that these elements are not directly measured undermines the understanding of their relative contributions to walkability, thus limiting their potential use in the design domain in particular, and the place-making agenda in general.

A technical limitation of recent indices across all sectors has to do with methodological heterogeneity. Most approaches only partially cover the spectrum of elements suggested in the 5Ds theory [42,50], and overlook some innovative metrics that have been recently proposed [73,75]. For example, the index proposed by Al Shammas et al. [74], included sophisticated metrics of sound levels and shade factor but did not account for Destination accessibility nor for slope or greenery. Trolese et al. [71], while quantifying green areas and several small-scale street features (e.g., sidewalk width, number of signalized intersections and crosswalks, presence of lighting, benches, and fountains), did not consider Diversity, connectivity aspects of the Design domain, slope, or thermal comfort at the street level. Similarly, recent commercial and public indices of walkability overlooked both important components of the 5Ds theory and advancements attained by recent works. Walkonomics, for example, uses available public datasets to measure tens of previously ignored aspects of the urban environment and offers to users the possibility of adjusting the final score based on personal judgment, but it only accounts for *Destination accessibility*. The US National Walkability Index accounts for metrics related to the original 3Ds (i.e., Design, Distance to transit, and Diversity), however it does not consider aspects related to the other Ds nor novel metrics included in recent indices, such as levels of greenery, slope, or air pollution.

The exclusion of specific metrics may have been dictated by potential cross-correlations, for example, population density and intersection density are usually related (high population densities are usually associated with dense urban areas, which, in turn, tend to have more street intersections per surface area). However, virtually none of the approaches presented in this review considered a comprehensive pool of metrics and used statistical techniques (e.g., cross-correlation, feature selection) to ascertain this point and eventually filter out highly cross-correlated metrics before computing the overall index. A further possible obstacle may have been related to data availability. Today, however, there exist several openly accessible repositories and datasets from which to extract the necessary information. For example, metrics related to streets and buildings can be obtained from official as well as crowd-sourced repositories, such as Ordnance Survey (OS) Data Hub in the UK (https://osdatahub.os.uk/downloads/open, accessed on 15 February 2024), the BD TOPO in France (https://www.data.gouv.fr/en/datasets/bd-topo-r/, accessed on 15 February 2024), and OpenStreetMap (OSM) (https://www.openstreetmap.org, accessed on 15 February 2024), the first free editable map of the entire world. Openly accessible satellite imagery, such as Copernicus data (https://www.copernicus.eu/en/access-data, accessed on 15 February 2024), can also be used for computing metrics of green and blue infrastructures or air pollution at a fairly fine level of spatial granularity (NDVI data, for example, is provided at 10 m of resolution). As previously stated in Section 1, walkability can be defined differently depending on who the walkers are and their reasons for walking [41]. However, there are likely sweet spots that will work for most people in most cases. While bespoke indices may excel at precisely quantifying walkability in certain locales, demographic groups, or for specific travel needs, more holistic and replicable indices, though potentially less accurate, can still offer valuable insights into walkability across diverse geographic contexts, especially when grounded in a comprehensive set of metrics informed by prior literature.

As presented in Section 1, the concepts of compact city and place-making are very much related to measurable aspects of cities, such as street width, building size, and built-up density. Understanding the partial contributions that these aspects have in relation to walking would greatly benefit the current discussion around the design of future sustainable cities brought forward by both national (e.g., [89]) and international organizations (e.g., [90]). A further limitation of existing approaches has therefore to do with their inability to provide design relevant measurements, at the scale of the building, plot, and street, which would allow the definition of *best practice* recommendations on how to design streetscapes that are more conducive to walking. These recommendations could include, for example, windows of target values for specific metrics of urban form, such as building size, width of building façades, street enclosure, and presence/quantity of greenery. Even more sophisticated tools (e.g., Walkonomics, SOP), which claim to assess urban design dimensions, use automatic interpreters on public data and image recognition techniques on street views, making it extremely difficult to reverse engineer the output and ultimately trace the real dimensions of the physical components of the built environment under examination. SOP, for example, claims to include a metric of building heights; however, what is actually measured is the relationship between audit outcomes and specific configurations of pixels representing buildings in street views. This metric, alongside several others obtained in the same manner, is then used to train a ML model to predict walkability scores in a given place. While this may be very efficient in terms of predictive capacity, it does not provide information on morphological features of the built environment.

A final limitation is related to the system used to assign metric weights. Most indices across all sectors did not consider any weighting and were obtained by just adding the standardized scores of each individual metric. This approach is, to a certain extent, concerning since it treats all metrics at the same level, even though some may be more important than others in relation to walkability. For instance, the ability to reach a mix of amenities and services may be more important than footpath conditions. Some indices in the academic (e.g., [55,59]) and public sectors (e.g., [79]) used metric weighting derived from prior evidence (e.g., [91]) which is a step forward compared to not using it at all. However, weighting systems may change in relation to the geographic context of application. For this reason, a few indices in the academic [65,71,72] and commercial sector (SOP) use questionnaire outcomes to fine-tune the weighting system. Questionnaires usually ask people to score a set of features of the urban environment related to the metrics used to compute the indices [65,72,87]. Such scores are then analyzed via decision-making protocols that convert the answers into numerical factors used for weighting. While this is a robust approach, interviewees may find it difficult to mentally visualize and score domain-specific elements, such as levels of street connectivity, pavement types, and street enclosure. Future work might thus consider weighting systems based on questionnaires that do not require interviewees to evaluate technical elements but rather focus on their cognitive-emotional [92] and physical [93] responses to the urban environment.

6. Future Work

Walkability indices across the three sectors considered in this paper are mainly limited by a rather exclusive reliance on the logic of the catchment area. This is, to a certain extent, a reductive approach that does not fully capture the nature of walkability as a central contributor to the place-making agenda in urban design. As a result, we suggest that future research on walkability indices should be more detailed and comprehensive, in particular by expanding the representation of the morphological quality of places. Recent studies in the emergent field of *urban morphometrics* have marked a significant advancement in this area, by operationalizing a long tradition of regionalization studies and scaling up the characterization of urban form to unprecedented levels. The comprehensiveness achieved in these studies is also unprecedented, by including dozens and often hundreds of dimensions measured at the building, plot, and street level, along with clustering analysis to identify morphological regions and profiling techniques for their characterization and cross-comparison. Three leading approaches include Multiple Fabric Assessment (MFA) [94], Bobkova et al.'s plot classification [95], and Urban MorphoMetrics (UMM) [96]. MFA extracts 21 metrics of urban form, quantifying aspects of built-up and site morphology, network-building, network-plot, network-site relationships, from datasets on buildings, streets, and terrain elevation. The method by Bobkova et al. extracts 6 metrics quantifying geometric and accessibility features of plots from cadastral data. UMM uses open data on buildings and streets to compute a set of 74 *primary characters* spanning different morphological categories (i.e., dimension, shape, spatial distribution, intensity, connectivity, diversity) at the building, plot, and street level, aiming at covering all the measurable aspects (e.g., building footprint, floor area ratio, street height to width ratio) identified relevant in the domain-specific literature. Integrating a comprehensive set of metrics to describe the built environment's morphological structure would not only render a future index better suited to describe walkability, but also be useful when it comes to design. Metrics can be queried to understand what the best values are in relation to survey outcomes or benchmark data. Such evidence-based ground would ultimately support best practice recommendations for the creation of walkable places or the redesign of car-oriented ones, which are understandable and workable for designers as well as developers, policymakers, and community groups. The provision of such capability would pave the way to an avenue of innovative practices that go beyond the simple mapping of walkability. A next-generation of best design practices to achieve more pedestrian-oriented streets, neighborhoods, and cities worldwide would be made available on the ground of rigorous evidence.

To address the methodological heterogeneity which hampers replicability of recent indices in all sectors, future work may consider reaching a compromise between including the most comprehensive set of metrics found relevant in the literature and data availability. The latter, in particular, is related to the scale that the assessment is designed to cover, where the larger the scale the more challenging the problem. In principle, such future efforts would ideally include metrics pertaining to the 5Ds theory [43,51], but also metrics providing better descriptions of urban form and metrics recently introduced to account for environmental and sustainability aspects, such as presence and quantity of greenery and thermal comfort. As highlighted in the previous section, this seems feasible nowadays thanks to the widespread availability of official (e.g., OS, in the UK) and crowd-sourced (e.g., OSM, worldwide) data on streets and buildings, and high-resolution satellite imagery (e.g., Copernicus data), from which to extract information to compute such metrics.

Related to the above point, it is unclear why several indices in all sectors did not include metrics which were found previously relevant. While this may have been decided to create bespoke indices targeting specific places or population segments, in the absence of a solid justification—either qualitative or quantitative—the selection appears somewhat biased. Future work may thus investigate providing a robust background for metric choice. Recent feature selection algorithms, such as the one proposed by Raschka [97], can help to systematically select a pool of metrics that best capture survey outcomes or benchmark data and, ultimately, create a more fit-for-purpose walkability index.

Finally, future work may consider alternative survey methodologies that do not ask domain-specific questions but rather focus on people's cognitive-emotional [92] and neurological responses [93] to the built environment. This survey would directly tap into our pre-existing ability as *urban* human beings to perceive and feel our surroundings without the filter imposed by domain-specific questionnaires. The outcomes of such surveys would then allow a weighting system based on what values of each specific metric work best for positive cognitive-emotional and neurological responses. A schematic framework derived from this discussion is provided in Figure 2.

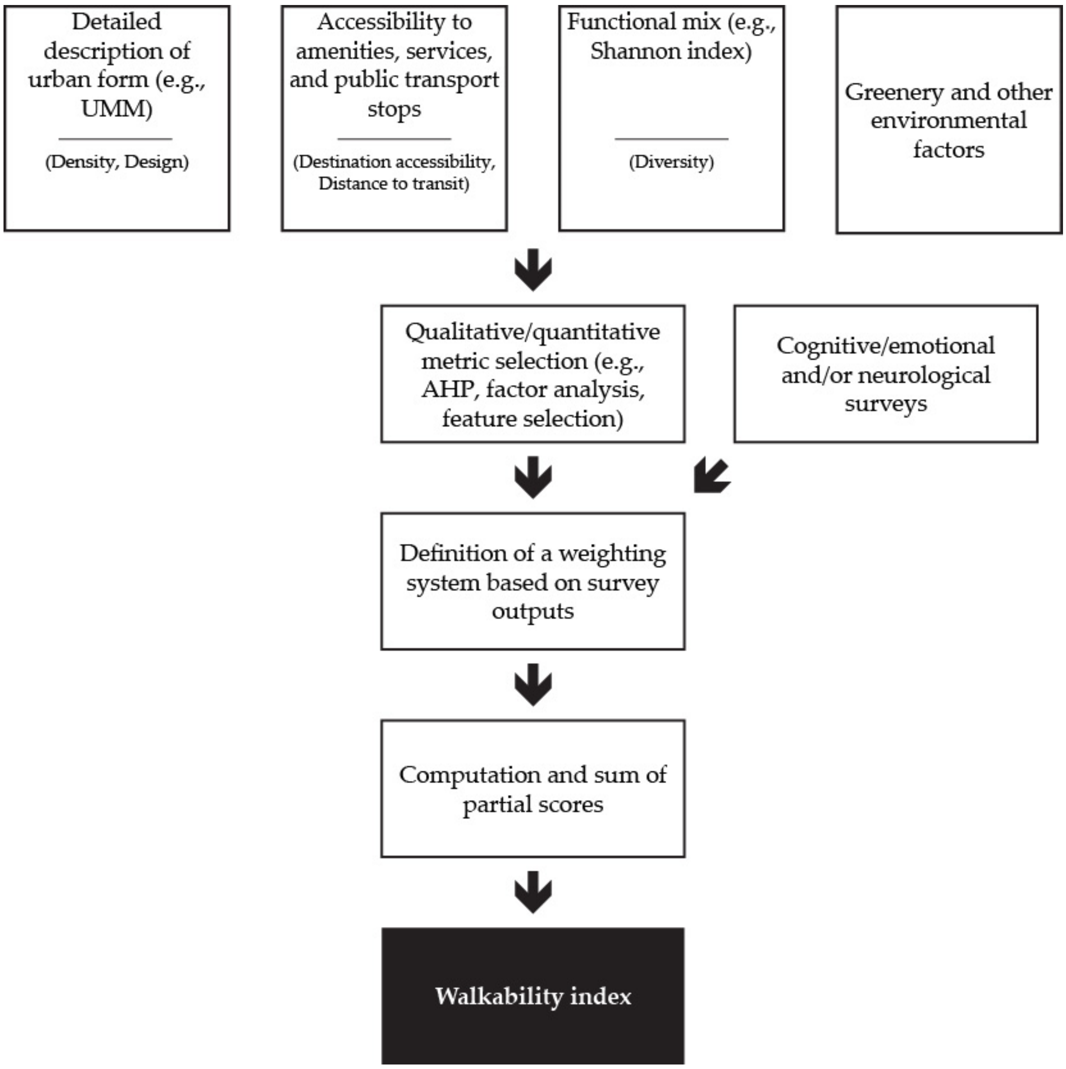

Figure 2. Schematic framework for future developments of walkability indices. Source: the authors.

7. Conclusions

As the world is becoming more urban by the day, the negative effects of mass-scale urbanization and environmental issues are posing serious threats to the global social, economic, and ecological systems. To achieve more sustainable forms of urban development, either by retrofitting existing places or building better urban expansions, the concepts of compact city and place-making have emerged as models of reference. Several methodologies have been developed to measure walkability (a fundamental aspect of those concepts) and build momentum around this topic. The 5Ds theory is a step forward in this direction as it identified a set of metrics related to walkability accounting for catchment areas to amenities and services, diversity of land uses, but also elements of urban form, although measured in a fairly coarse manner. With the advent of more capable computers, GIS systems, and open data, recent contributions in the academic, commercial, and public sectors have built upon the 5Ds theory and integrated previously disregarded elements such as presence of greenery, design features of footpaths, and noise pollution. However, these recent contributions are still largely tied to the catchment area logic and provide unrefined descriptions of the morphological features of the built environment, underplaying the role of walkability in relation to the compact city and place-making concepts. Furthermore, they are methodologically heterogenous as the indices did not include metrics found relevant in previous studies without a sufficient ground of justification. A final significant limitation has to do with metric weighting. While this technique is useful to capture the relative importance of metrics in different contexts, the most advanced indices presented in this paper largely relies on technical questionnaires, which interviewees may find difficult to answer. To address these limitations, we suggest that: (i) future indices should incorporate detailed descriptions of the urban form, potentially utilizing methodologies like UMM, which provide a comprehensive set of metrics at the building, plot, and street level; (ii) future methodologies should aim to strike a balance between including a comprehensive set of relevant metrics and considering data availability, potentially incorporating metrics related to the 5Ds theory, urban form, and environmental sustainability aspects; (iii) future methodologies should investigate robust methods for metric selection either qualitative or quantitative, such as feature selection algorithms; (iv) metric weighting should be based on alternative questionnaires focusing on cognitive-emotional and neurological responses to the built environment, bypassing the limitations of domain-specific questionnaires and offering a more direct understanding of human perceptions and feelings toward the urban environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16166730/s1, File S1: PRISMA 2020 Main Checklist. Reference [98] is cited in the Supplementary Materials.

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