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Assessing Walkability in Urban Environments: A Comprehensive Overview

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Abstract: Walkability, defined as the degree to which urban environments encourage walking, is a vital component of sustainable urban development. It enhances public health, reduces environmental pollution, and fosters social cohesion. This review investigates the current state of walkability research, emphasizing tools such as Geographic Information Systems (GIS), Walk Score, and Agent-Based Modeling (ABM). While traditional methods offer valuable insights, they often neglect socio-economic and demographic factors influencing walking behaviors. ABM enables dynamic simulations that incorporate individual preferences, environmental conditions, and urban design features, offering a deeper understanding of pedestrian movement. Key components of walkability, including density, diversity, design, and safety, are examined alongside the application of multi-criteria decision-making frameworks (e.g., MCDM/MABAC). Insights from global case studies highlight the effectiveness of these tools in modeling pedestrian flows and assessing urban design interventions. This study identifies critical gaps, including the integration of emerging technologies, mental health outcomes, and inclusive design for diverse populations. The findings underscore the need for a global walkability assessment platform, integrating ABM, GIS, and real-time data to guide urban planners in creating healthier, more sustainable cities. Enhancing walkability can significantly improve public health, environmental quality, and quality of life in urban areas worldwide.

Keywords: walkability; sustainable urban development; Geographic Information Systems (GIS); Agent-Based Modeling (ABM); urban planning; pedestrian mobility; multi-criteria decision-making

1. Introduction

1.1. Defining Walkability

Walkability refers to the extent to which the built environment encourages and facilitates walking by ensuring pedestrian comfort and safety, providing convenient access to diverse destinations, and creating visually engaging pathways [1,2]. Recognized as a critical component of urban planning and sustainable development [3], walkability offers numerous benefits, including improvements in public health [4], reductions in environmental pollution [5], and enhancements in social connectivity [6].

1.2. Global Importance

High walkability in cities is associated with improved physical health, reduced stress levels, and increased social interaction [7]. As walking becomes a primary mode of transportation in urban areas, it plays a pivotal role in reducing greenhouse gas emissions, fostering more sustainable communities, and enhancing overall quality of life [8]. As cities worldwide strive to become more sustainable and livable, promoting walkability is increasingly seen as essential to achieving these goals.

1.3. Advancements in Walkability Assessment

Growing research on walkability underscores the need for effective assessment methods to guide urban planning decisions [9]. Traditional methods, such as qualitative audits and questionnaires, offer valuable insights but often lack the spatial precision and scalability required for detailed urban planning [10]. In response, advancements in quantitative methods—including Geographic Information Systems (GIS), walkability indices, and Agent-Based Modeling (ABM)—provide robust tools for assessing walkability through spatial analyses and simulations. These tools enable urban planners to consider a wider range of factors that influence pedestrian experiences and make data-driven improvements to urban design [3].

1.4. Examples from Global Cities

Cities worldwide have increasingly recognized the importance of improving walkability as part of their urban development strategies. For instance, Seoul has implemented extensive pedestrian zones and connected public spaces to reduce car dependency [11] while Lisbon has focused on improving street connectivity and pedestrian comfort [12]. Similarly, cities like Geneva (Figure 1) and Kraków [13] have begun to integrate walkability enhancements into their urban plans, creating pedestrian-friendly zones and investing in public spaces to foster healthier, more accessible urban environments. Such initiatives demonstrate how diverse cities are prioritizing walkability to address common challenges, such as traffic congestion, air pollution, and limited green spaces. Implementing these changes requires detailed planning and assessment, where tools like ABM, GIS, and Multi-Criteria Decision-Making (MCDM) frameworks play a critical role in evaluating the effectiveness of walkability interventions.

Figure 1. Pedestrian Zone Marking on Avenue de Sécheron, Geneva - Photo: Obayd Sadeghi.

1.5. Role of Agent-Based Modeling (ABM)

Agent-Based Modeling (ABM) has emerged as an advantageous tool for assessing walkability, alongside other data-driven methods. ABM enables the simulation of pedestrian behaviors and allows for evaluating different urban designs by incorporating factors such as individual preferences, environmental conditions, and infrastructure features. This approach helps urban planners model pedestrian flows and explore how various design elements impact walkability [3]. Platforms like GAMA, with advanced modeling capabilities, make ABM a valuable tool for urban planning. By

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using ABM in conjunction with GIS and other methods, planners can gain a deeper, dynamic understanding of how urban designs influence pedestrian movement and accessibility.

1.6. Purpose and Structure

This state-of-the-art review provides a comprehensive overview of current research and practices in walkability assessment, with a focus on the tools and methodologies used to evaluate and improve pedestrian environments. By examining relevant literature, theoretical models, case studies, and identifying research gaps and opportunities, this review aims to outline strategies that can enhance walkability in urban environments globally. The remainder of the paper is organized as follows: Section 2 presents a literature review of key studies on walkability, discussing theories and frameworks for evaluating walkability; Section 3 introduces the MABAC Method as a multi-criteria decision-making tool; Section 4 reviews applications of ABM in walkability studies; Section 5 examines case studies of successful walkability initiatives; and Section 6 identifies gaps and proposes new research directions.

2. Literature Review

2.1. Key Components of Walkability

Evaluating walkability involves assessing various aspects of the built environment that influence people's willingness and ability to walk. Understanding these key components is essential for urban planners and policymakers aiming to create pedestrian-friendly environments. The following elements are commonly considered:

2.1.1. Density

- Residential Density: Higher concentrations of housing units encourage walking by bringing destinations closer together [1,14]. In other words, increased residential density reduces the distance between homes and essential services, promoting walking as a convenient mode of transportation.
- Employment Density: Similarly, areas with a high number of jobs promote walking commutes and lunchtime pedestrian activity [14]. High employment density fosters economic vibrancy and supports local businesses accessible by foot.

2.1.2. Diversity (Land Use Mix)

- Mixed-Use Development: The integration of residential, commercial, and recreational spaces allows for multiple destinations within walking distance [5,14]. This diversity reduces the need for vehicular travel and enhances the convenience of walking.
- Access to Amenities: Likewise, proximity to shops, restaurants, schools, parks, and services encourages walking for various purposes [15]. Accessibility to amenities increases the utility of walking for daily activities.

2.1.3. Design (Urban Design and Pedestrian Infrastructure)

- Street Connectivity: A well-connected grid of streets with numerous intersections reduces walking distances and provides route options [1,14]. High connectivity, therefore, facilitates direct and efficient pedestrian movement.
- Sidewalk Quality: In addition, the presence of wide, well-maintained sidewalks, pedestrian crossings, and curb ramps enhances safety and comfort [16]. Quality pedestrian infrastructure is essential for accommodating all users, including those with disabilities.
- Aesthetic Appeal: Moreover, attractive streetscapes with landscaping, street art, and street furniture make walking more enjoyable [6]. Visual interest and environmental aesthetics can motivate people to choose walking over other modes.

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- Human-Scale Architecture: Buildings designed with pedestrian-friendly features, such as ground-level windows and active frontages, further enhance the walking experience [1].

2.1.4. Distance to Transit (Transit Accessibility)

- Proximity to Public Transportation: Easy access to bus stops, train stations, and other transit hubs complements walking and reduces car dependency [14]. Integration of walking and public transit extends the reach of pedestrians and supports sustainable mobility.

2.1.5. Safety and Security

- Traffic Safety and Conditions: Implementation of traffic calming measures, such as speed bumps, narrow lanes, and reduced speed limits, decreases vehicle speeds and enhances pedestrian safety and comfort [1,17]. Additionally, lower traffic volumes reduce the risk of accidents and improve air quality, making walking more pleasant.[1] Providing safe crossing points, visible signage, and pedestrian signals is critical for preventing accidents and facilitating safe street crossings [17].
- Personal Security: Adequate street lighting, visible sightlines, and active street life deter crime and increase pedestrians' perception of safety [18]. The fear of crime can significantly deter walking, especially during evening hours. Consequently, a safe environment encourages more people to walk, contributing to a vibrant street life.

2.1.6. Accessibility

- Universal Design: Infrastructure accommodating people of all abilities, including ramps, tactile paving, and audible signals, ensures inclusivity [19]. Universal design principles make walking feasible for the elderly and those with disabilities.
- Barrier-Free Routes: Similarly, minimizing obstacles like stairs, steep slopes, and uneven surfaces ensures ease of movement for all pedestrians [20].

2.1.7. Environmental Quality

- Air Quality: Lower levels of pollution make walking healthier and more pleasant [5]. Clean air is essential for the well-being of pedestrians.
- Noise Levels: Likewise, reduced noise pollution from traffic enhances the walking experience [21]. Quieter environments make walking more relaxing and enjoyable.
- Green Spaces: Furthermore, the presence of parks, trees, and landscaping improves environmental aesthetics and provides shade [1]. Greenery contributes to psychological well-being and encourages more walking.

2.1.8. Topography

- Terrain: Flat or gently sloping areas are more conducive to walking than hilly or steep terrains [22]. Topography influences the physical effort required to walk, affecting people's willingness to choose this mode.

2.1.9. Wayfinding and Signage

- Clear Signage: Directional signs, maps, and markers help pedestrians navigate efficiently [1]. Effective wayfinding reduces confusion and ensures that pedestrians can find the most direct and safe routes to their destinations, enhancing the overall walking experience.
- Landmarks: Additionally, recognizable features such as statues, distinctive buildings, or natural elements assist with orientation and make walking more engaging [6]. Landmarks serve as visual cues that help pedestrians remember routes and feel more confident while navigating the urban environment.

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2.1.10. Social Environment

- Active Public Spaces: The presence of other pedestrians, street vendors, and public events fosters a sense of community [6,18]. Social interactions can enhance the attractiveness of walking, making it a more enjoyable and sociable activity.
- Cultural Vibrancy: Moreover, diversity of cultural and social activities enriches the walking environment [6]. Cultural events and diverse neighborhoods provide unique experiences that encourage exploration on foot.

2.1.11. Maintenance and Cleanliness

- Infrastructure Upkeep: Regular maintenance of sidewalks, lighting, and street furniture prevents deterioration and potential hazards [16]. Well-maintained infrastructure not only ensures safety but also signals that an area is cared for, which can encourage more people to walk.
- Litter Control: Similarly, clean streets and public spaces enhance the aesthetic appeal of the environment and reflect community pride [1]. Effective litter control improves pedestrians' perceptions of safety and comfort, making walking a more pleasant activity.

2.1.12. Pedestrian Amenities

- Rest Areas: Benches, water fountains, and shelters provide comfort during walks [15]. These amenities allow pedestrians to rest and refresh themselves, extending the distance and duration people are willing to walk.
- Public Restrooms: In addition, the availability of clean and accessible public restrooms supports longer walking trips and increases the convenience of walking as a mode of transportation [4]. This is especially important for families with children, the elderly, and individuals with medical conditions.

2.1.13. Weather Protection

- Shade and Shelter: Trees, awnings, and covered walkways protect pedestrians from sun and rain. Providing weather protection enhances comfort and encourages more frequent walking, regardless of weather conditions.
- Snow and Ice Removal: Similarly, in colder climates, timely clearing of pathways from snow and ice ensures year-round walkability. Proper maintenance during winter months prevents slips and falls, maintaining safe pedestrian access throughout the year.

Table 1. Reference-Based Mapping of Key Walkability Components.

Reference(s)	Year	Key Components Mapped
Southworth [1]	2005	Residential Density, Street Connectivity, Human-Scale Architecture, Green Spaces, Litter Control
Ewing and Cervero [14]	2010	Residential Density, Employment Density, Mixed-Use Development, Street Connectivity, Proximity to Public Transportation
Frank et al. [5]	2006	Mixed-Use Development, Air Quality
Walk Score [15]	2024	Access to Amenities, Rest Areas
Brownson et al. [16]	2009	Sidewalk Quality, Infrastructure Upkeep, Snow and Ice Removal
Welle et al. [17]	2015	Traffic Safety
Loukaitou-Sideris [18]	2006	Personal Security, Active Public Spaces, Cultural Vibrancy
NACTO [19]	2016	Universal Design
Boodlal [20]	2003	Barrier-Free Routes
Sundling and Jakobsson [21]	2023	Noise Levels
Reiss and Tchetchik [22]	2024	Terrain

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Wood et al. [6]	2010	Aesthetic Appeal, Landmarks, Active Public Spaces, Cultural Vibrancy
Tobin et al. [4]	2022	Public Restrooms

Evaluating walkability is a multifaceted process that considers physical infrastructure, environmental factors, social dynamics, and policy frameworks. By understanding and enhancing these key components, urban planners and policymakers can create environments that encourage walking, leading to numerous health, environmental, and social benefits.

2.2. Frameworks and Theoretical Models for Evaluating Walkability

To systematically assess and enhance walkability, researchers and practitioners have developed several frameworks that encapsulate the multifaceted nature of the pedestrian experience. These frameworks are supported by theoretical models, which offer a deeper understanding of the dimensions that contribute to walkability, ranging from physical infrastructure to social and environmental factors. Together, they provide comprehensive tools for creating and maintaining pedestrian-friendly environments, addressing both the tangible aspects of urban design and the subjective experiences of pedestrians.

2.2.1. The "5 D's" of the Built Environment

Ewing and Cervero [14] introduced the "5 D's" framework, encompassing:

1) Density: High concentrations of population and employment increase the likelihood of walking by reducing distances between origins and destinations.
2) Diversity: A mix of land uses (residential, commercial, recreational) promotes walking by offering various destinations within close proximity.
3) Design: Pedestrian-friendly Street networks with connected sidewalks and safe crossings facilitate ease of movement.
4) Destination Accessibility: The availability and accessibility of key destinations encourage walking for different purposes.
5) Distance to Transit: Close proximity to public transit stops enhances walkability by integrating walking with other modes of transportation.

This framework provides a comprehensive approach to understanding how different urban form factors influence walking behavior and has been instrumental in guiding urban design and policy interventions aimed at promoting walkability.

However, although the "5 D's" framework is comprehensive, it primarily focuses on physical attributes and may not fully capture social or perceptual factors influencing walkability. Elements such as personal safety perceptions, cultural influences, and social cohesion are not explicitly addressed, which can be significant determinants of walking behavior.

2.2.2. Jan Gehl's Model of Public Spaces

Jan Gehl, a Danish architect and urban design consultant, is renowned for his human-centered approach to urban design. Gehl's model emphasizes the importance of designing public spaces that prioritize human scale and interaction. According to Gehl, walkability is enhanced when urban environments are designed to encourage social interaction, comfort, and safety [23]. His principles focus on creating inviting and engaging public spaces that foster pedestrian activity through thoughtful design of streetscapes, plazas, and other communal areas. Gehl advocates for wider sidewalks, pedestrian zones, and slower vehicle traffic to make cities more walkable and safer for pedestrians. By focusing on the human experience, Gehl's model addresses not only the physical but also the social and psychological aspects of walkability.

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2.2.3. Ten Principles for Building Healthy Places (ULI Walkability Framework)

Developed by the Urban Land Institute (ULI), the Walkability Framework identifies key factors that make neighborhoods walkable, including connectivity, density, mixed use, and street design[24] . Eitler et al. (2013) outline ten principles for building healthy places, emphasizing the need for interconnected street networks that reduce walking distances and enhance accessibility. The framework also highlights the importance of density and mixed land uses in creating vibrant, walkable communities. By integrating health into urban design and land use planning, this framework underscores how good design can promote physical activity, reduce stress, and improve overall quality of life.

2.2.4. Path Walkability Assessment (PWA) Index Model

The Path Walkability Assessment (PWA) Index Model evaluates neighborhood walkability using decision-tree-making (DTM) methodology. Developed by Keyvanfar et al. (2018) [25], it focuses on well-designed walkable routes and incorporates a wide range of walkability variables like safety, connectivity, comfort, and aesthetic appeal. The PWA model considers various layers of walkability, including features such as sense of safety and security, connectivity, comfort, convenience, and aesthetic appeal. It helps urban designers by offering a decision support tool to adapt neighborhood environments to pedestrians' needs and preferences. By translating qualitative pedestrian perceptions into quantifiable data, the PWA model enables designers to prioritize variables that enhance walkability.

2.2.5. Data-Driven Framework Using Open Data

This framework utilizes open data sources, like GIS and public databases, to compute walkability indexes. Deng et al. (2020) [26] present a data-driven framework for walkability measurement using open data, offering a high level of precision by generating synthetic walkability indices. The model incorporates a range of variables, including points of interest, land use mix, density, street connectivity, and topography. It is particularly useful for smaller cities or regions where traditional indices like Walk Score are not available. The framework can be applied across various cities, providing a more comprehensive and adaptable model for urban environments aiming to promote walking as a sustainable mode of transportation.

2.2.6. Walk Score

Walk Score is a widely used tool that measures the walkability of a specific address by calculating the distance to nearby amenities across various categories such as groceries, schools, parks, and entertainment [15]. It assigns a numerical score from 0 to 100, helping residents and planners assess and compare walkability across different areas. The higher the score, the more walkable the location is considered. Walk Score has been utilized in numerous studies to correlate walkability with health outcomes, real estate values, and transportation choices. Nevertheless, Walk Score is primarily available for addresses in the United States, Canada, and a limited number of other countries. This geographical limitation restricts its applicability for global walkability assessments. Additionally, Walk Score may not account for subjective factors such as street safety or sidewalk quality, focusing mainly on the proximity to amenities.

2.3. Methods of Assessing Walkability

Assessing walkability requires a combination of qualitative and quantitative methods to capture both the objective characteristics of the environment and the subjective experiences of pedestrians.

2.3.1. Qualitative Methods

- Walkability Audits: Tools like the Pedestrian Environment Data Scan (PEDS), involve trained observers systematically evaluating physical features like sidewalk conditions, street crossings, and aesthetics [27]. These audits provide detailed insights into the pedestrian experience at the street level.

- Pedestrian Surveys: Collect subjective data on individuals' perceptions of the walking environment, including factors like safety, comfort, and social interactions [28]. Such surveys can reveal barriers to walking that are not immediately apparent through objective assessments.

These methods provide valuable insights into user experiences but may lack spatial precision and scalability for detailed urban planning.

2.3.2. Quantitative Methods

- Geographic Information Systems (GIS): GIS allows for objective assessment by analyzing spatial data related to street connectivity, land use, and pedestrian infrastructure [3] thereby facilitating the creation of walkability indices derived from GIS data enable comparisons across different areas, which is crucial in understanding and improving urban walkability. GIS-based analyses can map walkability scores across regions, identify walkability deserts, and support data-driven interventions.
- Walkability Indices: Various indices quantify walkability based on measurable environmental factors. For instance, Ewing and Cervero's 5D model considers density, diversity, design, distance to transit, and destination accessibility [14], while the Walk Score methodology assigns scores based on proximity to amenities [15].
- Pedestrian Environment Index (PEI): Peiravian et al. (2014) [29] developed the Pedestrian Environment Index (PEI), a comprehensive metric evaluating urban areas' pedestrian friendliness based on four components: land-use diversity, population density, commercial density, and intersection density. Unlike additive indices, the PEI uses a multiplicative formula, allowing for interaction between factors and offering a more nuanced assessment.
    - o Advantages of PEI: The PEI utilizes commonly available data, making it practical for urban planners and policymakers. Its region-specific nature enables comparisons within a city or region, providing detailed insights for targeted interventions.
    - o Comparison with Other Indices: While Walk Score focuses primarily on the proximity to amenities and may not account for factors like street layout or land-use diversity, the PEI addresses these limitations by incorporating multiple variables that influence walkability.
    - o Application Example: In their study, Peiravian et al. applied the PEI to Chicago, revealing that areas with high land-use diversity and intersection density were more pedestrian-friendly. This case study demonstrates the PEI's utility in identifying areas that need improvement.

As illustrated in Figure 2, these indices offer spatial representations of walkability components. Quantitative methods like GIS analyses and walkability indices, including the PEI, provide objective metrics essential for evaluating and comparing walkability across different urban environments. While these tools support evidence-based planning and can inform policies aimed at enhancing pedestrian infrastructure, they may not fully capture the nuanced human experiences of walking.

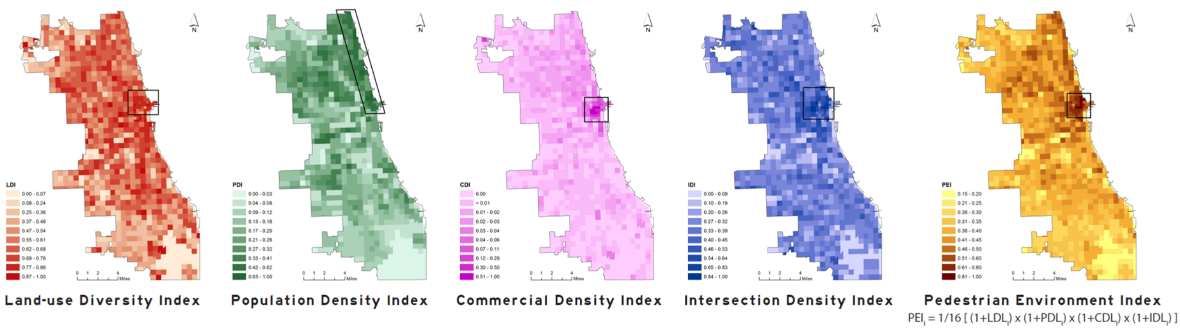

Figure 2. Spatial distributions of different indices: Land-use diversity index (LDI), Population density index (PDI), Commercial density index (CDI), Intersection density index (IDI) and the Pedestrian Environment Index (PEI). [29].

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2.3.3. Mixed-Methods Approaches

Combining quantitative and qualitative methods can provide a more comprehensive assessment of walkability. For example, GIS-based models can be used to identify areas with low walkability, which can then be further investigated through pedestrian surveys or focus groups to understand the underlying issues. This mixed-methods approach allows for both objective measurement and subjective evaluation, providing a fuller picture of walkability in urban environments. By integrating statistical data with human experiences, planners can develop more effective interventions tailored to community needs.

2.3.4. Agent-Based Modeling (ABM)

Agent-Based Modeling (ABM) has emerged as a powerful tool that combines elements of both qualitative and quantitative methods for assessing walkability:

- Simulation of Individual Agents: ABM simulates individual agents with specific behaviors and preferences within a virtual environment, allowing researchers to observe emergent patterns of pedestrian movement [30].
- Evaluation of Urban Design Scenarios: By adjusting variables such as infrastructure changes or policy interventions, ABM can predict how these factors might influence walking behaviors. Furthermore, ABM enables the testing of various urban design interventions and their potential impact on walkability, helping planners understand how different land use configurations and environmental factors affect pedestrian movement [3,31].

Agent-Based Modeling (ABM) offers a powerful and versatile platform for understanding and enhancing walkability by simulating pedestrian behaviors and testing urban design interventions. Through the integration of technologies such as Geographic Information Systems (GIS) and real-time data collection, ABM's potential for urban planning is further amplified, making it a valuable tool for researchers and policymakers. ABM enables the simulation of different urban design scenarios, such as the impact of pedestrian crossings or sidewalk expansions, providing detailed insights into pedestrian movement and behavior patterns.

When combined with theoretical models like the 5D framework, which emphasizes aspects such as density and diversity, and Jan Gehl's focus on human-scale design and social interaction, ABM offers a holistic and dynamic understanding of walkability. This integration allows urban planners to develop strategies that not only improve the physical infrastructure of cities but also create spaces that are functional, inclusive, and socially engaging. By incorporating data from GIS analyses and qualitative assessments, ABM supports evidence-based planning, leading to more informed policy decisions that enhance walkability in urban environments.

2.4. Advances in Technology for Enhancing Walkability

Recent technological advancements have introduced innovative methods for enhancing walkability.

2.4.1. Smart City Technologies

- Objective Assessment Tools: Smart city technologies, particularly geospatial tools like GIS, are used to objectively assess walkable environments. Geospatial Information Systems (GIS), combined with spatial network analysis and open data, are increasingly employed to analyze street connectivity, land use, and pedestrian infrastructure. These tools allow for data-driven urban planning and walkability assessments by leveraging large datasets from sources such as satellite imagery and sensors [32,33].
- Real-Time Data Collection: In addition to assessment tools, real-time data collection plays a crucial role. The integration of Internet of Things (IoT) devices and sensors provides real-time data on pedestrian flows, traffic patterns, and environmental conditions. This data enhances urban mobility management by allowing cities to monitor and optimize walking routes, manage

public transportation systems, and improve urban infrastructure, thereby creating safer, more efficient pedestrian environments [34,35].

2.4.2. Machine Learning and Big Data

Machine learning and big data are transforming walkability assessments through advanced analytical techniques.

- Predictive Modeling: Alfosool et al. (2022) [36] developed a predictive network-based walkability scoring system using machine learning frameworks. This research applies machine learning frameworks to generate walkability scores based on urban features extracted from high-resolution spatial data, including road networks and points of interest.
- Data Analytics: In Yin and Wang (2016) [37], machine learning and big data analytics, especially Google Street View imagery, are applied to measure urban design qualities at a large scale. This method allows the identification of patterns and factors influencing walkability, supporting data-driven decision-making through objective metrics.

2.4.3. Mobile and Wearable Technologies

- GPS Tracking: Research shows that smartphone GPS, combined with accelerometer data, can effectively track walking behaviors and environmental exposures like air pollution. For instance, studies have used this technology to analyze real-time data on pedestrian movements and correlate them with air pollution levels, providing insights into how environmental factors impact health. Studies by Yi et al. (2024) [38] and Park et al. (2023) [39] demonstrate how GPS-enabled technology can offer a detailed view of personal exposure across various microenvironments.
- Wearable Devices: Similarly, wearable devices offer additional insights into pedestrian behaviors. Singleton (2019) [40] examined how walking influences commuters' subjective well-being using data from wearable devices, revealing that active modes of transport like walking are associated with higher levels of happiness and reduced stress compared to passive modes. The study highlighted how walking commutes contribute to both physical health and emotional satisfaction, showing strong links between pedestrian activity and overall well-being.

Collectively, these technologies enhance the precision and scope of walkability assessments, allowing for personalized and context-specific insights.

3. Applying the MABAC Method to Evaluate Walkability

3.1. Overview of the MABAC Method

The Multi-Attributive Border Approximation Area Comparison (MABAC) method is a relatively recent addition to multi-criteria decision-making (MCDM) tools, developed at the University of Defence in Belgrade by Pamučar and Ćirović in 2015 [41]. It is designed to handle complex decision-making tasks by ranking alternatives based on their proximity to an ideal "border approximation area." The MABAC method stands out for its:

- Ability: It can handle both quantitative and qualitative criteria.
- Stability and Consistency: It maintains stable results even when criteria or measurement units change.
- Simplicity: It involves straightforward mathematical procedures.
- Versatility: It can handle both profit and cost criteria effectively.
- Integration with Other Methods: It is compatible with other approaches, enhancing its applicability.

3.2. Previous Applications of MABAC

MABAC has been successfully applied in various fields, including logistics, transportation, and urban planning. Notably, Nooraie et al. (2023) [42] used MABAC to assess cycling routes in Isfahan

City, Iran. Their study demonstrated the method's effectiveness in evaluating movement and accessibility indicators, resulting in a prioritized list of cycling routes based on desirability.

3.3. Applicability to Walkability Assessment

Given the similarities between cycling route assessment and walkability evaluation, the MABAC method can be adapted to assess walkability in urban environments. The method's advantages include:

- Handling Multiple Criteria: Captures the multifaceted nature of walkability by considering various factors.
- Integration of Data: Combines quantitative measurements with qualitative perceptions.
- Robustness: Provides consistent rankings even when adjusting criteria weights or data scales.
- Decision Support: Assists urban planners in identifying priority areas and formulating improvement strategies.

3.4. Proposed Methodology

To apply the MABAC method in evaluating walkability, we propose the following steps:

3.4.1. Criteria Selection

Based on the key components of walkability identified in Section 2, we can select relevant criteria grouped under the following categories:

- Physical Infrastructure:
  - Sidewalk Width and Condition: Adequate width and well-maintained surfaces facilitate comfortable walking.
  - Street Connectivity: A well-connected street network reduces distances and provides multiple route options.
  - Crosswalks and Pedestrian Signals: Availability and quality enhance safety at intersections.
- Safety and Security:
  - Traffic Volume and Speed: Lower volumes and speeds reduce the risk of accidents.
  - Street Lighting: Adequate lighting improves visibility and personal security.
  - Crime Rates: Lower crime rates increase pedestrians' sense of safety.
- Accessibility:
  - Proximity to Amenities: Close access to shops, parks, schools, and services encourages walking.
  - Access to Public Transportation: Nearby transit stops extend the range of walking trips.
- Environmental Quality:
  - Air Quality: Clean air promotes health and comfort.
  - Noise Levels: Lower noise pollution enhances the walking experience.
  - Presence of Green Spaces: Parks and trees provide aesthetic and health benefits.
- Social Environment:
  - Pedestrian Density: Active street life fosters a sense of community.
  - Cultural Vibrancy: Diversity of activities enriches the environment.
  - Inclusivity: Universal design features accommodate all users.
- Maintenance and Cleanliness:
  - Cleanliness of Public Spaces: Well-kept areas are more inviting.
  - Infrastructure Upkeep: Regular maintenance prevents deterioration.
- Weather Protection:
  - Shelters and Shaded Areas: Protect pedestrians from sun and rain.

3.4.2. Criteria Weighting

We can use the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to assign weights to each criterion:

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- Expert Consultation: Engage urban planners, local authorities, and community representatives to evaluate the influence and interrelationships among criteria.
- DEMATEL Analysis: Model the causal relationships, resulting in a structured weighting scheme that reflects the relative importance of each criterion.

3.4.3. Data Collection

- Quantitative Data:
  - GIS Databases: Obtain spatial data on street networks, land use, and infrastructure.
  - Urban Infrastructure Records: Access information on sidewalk conditions, lighting, and maintenance schedules.
  - Environmental Measurements: Gather data on air and noise pollution from monitoring stations.
- Qualitative Data:
  - Pedestrian Surveys: Conduct surveys to capture perceptions of safety, comfort, aesthetics, and social interactions.
  - Focus Groups: Hold discussions with community members to gain deeper insights.

3.4.4. Construction of the Decision Matrix

- Compile the collected data into a matrix where each row represents an alternative (e.g., different neighborhoods or routes), and each column represents a criterion.
- Ensure that all relevant data are accurately represented.

3.4.5. Normalization of Data

- Normalize the data to make criteria comparable:
  - Beneficial Criteria: For criteria where higher values are better (e.g., sidewalk width), use linear normalization.
  - Non-Beneficial Criteria: For criteria where lower values are better (e.g., crime rates), adjust the normalization accordingly.

The normalization formula for beneficial criteria:

$$R_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}$$

For non-beneficial criteria:

$$R_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}}$$

Where:
R_{ij} is the normalized value.
X_{ij} is the original value.
X_{max} and X_{min} are the maximum and minimum values of criterion j.

3.4.6. Calculation of the Border Approximation Area (BAA)

Calculate the average normalized value for each criterion across all alternatives:

$$G_j = \frac{1}{m}\sum_{i=1}^{m} R_{ij}$$

Where:
G_j is the BAA for criterion j.
m is the number of alternatives.

3.4.7. Distance Measures and MABAC Score Calculation

Compute the distance between each alternative and the BAA for each criterion:

$$Q_{ij} = R_{ij} - G_j$$

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Sum these distances to obtain the MABAC score for each alternative:

$$S_i = \sum_{j=1}^{n} Q_{ij}$$

Where:
S_i is the MABAC score for alternative i.
n is the number of criteria.

3.4.8. Ranking of Alternatives

- Rank the alternatives based on their MABAC scores.
    - A higher S_i indicates closer proximity to the ideal solution and, therefore, higher walkability.
- Prepare a ranked list from the highest to the lowest score.

3.4.9. Analysis and Interpretation

- High-Scoring Areas: Identify neighborhoods with high walkability scores. Analyze the factors contributing to their success.
- Low-Scoring Areas: Identify areas with low scores. Investigate the criteria where they perform poorly.
- Comparative Analysis: Compare areas to understand disparities and common issues.

3.4.10. Validation and Sensitivity Analysis

- Sensitivity Analysis: Test the robustness of the results by varying criteria weights and observing changes in rankings.
- Validation: Cross-validate findings with real-world observations and feedback from stakeholders.

3.5. Integration with Agent-Based Modeling

The MABAC evaluation results enhance the Agent-Based Modeling (ABM) simulations:

- Identifying Focus Areas: Select specific neighborhoods for detailed simulation based on their walkability scores.
- Parameter Calibration: Use data on pedestrian preferences and behaviors to set realistic parameters in the ABM.
- Scenario Testing: Simulate the impact of proposed interventions (e.g., infrastructure improvements) on pedestrian flows and walkability scores.
- Model Validation: Compare ABM outputs with actual pedestrian movement patterns and MABAC rankings to validate the model's accuracy.

3.6. Advantages of Using MABAC in Walkability Assessment

- Comprehensive Evaluation: Accommodates a wide range of criteria, providing a holistic assessment.
- Objective and Subjective Data Integration: Merges quantitative data with qualitative insights.
- Robustness and Reliability: Maintains consistent results under varying conditions.
- Practical Applicability: Offers clear rankings that can inform policy decisions and prioritize interventions.

The MABAC method offers a robust and comprehensive approach to evaluating walkability. By integrating this method into this study, we can enhance the assessment's accuracy and provide valuable insights for urban planning and policy-making. Combined with Agent-Based Modeling, this approach enables us to simulate the effects of different urban design scenarios on pedestrian behaviors, supporting evidence-based decision-making aimed at improving walkability.

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4. Agent-Based Modeling in Walkability Studies

Agent-Based Modeling (ABM) has emerged as a powerful tool in walkability studies, offering insights into how micro-level behaviors of individual agents (pedestrians) influence macro-level outcomes in urban environments. By simulating the interactions between pedestrians and their environment, ABM allows researchers and urban planners to explore the complex dynamics of pedestrian movement and assess the impact of various urban design interventions on walkability.

4.1. Simulation of Pedestrian Behaviors

ABM enables detailed simulation of pedestrian behaviors by representing each pedestrian as an autonomous agent with specific characteristics and decision-making processes. This approach allows for the modeling of heterogeneous populations and the emergence of complex patterns from simple behavioral rules.

4.1.1. Incorporation of Social and Physical Factors

ABM allows for the integration of both social and physical factors that influence pedestrian behaviors:

- Social Influences: Agents can be programmed to consider social norms, peer influences, and collective behaviors. For example, Yang and Diez-Roux [30] developed an ABM to simulate children's active travel to school, incorporating social influences such as parental attitudes, peer behaviors, and community norms. Their model demonstrated how social factors can significantly impact children's likelihood to walk or bike to school.
- Environmental Barriers: Physical barriers such as busy roads, lack of sidewalks, or unsafe crossings can be modeled to assess their impact on pedestrian movement. By simulating agents' responses to these barriers, ABM can identify critical impediments to walkability.
- Individual Preferences: Agents can have individual preferences and constraints, such as walking speed, route choice preferences, or sensitivity to environmental conditions. This heterogeneity allows for more realistic simulations of pedestrian behaviors.

4.1.2. Modeling Decision-Making Processes

ABM facilitates the simulation of pedestrian decision-making processes by incorporating variables such as:

- Route Choice: Agents can evaluate different routes based on factors like distance, safety, attractiveness, or effort. This enables the analysis of how changes in the environment affect route selection.
- Destination Selection: Agents can choose destinations based on accessibility, personal needs, or attractiveness, allowing the simulation of pedestrian flows to various urban amenities.
- Response to Environmental Stimuli: Agents can react to dynamic environmental factors such as traffic congestion, crowding, or weather conditions. This dynamic interaction enhances the model's ability to simulate real-world scenarios.

For instance, Liu et al. [3] used ABM to model pedestrian decision-making processes in urban environments, considering factors like street connectivity, land use diversity, and environmental aesthetics. Their study demonstrated how individual decisions aggregate to influence overall walkability.

4.2. Evaluation of Urban Design Scenarios

ABM provides a versatile platform for evaluating different urban design scenarios and their impact on walkability.

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4.2.1. Testing Design Interventions

By simulating pedestrian behaviors under various design interventions, ABM helps urban planners understand the potential effects of proposed changes:

- Land Use Changes: López Baeza et al. [31] utilized ABM to model pedestrian flows under different land use distributions. Their study assessed how changes in land use patterns, such as increasing residential density or introducing mixed-use developments, influence pedestrian movement and walkability.
- Infrastructure Modifications: ABM can simulate the impact of adding sidewalks, pedestrian crossings, or traffic calming measures on pedestrian safety and movement. For example, Welle et al. [17] demonstrated how implementing traffic calming interventions can reduce vehicle speeds and enhance pedestrian safety, which can be modeled effectively using ABM.

4.2.2. Scenario Analysis and Policy Testing

ABM allows for the testing of policy interventions and urban planning strategies:

- Pedestrianization: Simulating the effects of pedestrianizing streets or zones on pedestrian flows and local businesses.
- Public Transportation Integration: Assessing how improvements in public transit accessibility influence walking behaviors and modal shifts.
- Emergency Evacuation Planning: Modeling pedestrian behaviors during emergency situations to improve evacuation routes and safety measures.

4.3. Integration with Other Technologies

The effectiveness of ABM in walkability studies can be further enhanced by integrating it with other technologies and data sources.

4.3.1. Combining ABM with Geographic Information Systems (GIS)

Integrating ABM with GIS provides spatial accuracy and enhances the environmental representation within simulations:

- Spatial Data Integration: GIS provides detailed spatial data on urban infrastructure, land use, and environmental features, which can be incorporated into the ABM environment.
- Accurate Environmental Representation: By mapping agents' movements onto real-world geographies, simulations become more realistic and relevant for urban planning.

Liu et al. [3] integrated ABM with GIS to assess walkability in urban areas, demonstrating improved reliability in simulations due to accurate spatial representation.

4.3.2. Incorporation of Real-Time Data

Using real-time data from sensors and mobile devices enhances the accuracy and timeliness of ABM simulations:

- Dynamic Data Inputs: Real-time data on pedestrian counts, traffic conditions, or environmental factors can be fed into the model to reflect current conditions.
- Adaptive Simulations: Models can adjust to changing conditions, allowing for scenario planning and real-time decision support.

Incorporation of Real-Time Data is crucial for enhancing the accuracy of pedestrian movement simulations in urban environments.

- For instance, incorporating data from mobile GPS devices to track pedestrian movement patterns and update simulations accordingly has proven effective. [43] The study conducted at the University of Moratuwa utilized mobile GPS signals and machine learning algorithms to monitor pedestrian behavior, classifying walking speeds, directions, and times. This real-time

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data enabled urban planners to optimize pedestrian-friendly routes by identifying areas of high foot traffic and improving infrastructure.
- Similarly, Antonio Natale [35] discusses the importance of GIS in smart cities, emphasizing how real-time sensor data and geospatial analysis go beyond simple data pinning. Natale demonstrates that integrating real-time data from IoT platforms like FIWARE can help urban planners visualize pedestrian movement more comprehensively, offering insights into mobility dynamics and supporting informed decision-making.

Both studies highlight how real-time data can transform pedestrian simulations, contributing to more walkable and efficient urban environments.

4.4. Advantages and Limitations of ABM

Advantages:
- Dynamic Simulations: ABM captures the dynamic and emergent nature of pedestrian movements and interactions, allowing for the observation of complex system behaviors.
- Scalability: Models can be scaled from small neighborhoods to entire cities, making ABM suitable for various levels of urban planning.
- Customization: Agents can be programmed with specific characteristics, preferences, and behaviors, enabling tailored simulations that reflect diverse populations.
- Policy Testing: ABM allows for the safe and cost-effective testing of urban planning interventions before implementation.

Limitations:
- Data Requirements: ABM requires detailed data on agent behaviors, environmental conditions, and urban infrastructure, which may be difficult to obtain or validate.
- Computational Complexity: Large-scale simulations with numerous agents can be computationally intensive and require significant processing power.
- Validation Challenges: Ensuring that the model accurately represents real-world behaviors and outcomes can be challenging due to the complexity of human behavior and environmental interactions.
- Model Uncertainty: Simplifications and assumptions necessary for modeling can introduce uncertainties in the results.

4.5. Future Directions and Opportunities

ABM in walkability studies presents opportunities for further research and development:
- Enhanced Behavioral Models: Incorporating psychological and sociological theories to improve the realism of agent behaviors
- Interdisciplinary Approaches: Collaborating with experts in urban planning, transportation engineering, environmental science, and social sciences to enrich the models.
- Participatory Modeling: Engaging stakeholders and the public in the modeling process to incorporate local knowledge and preferences.
- Integration with Virtual Reality (VR): Using VR to visualize simulation outcomes and enhance stakeholder understanding of proposed interventions.

In summary, Agent-Based Modeling offers a powerful approach to understanding and enhancing walkability through the simulation of pedestrian behaviors and the testing of urban design scenarios. By capturing the complex interactions between individuals and their environment, ABM provides valuable insights into how urban design and policy interventions can influence pedestrian movement and walkability. When integrated with other technologies, such as GIS, real-time data collection, and machine learning, ABM's potential is further amplified, making it an invaluable tool for urban planners and researchers aiming to create more walkable and livable cities.

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5. Case Studies

5.1. Walk Score Method and Related Research

Introduction:

Walk Score [15] has become a widely accepted tool for assessing walkability in urban areas by measuring proximity to essential amenities. While its main strength lies in its simplicity and accessibility for users and researchers alike, it has limitations that require careful consideration. This section explores various studies that have tested the validity and applicability of Walk Score across different regions and urban environments. By analyzing its strengths and weaknesses, these studies provide insight into how Walk Score contributes to understanding walkability and where it might fall short, particularly in accounting for nuanced factors like street safety and environmental quality.

Methodology:

Walk Score calculates walkability by evaluating the shortest distance from a given address to a group of preselected amenities, factoring in block length and street connectivity. The final score is a composite measure of how easy it is to reach essential destinations on foot. Studies often compare Walk Score data with objective measures from Geographic Information Systems (GIS) and subjective perceptions gathered through surveys. Research has examined correlations between Walk Score and other variables like street connectivity, residential density, and crime rates to test the method's reliability across different urban settings.

Findings:

5.1.1. Walk Score™ as a Neighborhood Walkability Estimate

This study [44] compared Walk Score to objective GIS measures (street connectivity, residential density, public transit access) and subjective perceptions of walkability. Results showed strong correlations between Walk Score and objective measures, validating its use as a proxy for neighborhood walkability. However, positive associations with crime rates were also noted, highlighting potential limitations in urban safety considerations.

5.1.2. Critical and Systematic Review of Walk Score in Active Transport

A systematic review [45] of 42 journal articles revealed inconsistencies in Walk Score usage, with many studies supplementing it with other measures to capture walkability's multifaceted nature. Walk Score was primarily used to assess "walking potential" based on environmental density rather than walkability in a holistic sense.

5.1.3. Japan: Validity of Walk Score®

The study [46] validated Walk Score's accuracy in estimating walkability in Japan, where GIS-derived environmental factors (intersection density, local destinations, residential density) closely correlated with Walk Scores. This confirmed its adaptability beyond North America, although limitations were acknowledged due to a lack of data on sidewalk availability and street conditions.

5.1.4. Rhode Island: Walk Score Validation for Access to Walkable Amenities

GIS was used to objectively measure access to 13 amenity categories, revealing significant correlations with Walk Score. The study [47] demonstrated that Walk Score is a reliable proxy for estimating access to amenities, with test-retest reliability yielding perfect scores (1.0).

5.1.5. Elderly: Spatial Patterns of Walkability and Walk Score

In this study [48], a modified version of Walk Score was created for elderly populations, adapting the measure by considering gait speed and specific needs for nearby services. It revealed that 40% of elderly residents in two Czech cities lived in areas with unsatisfactory walkability, showcasing the tool's flexibility in being adjusted for different populations.

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Lessons Learned:

- Applicability Across Geographies: Walk Score has been validated across various regions, including the U.S., Canada, Japan, and Europe, proving to be a reliable estimate of walkability based on proximity to amenities. However, it is less effective in accounting for local factors like street quality or crime rates.
- Limitations in Subjective Measures: While Walk Score is an efficient tool for calculating amenity-based walkability, it fails to include subjective factors like safety, security, and environmental comfort, which are critical for understanding pedestrian experiences.
- Adaptability for Specific Populations: The modification of Walk Score to better assess elderly needs demonstrates the tool's potential for adaptation. This indicates that Walk Score can be refined to serve specific demographic groups or urban contexts better.
- Supplementing with Other Measures: Research consistently shows that Walk Score needs to be supplemented with other quantitative and qualitative methods, such as GIS analyses or pedestrian surveys, to comprehensively assess walkability in diverse settings.

5.2. Walkability and Environmental Benefits

5.2.1. Seoul: Implementing Walkability to Promote Environmental Benefits

Introduction:

Seoul has adopted a comprehensive walkability evaluation system [11] as part of its urban strategy to reduce environmental impact and foster sustainable transportation. Inspired by concepts like the "15-minute City" in Paris, Seoul seeks to create pedestrian-friendly zones that reduce reliance on cars, decrease carbon emissions, and encourage healthier, more sustainable modes of transport.

Methodology:

The methodology relies on the Betweenness Index, a metric that identifies key nodes in the city's transportation network where pedestrian activity is most likely to be concentrated. These nodes—known as mobility stations or hubs—are strategically placed transit centers designed to facilitate "last mile" connections, allowing citizens to transition from public transportation (such as buses, trains, or metro systems) to walking or biking for the remainder of their journey. Mobility hubs are equipped with amenities such as bike-sharing stations, pedestrian pathways, and accessible transport options that enhance connectivity within the urban fabric.

Findings:

The evaluation system revealed that focusing on high-betweenness areas where mobility hubs could be implemented significantly improves the efficiency of Seoul's transit system. By positioning these hubs in areas with the highest pedestrian potential, the city can optimize its public transport network, reduce traffic congestion, and increase the share of trips made by foot or bike. This strategy promotes environmental sustainability by decreasing carbon emissions and reducing the need for motorized transport in densely populated areas.

Lessons Learned:

Seoul's experience demonstrates that walkability improvements require a holistic approach that integrates pedestrian-friendly infrastructure with mobility hubs. These hubs are crucial for linking public transport to pedestrian traffic and play a central role in fostering sustainable urban environments. The findings underscore that well-placed mobility hubs not only enhance walkability but also provide significant environmental benefits by reducing car dependency and encouraging greener modes of travel.

5.3. Multi-Criteria Decision-Making in Walkability

5.3.1. Lisbon: Evaluating Walkability Using MCDA

Introduction:

Lisbon's urban planning framework [12] has increasingly prioritized walkability as a means of creating healthier, more sustainable cities. This case study evaluates the walkability of streets in

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Lisbon using a Multi-Criteria Decision-Making (MCDM) approach. By incorporating various factors such as street connectivity and pedestrian comfort, this method allows for a thorough assessment of how well the urban environment supports walking.

Methodology:

The study uses the PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations) method within the MCDM framework. It assesses streets based on five key walkability criteria: connectivity, convenience, comfortability, conviviality, and conspicuousness. Data were gathered through GIS, on-site observations, and municipal databases. Streets were then ranked based on their performance across these dimensions, offering a structured and replicable approach to walkability evaluation.

Relation to MABAC Method:

The MABAC [41,42] (Multi-Attributive Border Approximation Area Comparison) method, as discussed, also belongs to the family of Multi-Criteria Decision-Making tools. Both MABAC and PROMETHEE share common goals in evaluating complex urban features by comparing alternatives across multiple criteria. However, MABAC stands out for its ability to handle both qualitative and quantitative data in evaluating walkability, making it particularly robust for urban planning tasks that require both numerical precision and subjective assessment.

While the Lisbon case study uses PROMETHEE, the MABAC method could complement this by incorporating more subjective perceptions, such as pedestrian safety or aesthetic appeal, into the evaluation process. MABAC's ability to rank walkability alternatives based on their proximity to an ideal solution would enhance the decision-making process, making it more dynamic and adaptable for future urban policies. As both methods aim to evaluate urban walkability through a systematic, multi-criteria lens, they can be combined to offer a more comprehensive, data-driven understanding of pedestrian environments.

Findings:

The study found that Alameda dos Oceanos ranked highest for walkability, benefiting from wide sidewalks, pedestrian-friendly design, and proximity to public transport. In contrast, Rua de Marvila performed poorly due to inadequate pedestrian infrastructure. The MCDM approach successfully differentiated between streets with varying walkability and highlighted areas for improvement.

Lessons Learned:

The Lisbon study demonstrates the power of MCDM frameworks like PROMETHEE in evaluating walkability comprehensively. By integrating both quantitative data and qualitative factors, the methodology provides a nuanced view of urban environments. The potential application of MABAC could further enrich this approach by allowing for more flexible evaluations that integrate both subjective experiences and measurable data. This case also highlights the importance of continuous, data-driven assessments in improving urban walkability and guiding future urban planning efforts.

5.4. Geographic Information System (GIS)

5.4.1. Kraków: Measuring Walkability with GIS

Introduction:

Kraków, the second-largest city in Poland, is the focus of a new approach to measuring walkability using Geographic Information Systems (GIS) [13]. The study recognizes the need for cities to be attractive, safe, and accessible, particularly with increasing population density. To this end, GIS tools offer a way to evaluate urban walkability by analyzing pedestrian infrastructure, public transport access, and the density of key amenities.

Methodology:

The proposed walkability measurement method leverages GIS tools like Kernel Density and Line Density to calculate a synthetic walkability index. The study used open-source data, focusing on pedestrian infrastructure (paths and sidewalks) and public amenities (e.g., transport stops, parks, shops). The kernel density tool was applied to map urban objects with specific functions, while the line density tool was used to assess pedestrian infrastructure. These values were then combined to compute a synthetic index reflecting the accessibility of urban amenities via pedestrian infrastructure.

Findings:

The application of this GIS-based method revealed that the most walkable areas of Kraków were located around the Main Square in the historic Old Town, a central hub with high-density pedestrian infrastructure and access to public transport. In contrast, the city's outskirts, particularly industrial zones and suburban areas with single-family housing, had significantly lower walkability scores. These areas were less accessible to pedestrians and had fewer public amenities within walking distance.

Lessons Learned:

This study demonstrates that GIS-based analysis can effectively measure walkability in large urban areas by using spatial data to assess infrastructure and accessibility. By highlighting walkability disparities between the city center and peripheral areas, urban planners in Kraków can prioritize improvements in pedestrian infrastructure and access to amenities. The open-source, data-driven approach also proves scalable and adaptable for other cities facing similar challenges.

5.4.2. Triple Cities, New York: A Data-Driven Framework for Walkability Measurement

Introduction:

In the context of urban shrinkage and aging infrastructure, the Triple Cities (Binghamton, Johnson City, and Endicott) in New York State applied a data-driven framework to assess walkability [26]. Unlike larger urban centers, smaller cities often lack walkability indices, making this study a crucial step toward quantifying walkability in less studied, smaller urban areas.

Methodology:

The study introduced a computational framework that uses open data for walkability measurement. The framework includes three main steps: web scraping publicly available data, assigning weights to different walkability variables, and generating a synthetic walkability index. This synthetic index incorporated factors such as the availability of public transport, access to amenities, and street network connectivity. The data used in this framework was sourced from GIS systems, online databases, and local city records.

Findings:

The synthetic walkability index developed for the Triple Cities was comparable to other existing tools like Walk Score but was found to have higher sensitivity in highly walkable areas, particularly the urban core. The framework successfully identified walkable zones within the cities, with downtown Binghamton being the most walkable due to its dense urban infrastructure and accessible amenities. On the other hand, the framework revealed that suburban and rural areas in the region had much lower walkability scores, largely due to a lack of pedestrian infrastructure and access to public services.

Lessons Learned:

The data-driven framework proved to be a reliable method for assessing walkability in smaller, often overlooked urban areas. By using open data and scalable computational methods, cities like Binghamton, Johnson City, and Endicott can create informed walkability improvements. This framework can be replicated in other small- to mid-sized cities, enabling them to address walkability gaps and promote more pedestrian-friendly urban environments.

5.5. Agent-Based Modeling

5.5.1. Hamburg: Modeling Pedestrian Flows

Introduction:

In Hamburg, Germany, pedestrian activity plays a critical role in urban sustainability by affecting public health, social cohesion, and the local economy [31]. This study explores how the placement of urban amenities influences pedestrian flows in both existing and planned urban areas.

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Pedestrian activity was modeled using agent-based simulations, considering the spatial distribution of land use and floor space.

Methodology:

The study employed an agent-based model (ABM) to simulate pedestrian activity flows. The model incorporated land use floor space data, street network configurations, and urban amenities as inputs. The researchers used real-world pedestrian activity data to validate the model for existing areas while using simulated data to predict pedestrian movement in planned developments.

Findings:

The model accurately predicted pedestrian flows, with results indicating a strong correlation between pedestrian intensity and the density and diversity of urban amenities. High pedestrian activity was noted in areas with diverse land use and accessible public spaces.

Lessons Learned:

This study highlights the value of agent-based modeling in predicting pedestrian behavior based on urban land use. The insights can inform urban planning decisions, particularly in designing public spaces that promote social interaction and pedestrian activity.

5.5.2. Lisbon: Walkability for Young People in Alvalade

Introduction:

In the Alvalade neighborhood of Lisbon, Portugal, a large population of children and teenagers attends schools located in the area [49]. This study investigates the walkability of the neighborhood, focusing on daily school commutes for young people and the factors affecting their mobility.

Methodology:

An agent-based model was employed to simulate pedestrian movement, with a particular focus on the daily commutes of children and teenagers to school. The model incorporated factors such as sidewalk availability, crosswalks, proximity to schools, and the presence of other amenities in the neighborhood.

Findings:

The results indicated distinct mobility patterns among schoolchildren, influenced by the proximity of schools and pedestrian infrastructure. Safe and accessible routes were essential in encouraging walking among young people.

Lessons Learned:

Agent-based modeling provided valuable insights into the daily commuting patterns of children and teenagers. The findings can inform urban policies aimed at improving pedestrian infrastructure and promoting safe walking routes for school-aged populations.

5.5.3. Salzburg: Large-Scale Pedestrian Traffic Simulation

Introduction:

In Salzburg, Austria, pedestrian mobility is a key component of urban planning, requiring a comprehensive understanding of traffic flows at both spatial and temporal scales [50]. This study developed a large-scale agent-based model to simulate pedestrian traffic at a regional level.

Methodology:

The model incorporated decision processes such as activity type, mode, and route choices using probabilistic rules based on empirical data. The simulation covered the entire city of Salzburg, including both residents and tourists, over the course of a day. GAMA software was used for the simulation, which allowed for detailed spatial and temporal analysis of pedestrian flows.

Findings:

The model showed traffic flows concentrated in the city center and along the river, with strong correlations between the simulated and observed data. The stepwise implementation of the model's concepts improved its accuracy and reliability.

Lessons Learned:

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This case study demonstrated the effectiveness of large-scale agent-based models in simulating pedestrian mobility patterns. The model's scalability and flexibility made it a powerful tool for predicting pedestrian flows and supporting urban planning strategies.

5.5.4. Buffalo: Walkability Assessment Using ABM

Introduction:

In Buffalo, New York, understanding the dynamics of pedestrian movement is essential for promoting walkability and public health [51]. This study applied agent-based modeling to assess walkability across the city, incorporating both physical and social environmental characteristics.

Methodology:

The agent-based model simulated individual pedestrian movements based on environmental attributes such as street connectivity, land use, and proximity to services. It also considered social interactions, with pedestrians' walking choices influenced by the presence of others. The model aimed to assess macro-level walkability patterns using micro-level data.

Findings:

The results highlighted the importance of both physical infrastructure and social interactions in influencing pedestrian behavior. Walkability was higher in areas with diverse land use, accessible services, and active pedestrian environments.

Lessons Learned:

The agent-based approach provided a nuanced understanding of how built and social environments interact to shape walking behavior. This method offers a framework for urban planners to assess walkability across large areas, taking into account both environmental and social factors.

6. Gaps and Opportunities

Despite significant advancements in walkability research and practice, several gaps remain that present opportunities for further investigation and improvement. Identifying and addressing these gaps is crucial for enhancing the effectiveness of walkability initiatives and ensuring they meet the diverse needs of urban populations.

6.1. Identification of Underrepresented Aspects in Current Research

6.1.1. Socio-Economic and Demographic Factors

While considerable research has focused on the physical aspects of walkability, such as infrastructure and urban design, socio-economic and demographic factors are often underrepresented. Variables like income, age, gender, and cultural background can significantly influence walking behaviors and preferences. For instance, lower-income individuals may rely more on walking due to limited access to private vehicles, while older adults might face mobility challenges that deter them from walking. Moreover, lower-income neighborhoods may face infrastructural barriers that affect walkability differently than wealthier areas, while gender-specific safety concerns could influence women’s walking habits. However, there is a need for more nuanced studies that explore how these socio-demographic factors interact with physical environment attributes to affect walkability. Understanding these interactions can help tailor walkability improvements to diverse community needs.

6.1.2. Integration of Emerging Technologies

The role of emerging technologies in enhancing walkability has not been fully explored. These technologies present untapped potential for enhancing walkability, but their integration into urban planning and walkability research remains limited. Technologies such as smart city infrastructure, real-time data analytics, mobile applications, and wearable devices can provide dynamic and personalized information to pedestrians, enhancing their walking experience. For example, smartphone apps can offer real-time navigation and suggest optimal and safe walking routes or

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provide alerts about environmental conditions. Future research should investigate how these technologies can be integrated into walkability assessments and urban planning to create more responsive and adaptive pedestrian environments.

6.1.3. Mental Health and Well-Being Outcomes

Although the link between walkability and physical health is well-documented, less emphasis has been placed on mental health and overall well-being outcomes. Walkable environments can reduce stress, improve mood, and enhance mental well-being by facilitating social interactions, providing access to green spaces, and promoting a sense of community. More research is needed to quantify these benefits and understand how different aspects of walkability contribute to mental health. This includes examining how factors like aesthetic appeal, environmental comfort, and social cohesion influence psychological well-being.

6.1.4. Environmental Sustainability Impacts

While walkability is often promoted as a strategy for reducing environmental impacts, the specific contributions of walkable environments to broader sustainability goals require further exploration. Current research should investigate how increased walkability directly affects key environmental metrics, such as carbon emissions, air quality, and urban heat island effects. More importantly, studies should explore how walkable urban designs can optimize these benefits, for instance, by incorporating green infrastructure and sustainable transportation options to create healthier, eco-friendly cities. Understanding these impacts can help optimize urban design strategies to maximize environmental benefits.

6.1.5. Inclusive Design for Diverse Populations

Inclusive design ensures that urban environments are accessible and enjoyable for all individuals, including people with disabilities, the elderly, and young children. Unfortunately, much of the existing research on walkability tends to overlook these populations, focusing instead on the general pedestrian population. There is a pressing need for studies that specifically address the barriers these groups face, such as the availability of accessible pathways, appropriate crosswalks, and age-friendly public spaces. Urban planners and policymakers must prioritize inclusive design to create cities that are walkable for everyone, regardless of physical ability or age.

6.1.6. The Need for a Comprehensive, Global Walkability Platform

There is a pressing need for a comprehensive and universal platform for scoring walkability. Existing platforms like Walk Score offer a convenient measure of walkability but are geographically limited, covering only the U.S., Canada, and a few other regions. Additionally, Walk Score evaluates only a subset of criteria relevant to walkability, ignoring essential factors such as street quality, safety, and environmental conditions. There is a need for a more universal, adaptable platform that can provide comprehensive walkability scores for cities worldwide. This platform should integrate a broader range of variables, including socio-economic data, environmental sustainability metrics, and real-time user feedback, to offer a more holistic view of urban walkability and address this gap.

6.2. Proposals to Address These Gaps

To bridge the identified gaps, the following six well-detailed proposals are put forward:

6.2.1. Integrating Socio-Economic and Demographic Factors into Walkability Research and Planning

Addressing Gap 6.1.1

Understanding the interplay between socio-economic and demographic factors and walkability is essential for creating inclusive urban environments. This proposal involves:

- Conducting Comprehensive Studies: Implement mixed-method research combining quantitative data (e.g., GIS analysis, pedestrian counts) with qualitative insights (e.g., surveys, interviews) to explore how variables like income, age, gender, and cultural background influence walking behaviors.
- Identifying Disparities: Map and analyze walkability disparities across different neighborhoods, particularly focusing on lower-income areas and communities with diverse cultural backgrounds. This can reveal infrastructural inequities and social barriers affecting specific groups.
- Tailoring Interventions: Develop targeted strategies to enhance walkability in underserved communities. For instance, improving infrastructure in lower-income neighborhoods or addressing safety concerns that disproportionately affect women and the elderly.
- Policy Integration: Advocate for urban policies that prioritize equitable distribution of resources, ensuring that walkability improvements benefit all segments of the population.
- Community Engagement: Involve local residents in the planning process to understand their needs and preferences, fostering a sense of ownership and ensuring interventions are culturally appropriate.

6.2.2. Leveraging Emerging Technologies for Enhanced and Inclusive Walkability

Addressing Gaps 6.1.2 and 6.1.5

Emerging technologies offer innovative solutions to enhance walkability and promote inclusive design. This proposal includes:

- Developing Smart Walkability Tools: Create mobile applications and platforms that provide real-time navigation, suggest safe and accessible routes, and offer alerts about environmental conditions. Features could include:
- Accessibility Mapping: Highlight barrier-free paths, accessible entrances, and facilities suitable for people with disabilities, the elderly, and families with young children.
- Personalized Route Planning: Use AI and machine learning to tailor walking routes based on individual preferences and needs, such as avoiding steep inclines for those with mobility challenges.
- Implementing Smart Infrastructure: Integrate sensors and IoT devices into urban environments to monitor pedestrian traffic, environmental conditions, and infrastructure status. This data can inform maintenance and planning decisions.
- Enhancing Safety and Security: Utilize technology to improve lighting, surveillance, and emergency communication systems, addressing safety concerns that may deter certain groups from walking.
- Inclusive Design through Technology: Employ virtual reality (VR) and augmented reality (AR) tools in the planning process to visualize and test urban designs from the perspective of diverse users.
- Research on Technology Adoption: Study how different demographic groups interact with technology to ensure that digital solutions are accessible and user-friendly for all.

6.2.3. Exploring Mental Health and Well-Being Outcomes of Walkable Environments

Addressing Gap 6.1.3

There is a need to deepen the understanding of how walkability influences mental health and well-being. This proposal involves:

- Empirical Research: Conduct studies that measure psychological outcomes associated with walking in various environments, using indicators such as stress levels, mood assessments, and social connectedness.
- Environmental Psychology Integration: Collaborate with psychologists to explore how environmental factors like aesthetics, noise levels, and greenery impact mental well-being.

- Longitudinal Studies: Track changes in mental health over time in relation to walkability improvements, providing robust evidence of causal relationships.
- Holistic Urban Design: Incorporate findings into urban planning by designing spaces that promote relaxation, social interaction, and sensory engagement.
- Public Health Collaboration: Work with health agencies to integrate mental health considerations into walkability initiatives, emphasizing the role of active transportation in overall well-being.

6.2.4. Quantifying Environmental Sustainability Impacts of Increased Walkability

Addressing Gap 6.1.4

To optimize the environmental benefits of walkable urban designs, this proposal suggests:

- Environmental Impact Modeling: Use computational models to simulate how increased pedestrian activity reduces carbon emissions, improves air quality, and mitigates urban heat island effects.
- Integration of Green Infrastructure: Research the synergistic effects of combining walkability with green spaces, such as parks and tree-lined streets, on environmental sustainability.
- Data Collection and Analysis: Gather empirical data on environmental metrics before and after implementing walkability improvements to quantify actual impacts.
- Policy Recommendations: Develop guidelines for urban planners to incorporate environmental sustainability goals into walkability projects, promoting practices like reducing impervious surfaces and enhancing biodiversity.
- Public Awareness Campaigns: Educate communities about the environmental benefits of walking to encourage behavioral shifts toward more sustainable transportation modes.

6.2.5. Developing a Comprehensive, Global Walkability Assessment Platform

Addressing Gap 6.1.6

To overcome limitations of existing platforms, this proposal aims to create a universal walkability assessment tool:

- Comprehensive Criteria Integration: Include a wide range of factors such as physical infrastructure quality, safety, environmental conditions, socio-economic variables, and user perceptions.
- Global Applicability: Design the platform to be adaptable to different urban contexts worldwide, accommodating varying data availability and cultural considerations.
- Use of Open Data and Crowdsourcing: Leverage open-source datasets and encourage user contributions to enrich the platform's data repository, ensuring up-to-date and locally relevant information.
- Advanced Analytics and Visualization: Incorporate GIS mapping, data analytics, and visualization tools to present walkability scores in an accessible and actionable format.
- Validation and Benchmarking: Collaborate with international organizations to standardize the assessment methodology, allowing for comparison and benchmarking across cities globally.
- Continuous Improvement Mechanism: Implement feedback loops where user input and new research findings can refine and enhance the platform over time.

7. Conclusion

This state-of-the-art review highlights the vital role of walkability in sustainable urban development. Research on walkability has demonstrated how pedestrian-friendly environments contribute to public health, reduce environmental impacts, and foster social cohesion. As cities worldwide aim to become more livable and sustainable, the importance of walkability in urban planning cannot be overstated. This review has explored a variety of tools and methodologies, from traditional walkability indices to advanced modeling approaches, that provide a comprehensive understanding of the factors influencing pedestrian environments.

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A central finding of this review is the emergence of advanced assessment tools such as Geographic Information Systems (GIS), multi-criteria decision-making (MCDM) frameworks, and Agent-Based Modeling (ABM), which offer new possibilities for evaluating and improving walkability. These tools enable urban planners to analyze the complexities of pedestrian behavior, environmental conditions, and infrastructure in detail. While ABM offers unique benefits through its capacity to simulate dynamic pedestrian interactions, it is most effective when used in conjunction with other tools like GIS and MCDM. The integration of these methodologies allows for a more holistic approach, capturing both the physical and social dimensions of walkability.

Additionally, case studies from cities around the world illustrate how diverse urban areas are prioritizing walkability to address shared challenges such as traffic congestion, air pollution, and limited green spaces. Lessons learned from cities like Seoul, Lisbon, and Kraków highlight the potential for cities of all sizes to improve walkability through targeted interventions, data-driven planning, and a focus on inclusivity. These examples underscore the importance of continuous, localized assessment and adaptive strategies to meet the specific needs of each urban context.

Despite these advancements, gaps in walkability research remain. There is a pressing need for further exploration of socio-economic and demographic factors, the impact of walkability on mental health, and the environmental benefits of pedestrian-friendly infrastructure. Furthermore, inclusive design practices must be prioritized to ensure that urban spaces are accessible to people of all ages and abilities. Emerging technologies, such as real-time data collection, wearable devices, and mobile applications, present new opportunities to enhance the pedestrian experience and enable more responsive urban environments.

Looking forward, there is a need for a comprehensive, globally adaptable platform that combines both objective data and subjective insights into walkability. Such a platform could provide a universal standard for assessing and comparing walkability across cities, offering urban planners a powerful tool to design healthier, more sustainable, and socially connected communities. By addressing these research gaps and leveraging emerging technologies, cities can continue to evolve into more walkable spaces that prioritize quality of life for all residents.

In conclusion, enhancing walkability requires a multi-faceted approach that integrates innovative assessment methods, evidence-based planning, and a commitment to inclusivity. As walkability remains a cornerstone of sustainable urban development, ongoing research and practical applications will be essential to making cities worldwide more walkable, resilient, and livable.

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