The Pedestrian Network Concept: A Systematic Literature Review

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Abstract

The design of urban spaces that foster sustainable practices requires new analytical and structural approaches to spatial planning. An appropriate pedestrian network could significantly contribute to sustainable urban development goals, particularly by promoting sustainable mobility and pedestrian friendliness. With such goals, several attempts have been made to develop suitable models for pedestrian networks. However, something that is missing from the current literature is a framework that incorporates the main findings of the various studies as an integrated concise concept of the pedestrian network. To address this knowledge gap, this paper reviews studies on pedestrian networks and evaluates this concept based on the systematic SWIH analysis method, which asks where, what, who, and how. In essence, the following questions are thus analyzed: Where is the pedestrian network located? What criteria play a role in the pedestrian network’s performance? Who uses the pedestrian network, and how can the pedestrian network be analyzed? In this context, a systematic literature review is carried out by investigating studies conducted during the period 2001 to 2023 that appear in the Scopus database. The paper presents the results of the review of a selection of 67 papers dealing with pedestrian networks. Findings show that different models have been developed based on particular characteristics. Overall, researchers aimed to identify the most suitable network based on specific criteria for optimizing the walking experience in urban areas. By synthesizing the findings reported in these papers, this paper arguably contributes to a more comprehensive understanding of pedestrian networks, provides insights into the prioritization of design phases, facilitates the use of pedestrian network assessment models for future research, and creates a bigger picture for urban planners with a multidimensional view to a new sustainable urban structure.

1. Introduction

Walking is considered to be one of the most important non-motorized modes of transport (Jabbari, Ahmadi, & Ramos, 2022). Pedestrian mobility, or the act of traveling on foot, is indeed the oldest form of mobility. Before the invention of wheeled vehicles, animals for transportation, or even boats, humans had to rely solely on their own two feet to get from one place to another. As civilizations began to evolve, pedestrian mobility remained an important mode of transportation. Ancient Greeks, Persians, and Romans, built networks of roads and footpaths to facilitate travel by foot, and even today, some of these ancient routes are still in use (Amato, 2004; Habibi, 1996; Hodza & Butler, 2022; Lay, 1999). In many parts of the world, a pedestrian network continued to be an essential means of transportation. The primary function of the pedestrian network is to provide mobility for pedestrians, allowing them to travel from one location to another on foot. The pedestrian network in Iranian cities worked as a city skeleton and there were main urban elements and activities included the bazaar complex, school, and neighborhood centers (Farkisch, Ahmadi, & Che-ani, 2015; Jabbari, Fonseca, & Ramos, 2021). The concept of the pedestrian network originated in 1797 when the French army occupied Venice and attempted to build a structure to connect the island groups by waterways (Vivo, 2016). They worked to transform the amphibious city into a homogeneous pedestrian network by creating canals, building bridges, and creating paths. De Vivo (2016) believes that walking was a daily habit and formed the pedestrian network in sixteenth-century Venice.
Despite being replaced by faster modes of transport for longer journeys, walking continues to be an essential means of transportation for shorter trips, and for changing between modes. The Personal, social, economic, and environmental benefits of walking are well documented: Walking reduces traffic congestion, air pollution, and noise; it is beneficial for individual health and well-being; it provides economic benefits; it affects property prices; and it improves the sociability and vitality of urban spaces (Bahrainy & Khosravi, 2013; H.-Y. Chan, Xu, Chen, & Liu, 2022; Kim, Park, & Lee, 2014; P. Zhao & Li, 2017). For these reasons, the promotion of walking and walkability has become a focus of various urban policies, especially since the rise of the green mobility debate. Green mobility has gained popularity in recent years due to growing concerns about the impact of transportation on the environment, climate change, and the public health issues associated with air pollution. Green mobility represents a shift towards more sustainable modes of transportation (Delso, Martín, Ortega, & Van De Weghe, 2019; Pamucar et al., 2022; Zamparini, Domènech, Miravet, & Gutiérrez, 2022). In addition, the COVID-19 pandemic has highlighted the importance of pedestrian networks in creating safe and healthy cities. In many cities around the world, there has been a shift toward prioritizing pedestrian infrastructure in response to the pandemic (Sainz-Santamaria et al., 2023).

Accordingly, the quality of the pedestrian network is arguably one of the most important parameters for sustainable urban development and sustainable mobility (Forsyth, Oakes, Lee, & Schmitz, 2009; Lilasathapornkit, Rey, Liu, & Saberi, 2022). A pedestrian network can be understood as a structure within an urban space, which consists of interconnected streets with elements of accessibility and connectivity (Fonseca, Fernandes, & Ramos, 2022; Gaglione, Cottrill, & Gargiulo, 2021; Jabbari et al., 2021; Pearce, Matsunaka, & Oba, 2021). More recently, two well-known pedestrian network projects were implemented in Hong Kong and Toronto. In Hong Kong, the at-grade pedestrian network was created in the 1970s, linking the different outdoor and indoor pedestrian areas into a continuous experience of movement and creating a collective urban identity (Z. Tan & Q.L. Xue, 2014; Z. Tan & Xue, 2015; Zhou, Zhang, & Jf Chiariad, 2022). Toronto’s pedestrian network is a largely underground downtown pedestrian network that spans more than 30 kms of restaurants, shopping, services, and entertainment and opened in 1987 (Bélinger, 2007; Cui, 2021).

Despite the many opportunities to study and implement pedestrian networks, there is limited research, both on technical and practical application issues (Kelly, Tight, Hodgson, & Page, 2011). Much of the work on pedestrian networks has been presented in processes that involve multiple stages with few components that did not consider a unit structure (Gaglione et al., 2021; Mitchell & MacGregor Smith, 2001; Xue X. Yang, Stewart, Fang, & Tang, 2022). To overcome this weakness, Hall and Ram (2018) pioneered the simplification of pedestrian network models using the well-documented Walk Score measure. However, it focused only on individual and independent variables of walking and not on the correlation of these variables in the context of urban planning. The literature review showed that the current models are complex, they are still not very application-oriented, they may be too articulate for urban planning, and they may not consider the pedestrian network assessment as an urban structure.

To address these knowledge gaps, the aim of this study is to review and synthesize the extant knowledge on pedestrian networks. To do this, the paper takes stock of papers published on PNs between 2001 and 2023 and utilizes the 3WIH method (Malik, Chandra, Rao, & Arora, 2020) to analyze these. As such, it analyzes where (W) is the pedestrian network located?, what (W) criteria play a role in the pedestrian network’s performance?, who(W) uses the pedestrian network? and how(H) can the pedestrian network be analyzed?

The rest of this paper is structured as follows. After explaining the applied method in Section 2, Section 3 outlines the results from the literature review. The discussion, including a conceptual model that arguably contributes to a more comprehensive understanding of PNs, is then presented in Section 4. Lastly, a few concluding remarks are provided in the fifth and final section.

2. Method

The aim of this study is to review the current pedestrian network models and simplify their processes and components in the context of urban planning using the 3WIH method. This method is a rational thought process and a well-documented method for decision-making (Chi, Lin, & Liu, 2008; Jagarajan et al., 2017; Malik et al., 2020; Y. Tang, Liu, Zhang, Shuai, & Shen, 2018), which has previously been successfully applied in other cases (Jagarajan et al., 2017; Y. Tan et al., 2018; J. Zhao, Sun, & Webster, 2020). The information processed by the 3WIH method identifies the relationship between the purpose and the components of a given model. The method includes three main questions: where, what, who, and how? The method provides a complete perspective for the construction of the assessment model. It consists of a set of concepts, relationships and their scope (Johannessen, Flak, & Sæbø, 2012).

Studying pedestrian networks involves a reflection on the theoretical and practical implications of the concept. This systematic literature review follows a four-step procedure that corresponds to the methodological approach used by Motomura et al. (2022), which is illustrated in Fig. 2. First, in step 1, the so-called identification step, the sources and procedures for the literature search are determined on the basis of the Scopus database. It focused on papers published since 2001 that appeared in the Scopus database. All studies are recent, with one-third of the total papers (24 out of 67) published since 2020. Step 2 is then to define the scope, which includes the objectives and a review protocol for the systematic review. The process consists in searching the expression “pedestrian network” in articles published in journals with more than four occurrences in the title, abstract, text, and keywords. This ensures that “pedestrian network” is a relevant expression used in the searched papers. The following step 3 is about the eligibility and identification of concepts through a focused synthesis of the results according to the 3WIH method. Finally, Step 4 is the evaluation and includes a comprehensive summary of the main processes and components in theory and practice in terms of Where, what, who, and how to influence the process of the pedestrian network.

3. Results

According to the described literature review method, 67 papers containing the expression “pedestrian network” were identified (Table 1). From these, 28% are within the scientific field of mathematics, 47% are related with urban planning, and 26% with remote sensing. The majority of these papers come from Asian research centers (Diagram 1). They include mathematical approaches that focus on developing algorithms to automatically identify the geometry of pedestrian routes; urban planning approaches that often focus on identifying and assessing the capacity of urban space for pedestrians including by conducting surveys to target groups; remote sensing approaches, on the other hand, typically focus on tracking the pedestrian environment using high quality imagery by satellite imagery and open data sources to identify patterns of pedestrian behavior.

Based on 677 papers found in the Scopus databases, 31 papers related to urban planning are considered in order to analyze more (Abass & Tucker, 2018; Arroyo, Mars, & T., 2018; Azad, Abdelqader, Taboada, & Cherry, 2021; D’Orso & Migliore, 2020; Delso, Martín, & Ortega, 2018; Fonseca et al., 2020; Garip, Dalgalçinoğlu, & Cimbit Köp, 2015; Q. Guo, Xu, Pei, Wong, & Yao, 2017; Hajrasouliha & Yin, 2015; J. He et al., 2016; Jabbari et al., 2022 M. Jabbari, Fonseca, & Ramos, 2018; Kwon, Kim, & Lee, 2017; Lunecke & Mora, 2018; Oswald Beiler, McGoff, & McLaughlin, 2017; Özbil, Yeliptepe, & Argyn, 2015; Pearce et al., 2021; Tal & Handy, 2012; Z. Tan & Q.L. Xue, 2014; Z. Tan & Xue, 2015; Ujang, 2016; X. Yang, Sun, Huang, & Fang, 2022; Zhou et al., 2022). This paper seeks to answer the following questions: (1) Where is the
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<th>Authors</th>
<th>Approach</th>
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<tr>
<td>1 Zhou et al. (2022)</td>
<td>Urban planning</td>
<td>Estimating wider economic impacts of transport infrastructure</td>
<td>Hong Kong</td>
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<tr>
<td>2 Laszkiewicz et al. (2022)</td>
<td>Mathematical</td>
<td>Valuing access to urban greenspace using non-linear distance decay in hedonic property pricing</td>
<td>Poland</td>
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<tr>
<td>3 Gaglione et al. (2022)</td>
<td>Urban planning</td>
<td>Where can the elderly walk? A spatial multi-criteria method to increase urban pedestrian accessibility</td>
<td>Italy</td>
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<tr>
<td>4 H.-Y. Chan et al. (2022)</td>
<td>Mathematical</td>
<td>Impacts of the walking environment on mode and departure time shifts in response to travel time change: Case study in the multi-layered Hong Kong metropolis</td>
<td>Hong Kong</td>
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<tr>
<td>5 Fonseca et al. (2022)</td>
<td>Urban planning</td>
<td>Walkable Cities: Using the Smart Pedestrian Net Method for Evaluating a Pedestrian Network in Guimarães, Portugal</td>
<td>Portugal</td>
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<tr>
<td>6 X. Yang et al. (2022)</td>
<td>Urban planning</td>
<td>A Framework of Community Pedestrian Network Design Based on Urban Network Analysis</td>
<td>China</td>
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<tr>
<td>7 H.-Y. Chan et al. (2022)</td>
<td>Urban planning</td>
<td>Pedestrian route choice with respect to new lift-only entrances to underground space: Case study of a metro station area in hilly terrain in Hong Kong</td>
<td>Hong Kong</td>
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<td>8 Jabbari et al. (2022)</td>
<td>Urban planning</td>
<td>Defining a Digital System for the Pedestrian Network as a Conceptual Implementation Framework</td>
<td>Sweden</td>
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<td>9 Gholami, Torreggiani, Tassinari, and Barbarei (2022)</td>
<td>Remote sensing</td>
<td>Developing a 3D City Digital Twin: Enhancing Walkability through a Green Pedestrian Network (GPN) in the City of Imola, Italy</td>
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<td>10 X. Yang et al. (2022)</td>
<td>Remote sensing</td>
<td>Attributing pedestrian networks with semantic information based on multi-source spatial data</td>
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<td>11 Azad et al. (2021)</td>
<td>Urban planning</td>
<td>Walk-to-transit demand estimation methods applied at the parcel level to improve pedestrian infrastructure investment</td>
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<td>12 Gaglione et al. (2021)</td>
<td>Urban planning</td>
<td>Urban services, pedestrian networks and behaviors to measure elderly accessibility</td>
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<tr>
<td>13 Cui (2021)</td>
<td>Urban planning</td>
<td>Building three-dimensional pedestrian networks in cities</td>
<td>Greece</td>
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<td>14 Georgiou, Skoufas, and Basbas (2021)</td>
<td>Urban planning</td>
<td>Perceived pedestrian level of service in an urban central network: The case of a medium size Greek city</td>
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<td>15 Carroll, Caulfield, and Ahern (2021)</td>
<td>Mathematical</td>
<td>Appraising an incentive only approach to encourage a sustainable reduction in private car trips in Dublin, Ireland</td>
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<tr>
<td>16 Moustaid and Flötteröd (2021)</td>
<td>Mathematical</td>
<td>Macroscopic model of multidirectional pedestrian network flows</td>
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<td>17 Pearce et al. (2021)</td>
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<td>Comparing accessibility &amp; connectivity metrics derived from dedicated pedestrian networks and street networks in the context of Asian cities</td>
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<td>18 Zhao et al. (2020)</td>
<td>Remote sensing</td>
<td>Walkability scoring: Why and how does a three-dimensional pedestrian network matter?</td>
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<td>19 Yang et al. (2020)</td>
<td>Remote sensing</td>
<td>Pedestrian network generation based on crowdsourced tracking data</td>
<td>China</td>
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<td>20 Vo, Qian, Lam, and Sumalee (2020)</td>
<td>Remote sensing</td>
<td>Modeling joint activity-travel patterns in pedestrian networks with use of Wi-Fi data</td>
<td>Hong Kong</td>
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<td>21 D’Orso and Migliore (2020)</td>
<td>Urban planning</td>
<td>A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments</td>
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<tr>
<td>22 Zuo et al. (2020)</td>
<td>Urban planning</td>
<td>First-and-last mile solution via bicycling to improving transit accessibility and advancing transportation equity</td>
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<td>23 Fonseca et al. (2020)</td>
<td>Urban planning</td>
<td>Smart Pedestrian Network: An Integrated Conceptual Model for Improving Walkability</td>
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<td>24 Sun, Wallace, and Webster (2020)</td>
<td>Mathematical</td>
<td>Unraveling the impact of street network structure and gated community layout in development-oriented transit design</td>
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<td>25 Higgins (2019)</td>
<td>Mathematical</td>
<td>A 4D spatio-temporal approach to modeling land value uplift from rapid transit in high density and topographically-rich cities</td>
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<tr>
<td>26 Bhattacherjee, Roy, and Das Bit (2019)</td>
<td>Remote sensing</td>
<td>Constructing digital pedestrian maps of the disaster affected areas</td>
<td>India</td>
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<td>27 Lesani and Miranda-Moreno (2019)</td>
<td>Remote sensing</td>
<td>To estimate travel times (speeds), to classify bicycle-pedestrian WiFi signals, and to extrapolate pedestrian MAC counts.</td>
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<tr>
<td>28 Itu, Cerbu, and Galatanu (2019)</td>
<td>Remote sensing</td>
<td>Modeling and Testing of the Sandwich Composite Manhole Cover for Pedestrian Networks</td>
<td>Romania</td>
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<td>29 Oyama and Hato (2018)</td>
<td>Remote sensing</td>
<td>To estimate the route choice parameters with the fewer personal approach</td>
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<td>31 Delso et al. (2018)</td>
<td>Urban planning</td>
<td>To provide a procedure to evaluate the impact of obstacles to pedestrian mobility and walkability</td>
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<td>32 Lunecke and Mora (2018)</td>
<td>Urban planning</td>
<td>Understanding the impact of downtown Santiago’s three-scale pedestrian network on walkability</td>
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<td>33 He et al. (2018)</td>
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<td>To explore the influences of various morphological features of non-uniform and orthogonal breezeway networks on pedestrian ventilation in high-density urban environments under Singapore’s climatic conditions.</td>
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<td>34 Arroyo et al. (2018)</td>
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<td>To identify factors that influence the decision to walk and cycle.</td>
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<td>35 Yao, Wang, Fang, and Wu (2018)</td>
<td>Remote sensing</td>
<td>To identify Vehicle-Pedestrian Collision Hotspots at the Micro-Level</td>
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<td>36 Hoogendoorn, Daamen, Knoop, Steenbakkers, and Sarvi (2018)</td>
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<td>To analyze relations between density network and speed pedestrian</td>
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<td>37 Jung and Hong (2017)</td>
<td>Remote sensing</td>
<td>Guiding network for pedestrian detection</td>
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<tr>
<td>38 Zhu, Liao, Lei, and Li (2017)</td>
<td>Remote sensing</td>
<td>To predict multiple attributes together in a unified framework</td>
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<td>39   Osama and Sayed (2017)</td>
<td>Mathematical</td>
<td>To assess the impact of network connectivity, directness, and topography on pedestrian safety</td>
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<td>40   Ki-Ho and Kang (2017)</td>
<td>Remote sensing</td>
<td>Aggregating Channel Features (ACF) and rich Deep Convolutional Neural Network (DCNN) features for efficient and effective pedestrian detection in complex scenes</td>
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<tr>
<td>41   Hänsteler, Lam, Bieraire, Lederrey, and Nikolić (2017)</td>
<td>Mathematical</td>
<td>To describe this interaction, a stream-based pedestrian fundamental diagram</td>
<td>China</td>
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<tr>
<td>42   Guo et al. (2017)</td>
<td>Urban planning</td>
<td>Focused on the role of different road network patterns on the occurrence of crashes involving pedestrians.</td>
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<tr>
<td>43   Kwon et al. (2017)</td>
<td>Urban planning</td>
<td>Locating Automated External Defibrillators in a Complicated Urban Environment Considering a Pedestrian-Accessible Network that Focuses on Out-of-Hospital Cardiac Arrests</td>
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<tr>
<td>44   Zheng and Eleftheriadou (2017)</td>
<td>Mathematical</td>
<td>Estimating pedestrian delay at unsignalized intersections in urban networks</td>
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<td>45   Oswald Beiler et al. (2017)</td>
<td>Urban planning</td>
<td>Trail network accessibility: Analyzing collector pathways to support pedestrian and cycling mobility</td>
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<td>46   Qu and Lim (2016)</td>
<td>Mathematical</td>
<td>Detecting pedestrian using neural network with a weighted fuzzy membership function</td>
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<td>47   Ujang (2016)</td>
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<td>Studying tourists’ expectations on the spatial characteristics of walkways in terms of accessibility, connectivity and continuity</td>
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<td>To improve traffic safety and protect pedestrians</td>
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<td>49   Dai and Jaworski (2016)</td>
<td>Remote sensing</td>
<td>Investigating the influence of built environment on pedestrian crashes</td>
<td>USA</td>
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<tr>
<td>50   Roshandeh, Li, Zhang, Levinson, and Lu (2016)</td>
<td>Remote sensing</td>
<td>Simultaneously assess the overall impacts of vehicle &amp; pedestrian crashes caused by signal timing optimization in dense urban street networks.</td>
<td>USA</td>
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<tr>
<td>51   Hong, Shankar, and Venkataraman (2016)</td>
<td>Remote sensing</td>
<td>To derive a modeling framework for characterizing the space-time exposure of pedestrians in crosswalks,</td>
<td>USA</td>
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<td>52   Rashidi, Parsafard, Medal, and Li (2016)</td>
<td>Mathematical</td>
<td>To minimize the safety hazard for pedestrians and the total transportation cost of the network</td>
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<tr>
<td>53   Z. Tan and Xue (2015)</td>
<td>Urban planning</td>
<td>To track the evolving concept of grade-separated pedestrian networks in Hong Kong, revisiting the critical actions from 1965 to 1997.</td>
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<td>54   Tiplica (2015)</td>
<td>Mathematical</td>
<td>Studying the behavior of drivers interacting with pedestrians and what might be the cause of their decisions of legitimate transgressions</td>
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<td>55   Yu, Ma, Lo, and Yang (2015)</td>
<td>Remote sensing</td>
<td>Optimizing mid-block pedestrian crossing network with discrete demands</td>
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<td>56   Hajrasouliha and Yin (2015)</td>
<td>Urban planning</td>
<td>Investigating the impact of street network connectivity on pedestrian volume</td>
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<td>57   Garip et al. (2015)</td>
<td>Urban planning</td>
<td>Studying the influence of architectural configuration on the pedestrian network</td>
<td>Turkey</td>
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<td>58   Özbek et al. (2015)</td>
<td>Urban planning</td>
<td>Understanding street-level urban design qualities and objectively measured street network configuration are related to pedestrian movement, controlling for land use</td>
<td>Turkey</td>
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<tr>
<td>59   Z. Tan and Q.L. Xue (2014)</td>
<td>Urban planning</td>
<td>Elevating pedestrian systems of Hong Kong in the context of planning regulation and land finance</td>
<td>Hong Kong</td>
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<td>60   Zhang and Chang (2014)</td>
<td>Mathematical</td>
<td>Defining model to evacuate pedestrian–vehicle mixed-flow networks in Hong Kong.</td>
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<td>61   Raghuram Kadali, Rathi, and Perumal (2014)</td>
<td>Mathematical</td>
<td>Evaluating the pedestrian mid-block road crossing behavior using artificial neural network</td>
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<td>62   Kaemuppakorn and Karimi (2015)</td>
<td>Mathematical</td>
<td>A pedestrian network construction algorithm based on multiple GPS traces</td>
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<td>63   Tal and Handy (2012)</td>
<td>Urban planning</td>
<td>Measuring nonmotorized accessibility and connectivity in a robust pedestrian network</td>
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<td>64   Chin et al. (2008)</td>
<td>Urban planning</td>
<td>Accessibility and connectivity in physical activity studies: The impact of missing pedestrian data</td>
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<td>66   Trépanier, Chapleau, and Allard (2002)</td>
<td>Mathematical</td>
<td>Transit Itinerary Calculation on the Web: Based on a Transit User Information System</td>
<td>USA</td>
</tr>
<tr>
<td>67   Mitchell and MacGregor-Smith (2001)</td>
<td>Mathematical</td>
<td>Topological network design of pedestrian networks</td>
<td>USA</td>
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Diagram 1. Division of the papers into approaches and continents.
pedestrian network located? (2) What criteria play a role in the pedestrian network’s performance? (3) Who uses the pedestrian network? and (4) How can the pedestrian network be analyzed? Fig. 2 shows the relationship between these questions based on the 3W1H method.

3.1. Where is the pedestrian network located?

The question “Where is the pedestrian network located?” identifies the place for which the model was designed at the site. In fact, the pedestrian network is closely related to the practical context in which the work is carried out. In order to understand the practical context, researchers have pursued a variety of objectives. The main objectives of this research, which addresses the concept of the pedestrian network, are: to promote social interactions at the neighborhood level; to increase urban vitality in the city center; to find the potential urban space for the pedestrian network in the city center; and to improve the conditions for visiting and promoting trade in city centers (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; T. Tan & Q.L. Xue, 2014).

The models analyzed different geographical scales including urban space, street network, and urban structure. As such, the research arguably included micro-scale, macro-scale, and even multi-scale approaches (J. He et al., 2016; M. Jabbari et al., 2018; Kwon et al., 2017; Lunecke & Mora, 2018; T. Tan & Q.L. Xue, 2014). Some researchers are currently using the specific scale of the pedestrian network model in the urban planning processes based on limited data (J. He et al., 2016; T. Tan & Q. L. Xue, 2015). Indeed, the pedestrian network model is applied at multiple scales based on the spatial hierarchical theory (M. Jabbari et al., 2018; Lunecke & Mora, 2018). This theory contains an integrated dataset at multiple scales and links planning, analysis and data to the hierarchical urban structure (Bereitschaft, 2018; Buckley, Stangl, & Guinn, 2017; Cheng & Masser, 2003; Girling, Zheng, Monti, & Ebnesahlidi, 2019).

The COVID-19 pandemic has had a significant impact on the pedestrian network. In many cities around the world, there has been a shift towards prioritizing pedestrian infrastructure in response to the pandemic. This has been driven by the need for physical distancing and the recognition of walking as a safe and healthy mode of transportation during the pandemic to provide safe and accessible routes for people to walk from one point to another. The primary function of pedestrian infrastructure is to provide mobility for pedestrians, allowing them to travel from one location to another on foot. The pandemic has highlighted the importance of the pedestrian network in creating safe and healthy cities. The changes made to the pedestrian infrastructure during the pandemic have the potential to create lasting improvements (Sainz-Santamaria et al., 2023) and redesign pedestrian networks as main urban structure.

3.2. What criteria play a role in the pedestrian network’s performance?

Pedestrian network models have a wide range of applications as they not only address physical environmental aspects but also consider some macro-level street network analyses (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; T. Tan & Q. L. Xue, 2014). In order to qualify and evaluate the different dimensions, this paper considers two main contexts. First, some pedestrian network models identified criteria related to the characteristics of each street suitable for walking (J. He et al., 2016; M. Jabbari et al., 2018; Lunecke & Mora, 2018; T. Tan & Q. L. Xue, 2014). Second, some other pedestrian network models assessed the position of the street in the network by using urban structure criteria such as connectivity, integration and distribution (Hajrasoulha & Yin, 2015; J. He et al., 2016; M. Jabbari et al., 2018; Özbil et al., 2015; T. Tan & Q.L. Xue, 2014). The studies on criteria related to the characteristics of streets show that they are very complex. By understanding what a pedestrian considers an attractive route, planners can build more pedestrian-friendly and liveable cities. In the beginning, it focuses on the majority criteria that most influence the definition of the street that the literature review revealed a large number of research findings and related attributes associated with walkability. The main criteria considered can be divided into four groups: built environment, urban function, accessibility, and natural environment.

**Built environment** includes several perceptual qualities that can affect the walking environment (Bahrainy & Khosravi, 2013; Garcia & Lara, 2015; Kim et al., 2014; Wey & Chiu, 2013). Some researchers have proposed six sub-criteria in this context: image, enclosure, human scale, transparency, complexity, and slope (Ewing & Handy, 2009; Lundberg & Weber, 2014). These criteria have been used to create urban design quality indices to capture aspects of the built environment that are related to people’s emotional responses to aesthetics in urban areas (Ferrer, Ruiz, & Mars, 2015; Garip et al., 2015; M. Jabbari et al., 2018; Lunecke & Mora, 2018).

**Urban function** affects spatial activity. Land use as one of the sub-criteria of urban function affecting pedestrian satisfaction and distribution in urban space (Bahrainy & Khosravi, 2013; Bélanger, 2007; Lamiquiz & López-Domínguez, 2015; Lerman & Omer, 2016). Population density is another sub-criterion most often used in this topic (M. Jabbari, Fonseca, & Ramos, 2018; T. Tan & Handy, 2012). Above all, population density correlates residual areas with pedestrian movements (Lerman & Omer, 2016; Peiravian, Derrible, & Jiaj, 2014). To be safe in a pedestrian network should consider the traffic condition because pedestrians are especially vulnerable on the roadway in the case of collisions and personal security (Fonseca et al., 2022). In fact, the urban function classifies three sub-criteria, including land use, population density and safety.

**Accessibility** is another criterion analysed by several authors that can improve pedestrians’ quick access to a given location. This includes public transport and intelligent transport systems (ITS) as a sustainable method of urban mobility (Grecu & Morar, 2013). Accessibility is a facilitating criterion that strongly links urban function to the built environment. For example, to connect suburban areas that are largely car-dependent, considering the accessibility criterion can promote the pedestrian network through transport purposes as intermodal transport (Gilderbloom, Riggs, & Meares, 2015b; Lamiquiz & López-Domínguez, 2015; Oswald Beiler et al., 2017).

**Natural environment** of streets and urban areas is also an important criterion, influencing walking and making a comfort zone (Panagopoulos, Duque, & Dan, 2016), pleasant conditions, by temperature control with artificial solutions (Peiravian et al., 2014) green spaces, sunlight, shade and wind are important for walking (Koh & Wong, 2013). Some authors have developed approaches to improve the walkability in green spaces of urban areas (Lwin & Murayama, 2011).

Another group of studies assessed the position of the street in the pedestrian network at the macro-level. Some structural criteria were assessed to get a better understanding of the spatial configuration of the streets, the road network and the location of economic activities (Chin, Van Niel, Giles-Corti, & Knuiman, 2008; Gilderbloom et al., 2015b; Kim et al., 2014; Lerman & Omer, 2016; Millward, Spinney, & Scott, 2013; Peiravian et al., 2014). The degree of connectivity in the street network is the most important parameter for any movement in urban space (Carpio-Pinedo, Martínez-Conde, & Daudén, 2014). The connectivity criterion joins places with people and defines how streets are networked (Azmi & Ahmad, 2015; Bahrainy & Khosravi, 2013; Pearce et al., 2021). Furthermore, the urban structure defines how the streets are arranged and interconnected and how they connect the different urban areas with their surroundings. A well-functioning urban structure has coherent neighborhoods where the centers of activities are within easy walking distance. In this context, walking creates economic value and social vibrancy (Gallimore, Brown, & Werner, 2011; Lindelow, Svensson, Brundell-Freij, & Winslott Hiselius, 2017; Loo, Mahendran, Katagiri, & Lam, 2017). The integration of the road network is also a morphological parameter with implications for pedestrian move-
ment (Carpio-Pinedo et al., 2014; Koh & Wong, 2013). Additionally, Z. Tan and Q.L. Xue (2014) examined the distribution of pedestrian mobility in the street network, as another parameter. He, Tablada, and Wong (2018) consider that the distribution of pedestrian flows characterizes these multi-level pedestrian systems.

### 3.3. Who uses the pedestrian network?

The organization of the pedestrian network based on the habits, pedestrian behavior and lifestyles of users living in cities has been discussed by many authors (Borst et al., 2009; Stevenson et al., 2017; X. Yang et al., 2022). However, it is only in recent years that attention has been focused on ‘vulnerable’ populations (children, older people, people with disabilities) in relation to the accessibility (Abass & Tucker, 2018). Gradients, pavement widths, obstacles on sidewalks, sidewalks in poor condition, traffic characteristics, etc. represent barriers for users walking in the city, especially for vulnerable populations. This is particularly important for users who require a wider space, such as pushchair and wheelchair users (H.-Y. Chan, Ip, Mansoor, & Chen, 2022; Fonseca et al., 2022; Gaglione et al., 2021; Šurdonja, Štokić, Deluca-Tibljaš, & Campisi, 2023).

In addition, some studies have developed level of service (LOS) measurement to assess and compare the quality of urban services for different user modes (i.e., car, pedestrian, bicycle and transit). Several factors contribute to the LOS: pedestrian satisfaction with the route to the stop, satisfaction of waiting passengers, and satisfaction of passengers using the pedestrian network as part of intermodal transport. Traditional cost-benefit analysis is usually applied in an evaluation context to capture direct benefits to users, such as savings in travel time and improved quality of transport services sought by the municipality (urban manager). In order to realize the potential of systematic use of urban space, it is necessary to learn lessons from existing cases and understand user (pedestrian) behavior and concerns (Azad et al., 2021; Jabbari et al., 2022 Zhou et al., 2022; Zuo, Wei, Chen, & Zhang, 2020).

### 3.4. How can the pedestrian network be analyzed?

The urban planning process to provide a pedestrian network model is a complex task. The physical structure of the city as well as economic, social and environmental factors of different scales must be taken into account in the planning process. However, 79% of the walk score studies conducted by Hall and Ram (2018) were based on independent variables, only once as a mediating-modulating variable (Abass & Tucker, 2018) and on no occasion as a dependent variable. Also, in a few papers a bivariate correlation model was applied (Duncan et al., 2016; Hall & Ram, 2018; Towne et al., 2016). Therefore, the urban information model about pedestrian network should integrate the multidimensional urban aspects of economy, society, and environment. In fact, bonding among different criteria through different models determine the relationships between the potential of urban space and pedestrian.

Furthermore, pedestrian network, including multifunctional spaces, is used by different users with often conflicting interests and pedestrian network models reflect aspects of the users (Herrmann, 2016). Elderly, children and disabled people are vulnerable users that should not be forgotten in pedestrian network planning in urban public spaces (Šurdonja et al., 2023; Wijayanti & Pandelaki, 2012). Some studies look at pedestrian flows and behavior, while others use surveys to collect pedestrian data (Arroyo et al., 2018; Cui, 2021; Duncan et al., 2016; Hall & Ram, 2018; Towne et al., 2016; Ujang, 2016). However, more work is needed on classifying users and combining the results from their feedback in the pedestrian network model.

An attempt is made to classify urban spaces in order to propose a new typology of public space based on the way public space is managed, the so-called urban space typology (Carmona, 2010). The typology approach was applied in the city center and classified into pedestrian zones based on the characteristics of the public space. These pedestrian zones provided a short design document to manage the PEDESTRIAN NETWORK based on specific characteristics (Z. Tan & Xue, 2015). In the 1960s, pedestrian zones emerged in Europe, especially in city centers, and spread rapidly. For example, in 1966 there were only 63 pedestrian zones in Germany, but by 1972 there were 182 and by 1977 there were 370 pedestrian zones (Kostof, 2004; Lunecke & Mora, 2018). Lunecke and Mora (2018) have shown that the high volume of pedestrians in the street network occurred at specific street sections. These areas were usually located near the pedestrian zones.

The pedestrian network requires full consideration of the spatial continuity of the city (Yücel, 1979). The connectivity of the street network has an important impact on walking and how streets are interconnected (Azmi & Ahmad, 2015; Bahrainy & Khosravi, 2013). Therefore, a convenient design of pedestrian network should be provided to encourage walking and minimize obstacles. The connectivity of the street network can be defined as the number of intersecting streets per unit area (Azmi & Ahmad, 2015; García & Lara, 2015). Space syntax was used to assess street network connectivity because it has several advantages over simpler measures of road network connectivity, such as passive graphical terms. By using axial lines, the space syntax is better suited to calculate movements in networked settlements and functional connectivity in networks (Gilderbloom, Riggs, & Meares, 2015a; M. Jabbari et al., 2018; Lerman & Omer, 2016; Tianxiang, Dong, & Shobuing, 2015).

In turn, the urban configuration is the most important factor in shaping pedestrian movement patterns. Peponis, Ross, and Rashid (1997) presented some findings on the morphology of Greek cities and their patterns of pedestrian movement. In their study, patterns of pedestrian movement and urban configuration were compared using the typological model of urban layouts. Different measures of urban configuration are related to aspects of social life. Accessibility is based on the relationships that each space has with the others in an urban system (Girling et al., 2019; Jabbari et al., 2022 Jeong & Bany, 2016). As a result, the use of integration analysis in urban studies has increased in recent years and the pedestrian network model has been developed (J. He et al., 2016). For instance, Li, Xiao, Ye, Xu, and Law (2016) measured the spatial configuration of street networks in the Chinese city of Gulangyu using integration analysis to guide urban planning and tourism management policies and tourist preferences. Cutini (2016) also used space syntax to analyze the relationship between movement and the urban structure of Florence to examine how movement patterns have changed over time as the metropolitan area has grown and its network has been progressively reshaped. In this sense, this method should be useful for further comparison with another model supporting pedestrian network, as it takes into account both spatial and functional aspects of urban form.

In the urban planning literature, numerous studies have focused on the relationships between walking and all these criteria. These factors are usually composed of multiple criteria and sub-criteria that are interrelated but weighted differently (Millward et al., 2013). The multi-criteria analysis (MCA) approach was used in the pedestrian network model to address the complexity of urban mobility issues reflected in the multiplicity of sustainability indicators (M. Jabbari et al., 2018). The MCA enabled through the structured prioritization of a number of nested variables of urban space in relation to pedestrians. These approaches were inspired by the study of Frank, Schmid, Sallis, Chapman, and Saelens (2005) which created a combined walkability index from three urban criteria to analyze their influence on physical activity. The MCA is also a commonly used tool, especially in spatial planning. The MCA evaluates decision problems and different options based on specific criteria or the preferences of decision makers, using a set of qualitative and/or quantitative criteria with different weights (Durmuş & Turk, 2014). Furthermore, H.-Y. Chan et al. (2022) based on a face-to-face questionnaire survey conducted in a new station area of a hilly neighborhood, developed a binary mixed logit model to estimate the effect of route attributes, trip characteristics, socio-demographics, and walking preferences on the decision to use alternative underground walking routes.
Table 2
Models Evaluation for Pedestrian Network.

<table>
<thead>
<tr>
<th>What: Goal</th>
<th>Where: Place-Scale</th>
<th>Who: User</th>
<th>How: Model Content</th>
<th>Method</th>
<th>Strength Model</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>To bring more walk-in shop visiting; purchasing opportunities; characteristics of a target group-friendly pedestrian network</td>
<td>Some streets, Urban spaces/Micro-scale</td>
<td>Citizen/Tourist</td>
<td>Static built environment data, dynamic environmental behavior data and Street network</td>
<td>Survey maps, GIS and Space Syntax software</td>
<td>Considering three main dimensions: sociology, economic and urban planning; Improving understanding of service proximity and user behavior</td>
<td>He et al. (2018); Hajrasouliha and Yin (2015); Delo et al. (2018); Oswald Beiler et al. (2017); Garip et al. (2015); Gaglione et al. (2022), Chin et al. (2008); Arroyo et al. (2018); Tan et al. (2015); Ujang (2016); Zuo et al. (2020); Cui (2021); Zhou et al. (2022)</td>
</tr>
<tr>
<td>To bring more walk-in shop visiting and purchasing opportunities; to improve wider economic impacts in transport infrastructure</td>
<td>Neighbourhood, City center/Macro-scale</td>
<td>Citizen/Commuters</td>
<td>Standard, Guideline, Survey &amp; Design code, Strategic plan, Represent the distributional equity of transit accessibility among social groups.</td>
<td>Processed to design pedestrian network zone and regulation, Survey</td>
<td>Creating standard document related to the pedestrian network; Place-based policies in a dense city require improvement in the pedestrian network; Interconnecting the pedestrian network in order to develop the well-function</td>
<td>Lunecke and Mora (2018); Osama and Sayed (2017); Pearce et al. (2021); Belanger (2007); Tal and Handy (2012); Özbil et al. (2015); Kwon et al. (2017); M. Jabbari et al. (2018); Fonseca et al. (2022); X. Yang et al. (2022); Azad et al. (2023); Zuo et al. (2020)</td>
</tr>
<tr>
<td>To increase urban vitality</td>
<td>Urban areas, Suburban/Multi-scale</td>
<td>Citizen/Tourist/Commuters</td>
<td>Public space typologies, pedestrian flows and retail uses</td>
<td>Survey, Typology, Using Open Street Map data</td>
<td>Developing model as a service in transportation system; Considering Multi-scale in model;</td>
<td></td>
</tr>
<tr>
<td>To find the potential urban space for the pedestrian network</td>
<td>Urban areas, Suburban/Multi-scale</td>
<td>Citizen/Tourist/Commuters</td>
<td>Static built environment data and Street network</td>
<td>Survey, GIS, Space Syntax, Rhino software</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The increasing availability of spatial data with greater disaggregation promoted the use of Geographic Information Systems (GIS) in pedestrian network models. GIS has been used by many authors for various tasks, such as identifying high and low walkability, providing information on the walkability characteristics of a given region, and creating a standardized benchmark to compare different environments in terms of the characteristics shown to create the pedestrian network (Badland et al., 2013; Kim et al., 2014; Tal & Handy, 2012). Indeed, many pedestrian network attributes, namely density, land use mix, road network and accessibility, can be analyzed in GIS (Azad et al., 2021; Z. Guo & Loo, 2013; Tal & Handy, 2012). For these authors, the combination of GIS data and an environmental audit has proven to be a valid tool for assessing pedestrian network. GIS has been used in spatial analysis to assess the connectivity of the road network for cyclists and pedestrians (Lundberg & Weber, 2014). The GIS techniques are often used in combination with other approaches, namely: agent-based simulations, where GIS provides geographical data to model the walkability of neighborhoods (Badland et al., 2013; D’Orso & Migliore, 2020).

4. Discussion - Future directions for pedestrian network models

The review focuses on pedestrian network approaches in the field of urban planning. These studies rely on different data sources to achieve different objectives at different scales and areas. It can be concluded that the identification and assessment of a pedestrian network is a challenging process; especially since there are various contexts and levels of application, associated to the multi-functionality, mixed spaces, and natural features found in urban areas (Table 2). The results show that the majority of the studies focused on how to assess pedestrian network and on what criteria should be used in the evaluations of pedestrian network. Researchers mainly examined criteria related to the built environment, urban functions, accessibility, and the natural environment of pedestrian networks. Finally, these criteria were assessed using analytical tools and methods at the micro and macro level. In this context, GIS was increasingly used as a tool to analyze urban spatial attributes. Moreover, space syntax is applied to assess urban configuration and street connectivity. Less studies have been focused on where is the pedestrian network and who use the pedestrian network.

There is little evidence of where will be located the pedestrian network characteristics at site and area scale how to impact on the urban planning process. It raises up the question when the considering the pedestrian network in the urban structure how to make relationship with path segments that will be well-connected in the transportation network and have specific destinations along them. In addition, some researches were limited to city centers and neighborhoods in terms of the pedestrian network place-making and could be extended to suburban or even a large area. Other researches have taken micro, macro and even multi-scale approaches, mainly focusing on policy and guide-

![Fig. 1. Correlation among questions in the pedestrian network.](image-url)
Pedestrians cross the current road network and there are various cars and other modes of transport. It seems that the pedestrian network should consider an independent urban structure and the urban transport system should support it as a main priority. However, since the role of conceptual research is to open more debate on where the pedestrian network is located and how to provide urban transport needs in the particular urban context, with a view to creating more sustainable urban transport.

Another question that would be highlighted for future studies is who uses the pedestrian network. Since the pedestrian network would be making attractive modes to a much wider range of people, not yet perceived: in particular paths are safer and pedestrian environments are more pleasant and such facilities are the norm in urban areas. Few researchers focused on pedestrians’ needs; especially vulnerable pedestrians and disabled people. Vulnerable pedestrian groups may include children, elderly individuals, and people with disabilities, as well as individuals who are under the influence of drugs or alcohol. Understanding the behavior of these groups is important for designing and implementing effective safety interventions to reduce pedestrian injuries and fatalities. Research has shown that vulnerable pedestrian groups may exhibit different behaviors and risk-taking tendencies as compared to the general population (Gaglione et al., 2021). For example, children...
may have limited cognitive and perceptual abilities that affect their capability to accurately judge distances and speeds of oncoming vehicles. Elderly individuals may have physical impairments that affect their gait and balance, making them more susceptible to falls and collisions. People with disabilities may have limited mobility or sensory impairments that affect their capability to navigate their environment safely. It is important to consider these differences in behavior when developing interventions to improve pedestrian safety. For example, interventions may need to be tailored to the specific needs and abilities of different vulnerable groups, such as improving crosswalk markings and signal timing for elderly individuals, or providing extra supervision and education for children. Overall, understanding the behavior of vulnerable pedestrian groups is an important component of improving pedestrian safety and reducing pedestrian injuries and fatalities. The pedestrian network should provide inclusive environments for all users, encouraging people to walk and offering vibrant walking experiences.

Additionally, when designing a pedestrian network as an urban structure, it is significant to consider the element of a sufficient capacity of the transportation system. Parking often takes up valuable space that could be used to improve the pedestrian infrastructure. This can lead to conflicts between pedestrians and vehicles, making it unsafe for people to walk and increasing the risk for accidents. To address these issues, it is important for urban planners and policymakers to prioritize the pedestrian infrastructure in transportation plans and policymaking. This may involve reallocating space currently used for vehicle parking for the pedestrian infrastructure, such as wider sidewalks, improved lighting, and more accessible crosswalks. It may also involve developing and enforcing policies that prioritize pedestrian safety and convenience over vehicular traffic, such as reducing speed limits, creating more pedestrian-only zones, and installing more traffic calming measures. Overall, improving the pedestrian network infrastructure is critical for promoting safe and convenient pedestrian movement and creating more livable and sustainable urban environments.

Likewise, it seems to define a combined system involves an urban planning process and also the opinions of residents, which can be useful to strengthen the robustness of the assessment approach based on Sustainable Urban Mobility Plans (SUMPs). In addition, the physical environment is expressed through the structural characteristic of the space, which influences the overall perception of walkability. For this reason, many pedestrian studies in the literature refer to behavioral experiences related to the physical environment (Bahrainy & Khosravi, 2013; Forsyth et al., 2009; Gaglione, Gargiulo, & Zucaro, 2022; Gilderbloom et al., 2015b; Lamíquiz & López-Domínguez, 2015; Nasir, Lim, Nahavandi, & Creighton, 2014). It is important to check the results of the pedestrian models and compare them with real pedestrian behavior. Such a comparison is useful to identify the discrepancy between the pedestrian requirements and the results of the model defined by urban planners, providing additional support for the creation of the pedestrian network.

5. Conclusion

This paper examines the pedestrian network concept through a systematic literature review. The aim of this paper is to evaluate the theoretical and practical questions about pedestrian networks in an urban planning approach in order to support the development of future models/plans for pedestrian networks. Hence, the analysis of the literature review was carried out using the 3WH method by answering the following questions: (1) Where is the pedestrian network located? (2) What criteria play a role in the pedestrian network’s performance?, (3) Who uses the pedestrian network? and (4) How can the pedestrian network be analyzed?

Given the ever-increasing complexity of cities and the increasing focus on sustainability, urban structures may be undergoing major changes (S. Hong, Hui, & Lin, 2022). This paper has conducted a comprehensive systematic literature review focused on the concept of pedestrian Network studies by applying 3WH analysis method. The review showed that there is a significant body of research that emphasizes the importance of well-designed and connected pedestrian networks in promoting walking, active transportation system, and improving the overall livability of cities. It was found that connecting the pedestrian network to the transportation system requires a comprehensive and integrated approach that considers the needs and safety of pedestrians in transportation master plans and policy-making. This will support the creation of a more accessible, safe, and efficient transportation system for all users. Although, many research projects on the topic have been conducted over more than a decade, and some of them even predict and conceptualize the future, there is not yet a systematic and coherent study that synthesizes the full range of knowledge concerning “pedestrian network”. In addition, there is a need for further research on the topic, particularly in the areas of network analysis, design guidelines, and implementation strategies to effectively promote pedestrian active mobility and safety.

Hence, it is crucial to shed light on the existing and new concepts underlying the vision of the future urban fabric and to capture and analyze the perceptions, insights and expectations of relevant scholars and practitioners. Addressed to analyze the condition of pedestrian networks is still a challenge due to the diverse urban environments and the different attributes that influence the decision to walk. However, considering the pedestrian network as a new urban structure in the urban planning process include global overview to where, what, who, and how that will provide good conditions for walking, encourage people to walk and change cities towards more sustainable urban development is a crucial goal. (Fig. 1)

Declaration of Competing Interest

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

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