Journal of Urban Mobility 3 (2023) 100052

Contents lists available at ScienceDirect

Journal of Urban Mobility

journal homepage: www.elsevier.com/locate/urbmob

Walkability for children in Bologna: Beyond the 15-minute city framework☆

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ARTICLE INFO

Keywords:
Walkability
Children
GIS
15-Minute city
Bologna

ABSTRACT

The current research work is based on an extended spatial analysis executed through the application of GIS, aiming at assessing the level of walkability in the city of Bologna (Italy). In particular, the research focused on walkability for children (aged between 5 to 13 years old), as they experience the city differently than adult pedestrians, since they are more vulnerable to road accidents and they need proper infrastructures to freely play outdoors and walk independently. The GIS analysis was based on a series of location-based data retrieved from different open source repositories and focused on the level of usefulness, comfort, safety, and attractiveness of Bologna for child pedestrians. The proposed Walkability for Children Index was aimed at identifying the neighborhoods characterized by the lowest level of pedestrian friendliness in relation to the childrens needs while walking. Results helped to identify and characterize a short list of suitable areas where to prioritize interventions focusing, for example, on guaranteeing the presence of relevant public services within a walkable distance of 15 minutes from place of residence and on the implementation of urban regeneration projects through the tactical urbanism approach.

1. Introduction

Encouraging the shift towards Sustainable Urban Mobility Plans (i.e., *SUMPs*) based on public transport, shared-micro mobility, and active modes of travel such us walking and cycling is one of the main challenges of European cities (Buhrmann et al., 2019), since they are increasingly facing problems of traffic congestion, road safety, energy dependency, and air pollution linked to the urbanisation global trend (United Nations, 2016).

In this context, the activities of urban mobility planners are shifting towards a focus on walkability, namely how friendly the urban environment is for walking, living, visiting, or spending time in public spaces (Abley and Hill, 2005; Annunziata and Garau, 2020; Forsyth, 2015). Walkability contributes to the quality of life of citizens by enhancing physical activity, road safety, well-being, air quality, and social inclusion (Forum, 2012). Improving pedestrian mobility implies barrier-free and safe sidewalks, but also human-scale environments which allow people to enjoy walking and gather in comfort (Gehl, 2013). In this regard, the General Theory of Walkability proposed by Speck (2013) explains the essential elements for evaluating the level of walkability of an urban environment, such as: the presence of public services within a walkable distance, the level of comfort and road safety experienced by people while walking, and the attractiveness of the urban areas in terms of architectural design and social context.

The attention to pedestrian mobility started with the principles highlighted by the European Charter of Pedestrian Rights issued by the European Parliament in 1988[1], that focused on the need to ensure the comfort and safety of all pedestrians in urban areas:

> Article I: "*The pedestrian has the right to live in a healthy environment and freely to enjoy the amenities offered by public areas under conditions that adequately safeguard his physical and psychological well-being.*"

[1] See: https://goo.gl/0vKTJ9

☆ The authors thank the Department of Urban Planning of the Municipality of Bologna and the team of Foundation for Urban Innovations for sharing data and information for the calibration process of the proposed Walkability for Children Index. The research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The analyzed data were treated according to the GDPR-General Data Protection Regulation (EU, 2016/679). An interactive map about the proposed Walkability for Children Index in the city of Bologna is accessible at this link: https://studio.foursquare.com/public/a6d16583-4641-4fd8-ba0f-9a2cccbebd95/embed.

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https://doi.org/10.1016/j.urbmob.2023.100052
Received 29 June 2022; Received in revised form 10 March 2023; Accepted 30 March 2023

Since then, walkability has become even more crucial considering the unprecedented effects of the Covid-19 pandemic on urban mobility (Gargiulo et al., 2021; Hayrullahoğlu and Varol, 2022; Rahman and Thill, 2022; Transport, 2022). In July 2020, the European Commission (European Platform on Sustainable Urban Mobility Plans, 2020) provided *ad hoc* guidelines for implementing short-term transport planning interventions to face the current critical situation. Among the principles included in the document, the section "Active Mobility" has a specific focus on pedestrian mobility.

In this regard, the activity of transport planners and decision makers is projected ahead towards sustainable, healthy, and equitable urban development solutions, which could enhance the social, environmental and economic resilience. This includes a reorganization of the urban system as a whole, focusing on its physical and functional characteristics (e.g., land use, road network, transport infrastructures, etc.) and the mobility demand of the users, in order to guarantee the possibility to access necessary goods, services, and amenities within a comfortable walking distance from any residential area.

In this framework, the goal of a *15-minute city* (Moreno et al., 2021) is to create a more livable and sustainable urban environment by reducing the need for car travel and promoting the use of more active and environmentally friendly modes of transportation. This can help to reduce traffic congestion, air pollution, and carbon emissions, and make it easier for people to access the things they need on a daily basis.

Although traditional approaches about pedestrian mobility tend to focus on the spatial dimension (Annunziata and Garau, 2020) and on universal design indicators (Steinfeld, 2011), individual characteristics of pedestrians have a significant impact on the perceived level of walkability. As highlighted by the 2030 Agenda for Sustainable Development adopted by all United Nations Member States (United Nations, 2016) (i.e., *SDG 11.2-Sustainable Transport for All*), urban mobility should be designed to be more inclusive to the needs of those in vulnerable situations, such as women, children, persons with disabilities and older persons:

> "*By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.*" (United Nations, 2016, p. 24)

Within the investigation of vulnerable city users' needs for walkability assessment, the current research work focuses on child pedestrians aged between 5 to 13 years old (primary and secondary schools students). Despite recent efforts in the design of safe, comfortable, and livable streets and public spaces for children (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019), there is still a lack of knowledge regarding walkability for children, especially due to the lack of available data.

Research about this topic has often been motivated by the necessity to contrasts the social costs of child pedestrian crashes. Compared to adults, children are indeed more vulnerable to road traffic collisions (World Health Organization, 2018), due to poor knowledge of regulations and the complex interaction of psychological and contextual factors, such as the coordination of attention and motor functions, and the individual perception of road risk (Evans and Norman, 2003; Rosenbloom et al., 2008; Sisiopiku and Akin, 2003).

However, various bodies of research point to the necessity of adopting a more comprehensive child-friendly urban planning approach (Korpela, 2003), taking into account social facets of public space starting from a broader understanding of walkability. This means understanding opportunities for urban areas to provide comfort and joy as well as safe and inclusive experiences through public spaces, playgrounds, and green areas (Voce, 2018). Walkability for children includes, in fact, opportunities to freely play outdoors, walk independently and safe, and feel a sense of belonging within their neighbourhoods (Krysiak, 2020).

In this framework, the current study was conducted in collaboration with the Department of Urban Planning of the Municipality of Bologna and the Foundation for Urban Innovations, aiming at supporting the planning of future sustainable and inclusive mobility strategies in the city of Bologna. In particular, the research started from the theoretical background about the evaluation of the level of walkability for children (see Section 2). According to the proposed methodology (see Section 3), a series of location-based open data were analysed by using Geographic Information Systems (see Section 4) to assess the level of usefulness, comfort, safety, attractiveness, and accessibility of the city for child pedestrians. The analyses were particularly focused on the neighborhood Navile of the City Bologna, which was selected by the Department of Urban Planning for the future implementation of an interim public space by using the tactical urbanism approach[2] (Peyton, 2019). The paper concludes with final remarks about results and future works.

2. Related works

Starting from to the General Theory of Walkability (Speck, 2013), and taking advantage of previous works already presented by the authors about this topic (Abdelfattah et al., 2021; Gorrini et al., 2021), the current Section presents some of the most relevant contributions about walkability assessment for children. The considered scientific contributions were organized in a tabular structure considering a series of walkability assessment criteria and methods (see Table 1).

2.1. Walkability assessment criteria

The proposed walkability assessment criteria are focused on the accessibility of public services within a walkable distance and on the level of comfort, road safety, and attractiveness of urban areas (see Table 1):

- *Usefulness* (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019): the urban territory should be designed and planned with an adequate level of land-use mix, street connectivity and commercial density, to guarantee the accessibility of relevant services for children (e.g., local shops, schools, libraries, health services, etc.) within a walkable distance from their place of residence;
- *Comfort* (Aerts, 2018; Danenberg et al., 2018; Peyton, 2019; Rothman et al., 2014; Sisiopiku and Akin, 2003; Voce, 2018): streets should be designed according to a series of standard criteria of quality (e.g., pavement type and continuity on side-walks, adequate width of side-walks to avoid crowding in case of intense pedestrian flows, etc.), but also according to a set of highly recommended elements for the comfort of children while walking (e.g., playgrounds, green areas, benches, fountains, etc.);
- *Safety* (Aerts, 2018; Danenberg et al., 2018; Evans and Norman, 2003; Peyton, 2019; Rosenbloom et al., 2008; Rothman et al., 2014; Sisiopiku and Akin, 2003; Voce, 2018): streets should be designed to guarantee the safety of children while crossing during day and nighttime (e.g., speed bumpers in proximity of the zebra crossings, illumination systems at intersections to guarantee visibility, legible horizontal and vertical traffic signage, etc.);
- *Attractiveness* (Peyton, 2019): the city should be designed to have a polycentric structure, with several and distinctive areas of attraction for children (e.g., points of interest, events, quality of the architectural streetscape, vitality of the social context, etc.).

2.2. Walkability assessment tools

The proposed walkability assessment tools include a wide range of methodologies and techniques that have been developed to empirically measure walkability (see Table 1):

[2] As part of the EN-UAC research project EX-TRA "EXperimenting with city streets to TRAnsform urban mobility" (No. 99950032).

Table 1
Theoretical background about walkability for children, focusing on assessment criteria and tools.

	Walkability Assessment Criteria				Walkability Assessment Tools		
References	Usefulness	Comfort	Safety	Attractiveness	GIS analysis, Space Syntax	Observations, Sensors, Apps	Audit Tools, Co-creation
Aerts (2018)	•	•	•		•		•
Danenberg et al. (2018)	•	•	•				•
Evans and Norman (2003)			•				•
Peyton (2019)	•	•	•	•	•	•	
Sisiopiku and Akin (2003)		•	•			•	•
Rosenbloom et al. (2008)			•			•	
Rothman et al. (2014)		•	•			•	
Voce (2018)		•	•		•		•

- *Geographic Information Systems and Space Syntax* (Aerts, 2018; Peyton, 2019; Voce, 2018): these methods can be applied for characterizing a neighbourhoods suitability for walking activity among children through the analysis of location-based data related to the topographical, cadastral, infrastructural, and architectural features of urban areas (e.g., presence of public services, quality of road infrastructures, census indicators about the socio-demographic characteristics of the inhabitants, etc.). As an example, the use of GIS offer the possibility to evaluate if necessary goods, services, and amenities are within a 15-minute walk, bike ride, or public transit trip from any residential area through isometric and isochronal analyses. The use of Space Syntax allows to combine different attributes of the sidewalk network (e.g., level of integration of streets, shortest paths, type of land use, etc.);
- *Observations, Sensors and Smartphone Apps* (Peyton, 2019; Rosenbloom et al., 2008; Rothman et al., 2014; Sisiopiku and Akin, 2003): on-site observations can support the visual detection of the actual behaviour of children while walking and crossing in a certain street and public space (e.g., desired lines, jaywalking, impact of spatial elements, etc.). When supported by video analytics, observations can be applied to produce behavioural maps by systematically annotating where movements occur in a certain environment (e.g., people counting, pedestrian trajectories, pedestrian-vehicle interactions, etc.). Wi-Fi sensors, GPS tools, and smartphone applications can support, instead, the collection of disaggregated data about footfall activity patterns and OD matrices in large scale scenarios with high spatial and temporal granularity;
- *Audit Tools and Co-creation* (Aerts, 2018; Danenberg et al., 2018; Evans and Norman, 2003; Sisiopiku and Akin, 2003; Voce, 2018): audit tools are based on the use of validated measures, self-report, survey questionnaires, and interviews to study the subjective perception of children about the level of walkability of a determined urban area. Co-creation methods, such as focus groups and design laboratories, can be also applied to directly engage children into a participatory design process through interactive workshops.

3. Enabling data and methodology

The methodological approach which sets the current research is based on the application of GIS[3] for the analysis of a series of location-based data, which were select in collaboration with the Department of Urban Planning of the Municipality of Bologna and the team of Foundation for Urban Innovations and retrieved from several open-data repositories (see Table 2). According to the proposed theoretical background, the considered dataset spans several domains related to the study of walkability for children (i.e., *usefulness, comfort, safety, attractiveness*).

The analysis was focused on the territory of the City of Bologna (i.e., *macro scale*), aiming at identifying and characterizing the urban areas where to prioritize interventions for enhancing the level of walkability for children. In particular, a series of multi-layer thematic maps were produced according to the proposed walkability assessment criteria. The analysis was aimed at developing and testing an innovative walkability metric, against already available standard (i.e., Walk Score®).

As a preliminary step for the analysis of the retrieved location-based data, an *ad hoc* designed grid was implemented to calculate the spatial distribution of punctual, linear, and areal vectors on every cell (250 m x 250 m). In order to ensure a homogeneous dataset and a robust comparative basis, data was harmonized and normalized on cells level through a 0–1 scale (creating Z-scores that follow the normal distribution of the values).

The indicators were then included in the calculation of the Level of Usefulness Index (LUI), Level Comfort Index (LCI), Level Safety Index (LSI), and Level of Attractiveness Index (LAI). This was essentially based on weighted summations of the Z-scores of the variables proposed in this study (see Table 2).

The weights definition (Kalton and Flores-Cervantes, 2003) was based on a three-step process: (*i*) assigning a reference magnitude for the weights based on the proposed theoretical background, in order to strengthen the impact of the indicators and criteria which were defined by previous research works as more relevant considering the needs of children while walking; (*ii*) adjust the magnitude of the weights using information provided by the Department of Urban Planning of the Municipality of Bologna and the team of Foundation for Urban Innovations; and (*iii*) varying the definition of the weights through a sensitivity analysis to see how sensitive the results of the analysis were to changes in the definition of the indexes and to optimize the calculation of the proposed multidimensional data analysis.

Percentile frequency distribution of results made possible the identification of the cells (ce) characterized by the lowest level of Walkability for Children Index (WCI) of the City of Bologna, which represents a synthesis of four proposed indexes. The results of the analysis are visualized considering the administrative boundaries of the neighborhoods and the urban sub-areas of Bologna (namely *Areali*, a geographical unit between the statistical areas and the neighborhoods).

3.1. Level of Usefulness Index

The calculation of the Level of Usefulness Index (LUI) was focused on the local services that impact neighborhood quality for children and are owned, operated, and certified by the Municipality of Bologna. The considered dataset spans several domains, as follows: Education Services (Ed) (e.g., public kindergarten, nursery school, primary school, secondary school, etc.); Health Services (He) (e.g., hospital, local health service, clinic, consulting service, pharmacy, etc.); Local Shops (Sh) (e.g., grocery, local market, non-food local shop, tobacconist, newsstand, etc.); and Neighborhood Services (Ne) (e.g., bank and ATM, post office, personal service such as hairdresser, bar, local public administration office, etc.).

Data analysis was based on a series of isochrone maps showing lines of travel time by walking on the road network to reach each service on a 0–3 scale (considered walking speed of children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 1; > 15

[3] GIS analysis has been performed by using the software QGIS v.3.20.1.

Table 2
The open data that were retrieved and analyzed through GIS.

Criteria	Indicators	Label	Weight	Data Source	Year
Preliminary data	City of Bologna	-	-	Open Data Bologna	2021
	Neighborhoods	-	-	Open Data Bologna	2021
	Urban Sub-areas	-	-	PUG City of Bologna	2021
	Children Population	Ch	-	ISTAT	2011
	Road Network	Ro	-	Open Data Bologna	2021
	Land Use	La	-	Copernicus Service	2018
Usefulness	Education Services	Ed	0.25	PUG City of Bologna	2020
	Health Services	He	0.25	PUG City of Bologna	2020
	Local Shops	Sh	0.25	PUG City of Bologna	2019
	Neighborhood Services	Ne	0.25	PUG City of Bologna	2019
Comfort	Covered Walkways	Co	0.2	Open Data Bologna	2016
	Green Areas	Gr	0.3	PUG City of Bologna	2020
	Pedestrian Paths and Squares	Pe	0.4	PUG City of Bologna	2020
	Urban Furniture	Ur	0.1	Open Data Bologna	2017
Safety	Environmental Islands	Ei	0.4	Open Data Bologna	2017
	Pedestrian Road Accidents	Pr	-0.6	ISTAT	2018-20
Attractiveness	Community Services	Cm	0.33	PUG City of Bologna	2020
	Cultural Services	Cu	0.33	PUG City of Bologna	2020
	Sport Services	Sp	0.33	PUG City of Bologna	2020

minutes = 0), which were combined to the calculation of the distribution of each dataset on cells (ce). The calculation of the LUI was based on the weighted summation of the Z-scores of each indicator (see Eq. 1). The constant parameters KEd, KHe, KSh, and KNe were equally balanced ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Ed}} Z\_Ed_{ce} + {}_{K_{He}} Z\_He_{ce} + {}_{K_{Sh}} Z\_Sh_{ce} + {}_{K_{Ne}} Z\_Ne_{ce} \quad (1)$$

3.2. Level of Comfort Index

The calculation of the Level of Comfort Index (LCI) was focused on pedestrian infrastructures and facilities, as follows: Covered Walkways (Co); Green Areas (Gr), Pedestrian Paths and Squares (Pe); and Urban Furniture (Ur). This allowed to consider the planimetric base map containing sidewalks area, historical porticoes area (a landmark of the city center of Bologna, which was recently recognized as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization[4]), open space features, urban parks (entry points), urban community gardens (entry points), and the localization of urban furniture for sitting, resting, reading, and studying (e.g., benches, tables, bike parking racks, drinking fountains, etc.).

Regarding green areas, data analysis was based on an isochrone map showing lines of travel time by walking on the road network to reach them on a 0–3 scale (considered walking speed of children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 3; > 15 minutes = 0), which was combined to the calculation of the distribution of data on cells (ce). Regarding the other indicators, instead, data analysis was based on calculating the spatial distribution of each dataset on cell (ce). The calculation of the LCI was based on a weighted summation of the Z-scores of each indicator (see Eq. 2 and Fig. 1). According to the proposed theoretical background, the constant parameters KCo (corresponding to 0.2), KGr (corresponding to 0.3), KPe (corresponding to 0.4), and KUr (corresponding to 0.1) were weighted to accentuate the impact of sidewalk infrastructures on LCI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Co}} Z\_Co_{ce} + {}_{K_{Gr}} Z\_Gr_{ce} + {}_{K_{Pe}} Z\_Pe_{ce} + {}_{K_{Ur}} Z\_Ur_{ce} \quad (2)$$

[4] See: https://whc.unesco.org/en/list/1650

3.3. Level of Safety Index

The calculation of the Level of Safety Index (LSI) was focused on pedestrian road safety issues, as follows: Environmental Islands (Ei) and Pedestrian Road Accidents (Pr). The first dataset allowed to consider the localization of the urban areas in which a series of interventions were carried out by the Municipality of Bologna to improve the functionality and safety of the roads (e.g., 30 Km/h maximum speed limit, moderated traffic volumes, containment of crossing flows, etc.), but also to reduce atmospheric, acoustic and visual pollution. The second dataset allowed to consider the streets and road intersections with the highest number of pedestrians killed and severely injured due to road accidents during the period 2018-20[5]

Data analysis was based on calculating the distribution of the dataset on cell (ce). Moreover, the dataset related the pedestrian road accidents was also combined to the number of road intersections on cell (ce). The calculation of the LSI was based on a weighted summation of the Z-scores of each indicator (see Eq. 3). According to the proposed theoretical background, the constant parameters KEi (corresponding to 0.4) and KPr (corresponding to - 0.6) were weighted to accentuate the impact of road accidents on LSI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = {}_{K_{Ei}} Z\_Ei_{ce} + {}_{K_{Pr}} Z\_Pr_{ce} \quad (3)$$

3.4. Level of Attractiveness Index

The calculation of the Level of Attractiveness Index (LAI) was focused on the local services and facilities that impact neighborhood attractiveness for children and are owned, operated, and certified by the Municipality of Bologna, as follows: Community Services (Cm) (e.g., community centers, association centers, civic and multipurpose centers, neighborhood centers, places of worship, etc.); Cultural Services (Cu) (e.g., libraries, etc.); Sport Services (Sp) (e.g., gyms, sport facilities, etc.).

[5] A preliminary analysis showed 733 pedestrian road accidents (15 killed pedestrians, 820 seriously injured pedestrians), which were characterized for the large majority by the following circumstances: “He/She crossed the street at a pedestrian crossing not protected by traffic lights or by agents” (27%); ”He/She crossed the street at a pedestrian crossing protected by a traffic light or by an agent, respecting the signs” (17%); and “He/She crossed the road irregularly” (16%).

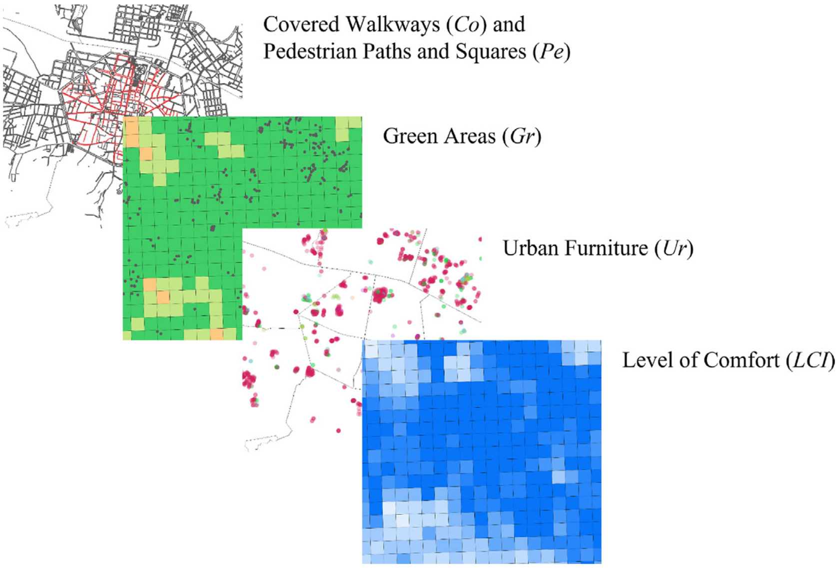

Fig. 1. An example of the proposed cartographic analysis, based on the spatial distribution of each dataset included in the analysis of the Level of Comfort Index (LCI).

Table 3
Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), Level of Attractiveness (LAI), and the Walkability for Children Index (WCI) of the Neighborhoods and urban sub-areas of the City of Bologna.

Neighborhoods	Urban Sub-areas	Z_LUI	Z_LCI	Z_LSI	Z_LAI	Z_WCI
Borgo Panigale - Reno	Borgo Panigale	0.390	0.360	0.471	0.354	0.385
	San Viola	0.807	0.766	0.623	0.750	0.795
	Barca	0.821	0.819	0.486	0.787	0.781
Navile	Lame	0.461	0.460	0.435	0.469	0.462
	Corticella	0.513	0.463	0.441	0.456	0.470
	Bolognina	0.819	0.733	0.444	0.830	0.761
Porto Saragozza	Costa Saragozza	0.395	0.394	0.493	0.406	0.400
	Saffi	0.788	0.755	0.534	0.758	0.763
	Marconi	0.925	0.965	0.803	0.938	0.893
	Malpighi	0.928	0.904	0.806	0.949	0.875
San Donato - San Vitale	San Donato	0.453	0.436	0.484	0.525	0.463
	San Vitale	0.625	0.585	0.427	0.615	0.569
Santo Stefano	Colli	0.240	0.262	0.454	0.273	0.274
	Murri	0.887	0.814	0.365	0.821	0.702
	Irnerio	0.917	0.928	0.782	0.943	0.893
	Galvani	0.923	0.923	0.872	0.954	0.885
Savena	San Ruffillo	0.573	0.439	0.518	0.529	0.468
	Mazzini	0.762	0.768	0.448	0.719	0.711

Data analysis was based on a series of isochrone maps showing lines of travel time by walking on the road netowrk to reach each service on a 0–3 scale (considered walking speed or children = 1 m/sec; travel time ≤ 5 minutes = 3; from 6 to 10 minutes = 2; from 11 to 15 = 3; > 15 minutes = 0), which were combined to the calculation of the distribution of each dataset on cells (ce). The calculation of the LAI was based on the weighted summation of the Z-scores of each indicator (see Eq. 4). The constant parameters KCm, KCu, and KSp were equally balanced ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values.

$$\sum_{k=1}^{0} = K_{Cm} Z\_Cm_{ce} + K_{Cu} Z\_Cu_{ce} + K_{Sp} Z\_Sp_{ce} \tag{4}$$

3.5. Walkability for Children Index

The results related to LUI, LCI, LSI, and LAI were further analyzed to calculate the proposed Walkability for Children Index (WCI). This was essentially based on a weighted summation of the Z-scores of each index proposed in this study (see Eq. 5). According to the results of the proposed theoretical background, the constant parameters $KLUI$ (corresponding to 0.15), $KLCI$ (corresponding to 0.3), $KLSI$ (corresponding to 0.4), and KAI (corresponding to 0.15) were weighted to accentuate the impact of the level of comfort and safety on WCI ($\sum$ constant parameters = 1). Results were normalized on a 0–1 scale, creating Z-scores that follow the normal distribution of the values. Finally, the results of the analysis were further filtered taking into account additional information related to census data. In particular, the cells characterized by the lower population density of children aged between 5 to 13 years old ($Ch \leq$ 4.310 children/Km^2 - 20th percentile) were not considered for presenting the results of the analysis[6].

$$\sum_{k=1}^{0} = K_{LUI} Z\_LUI_{ce} + K_{LCI} Z\_LCI_{ce} + K_{LSI} Z\_LSI_{ce} + K_{LAI} Z\_LAI_{ce} \tag{5}$$

[6] According to the latest available data from the Italian National Institute of Statistics (ISTAT) in 2021, the population of Bologna was approximately 400,000 people. Approximately 7.6% of the population are aged between 5 to 13 years old.

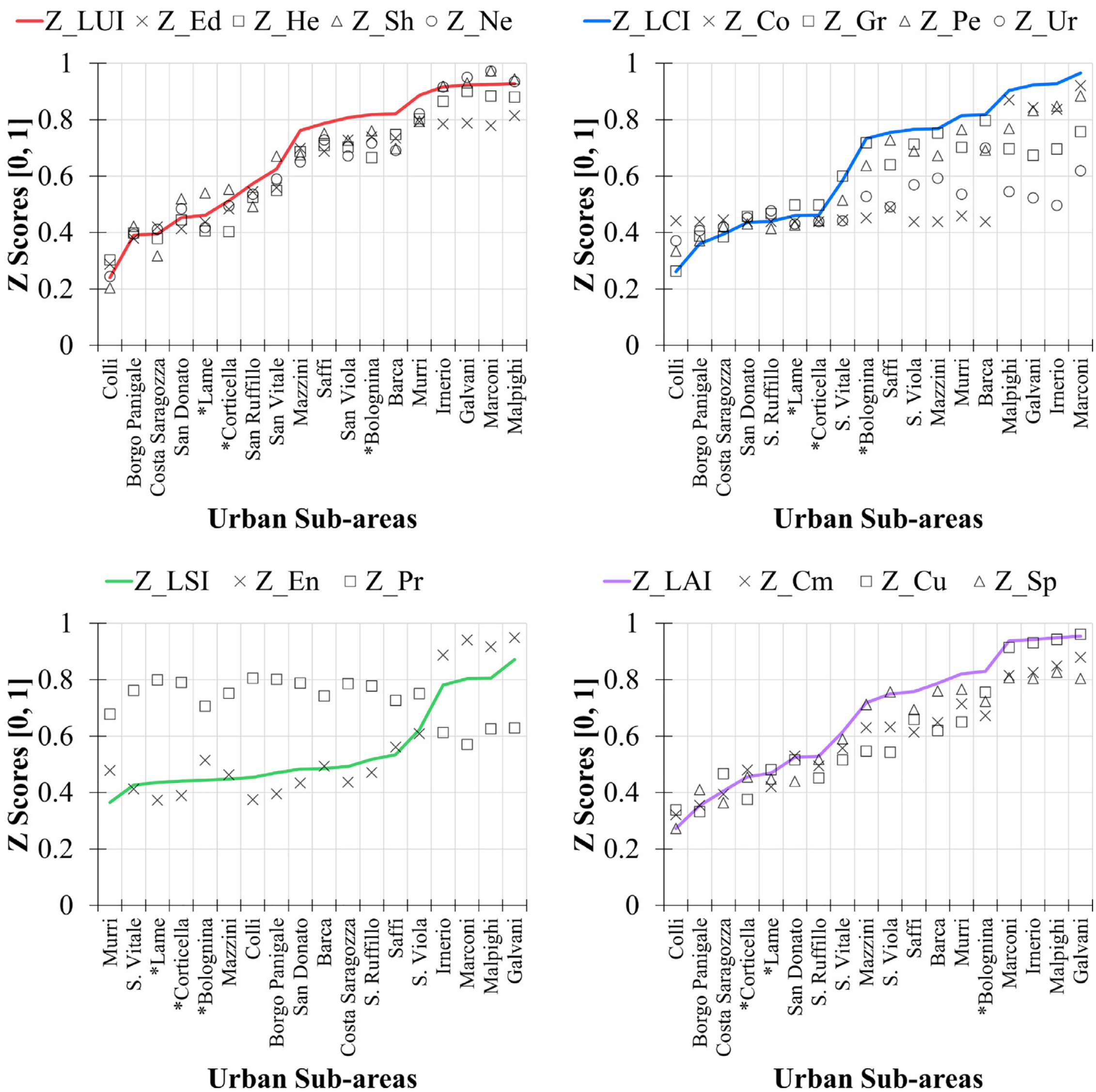

Fig. 2. Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), and Level of Attractiveness (LAI) of the urban sub-areas of the City of Bologna. The sub-areas marked with $*$ are those belonging to the neighborhood Navile.

4. Results

The proposed GIS-based analysis was applied to produce a cartographic analysis and a series of thematic maps focused on the proposed walkability assessment criteria (see Section 2). Results are visualized considering both the grid and the administrative boundaries of the neighborhoods and the urban sub-areas of Bologna, with a focus on the neighborhood Navile. In particular, results helped to identify the cells (ce) characterized by the lowest level of usefulness, comfort, safety, and attractiveness, as follows:

- Level of Usefulness Index ($LUI \leq 0.149$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas characterized by a scarce possibility for children to access relevant services within a comfortable walking distance;
- Level of Comfort Index ($LCI \leq 0.198$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas characterized by the lack of recommended elements for the comfort of children while walking (e.g., sidewalks, squares, green areas, etc.);
- Level of Safety Index ($LSI \leq 0.297$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the streets and intersections characterized by an insufficient level of road safety for pedestrians due to car accidents;
- Level of Attractiveness Index ($LAI \leq 0.128$ - 20th percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 4), highlighting the areas character-

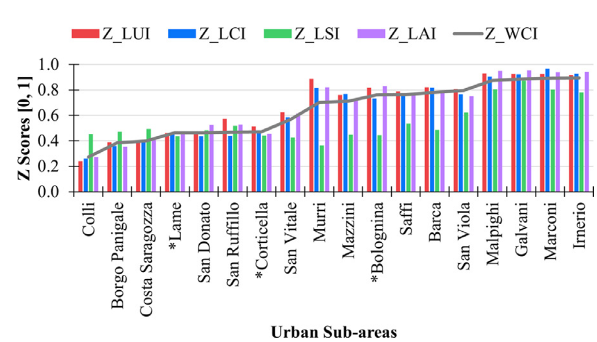

Fig. 3. Results of the Walkability for Children Index (WCI) of the City of Bologna. The urban sub-areas marked with $*$ are those belonging to the neighborhood Navile.

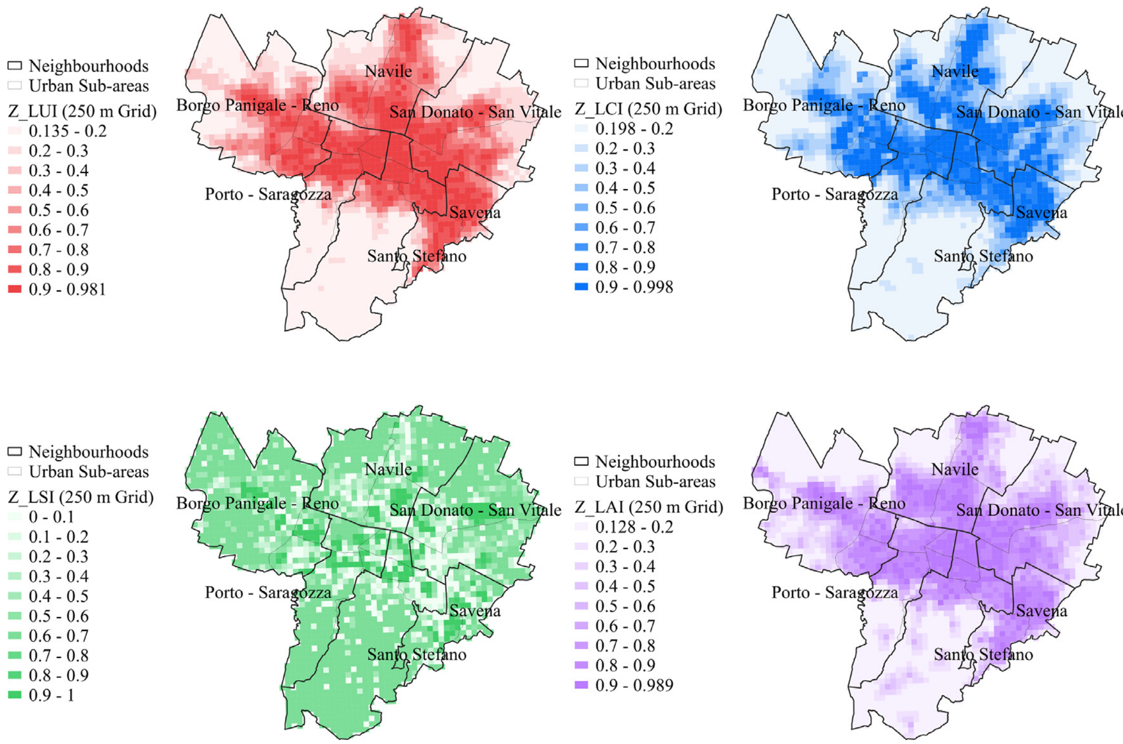

Fig. 4. Results of the Level of Usefulness Index (LUI), Level of Comfort Index (LCI), Level of Safety Index (LSI), and Level of Attractiveness (LAI) of the neighborhoods of the City of Bologna.

ized by the lack of distinctive points of interest for children (e.g., community services, sport facilities, etc.).

In terms of walkability, Bologna is considered a highly walkable city, with narrow streets and a compact layout that make it easy to navigate on foot (Fonseca et al., 2022). The city center is particularly pedestrian-friendly, with a network of narrow streets and alleys, as well as numerous piazzas and squares that are popular destinations for locals and tourists alike. Bologna is also home to a well-developed public transportation system, which includes buses, trams, and a light rail network. Overall, Bologna is a city that is well-suited for walking and using public transportation, with a variety of options available to suit the needs of different age groups and mobility levels.

In this context, the results of the mapping analysis revealed that Bologna performs very well overall in terms of walkability for children (see Fig. 5). More in detail, results helped to identify and characterize a short list of suitable urban areas of the city of Bologna where to prioritize future interventions to enhance the level of walkability for children, as mainly located in the peripheral areas of the city ($WCI \leq 0.214$ 20^{th} percentile, see Table 3, Fig. 2, Fig. 3, and Fig. 5). In particular, the maps related to the level of usefulness, comfort, safety, and attractiveness (see Fig. 4) demonstrates that most neighbourhoods are covered by essential services for children, although some southern neighbourhoods can benefit from a more diversified service supply to ensure a more balanced offering, as well as the implementation of additional infrastructures for pedestrians (e.g., green areas, urban furniture, community and sport services, etc.). Moreover, the streets in the city center of Bologna should be designed to guarantee an higher level of safety of children (e.g., speed bumpers in proximity of the zebra crossings, illumination systems at intersections to guarantee visibility, environmental islands, etc.).

The results of the analysis achieved through the proposed Walkability for Children Index have been compared to available standard walkability measures, with particular reference to the Walk Score® (see Fig. 6). A quantitative comparison was limited due to the different input data, considering that the Walk Score is based on the combination of three elements: the shortest distance to a group of pre-selected destinations (e.g., businesses, parks, theaters, schools, etc.), the block length, and the intersection density around the origin (Hall and Ram, 2018). However, the current study proposes a qualitative comparison between these two measures, in order to highlight the impact of individual characteristics of pedestrians, namely their age, on the perceived level of walkability. As an example, the central areas of the neighborhoods Navile, Santo Stefano, and Savena showed worse walkability scores in the WCI than in the Walk Score due to the lack of dedicated infrastructures (i.e., *comfort*) and pedestrian-car accidents in the areas (i.e., *safety*).

5. Conclusion and future work

Various bodies of research point to the necessity of adopting a user-centered approach for transport planning, that considers social facets of the city users (e.g., mobility impairments, age, gender, etc.) and a broader understanding of urban mobility. However, there is still a lack of knowledge about the needs and expectations of children regarding public spaces and walkability, primarily due to limitations in gathering data about this topic. In this framework, the current work was firstly aimed at presenting the theoretical background about the criteria and tools for the assessment of the level of walkability in urban environments, focusing on the specific needs of child pedestrians.

The objective of the research was the investigation of the level of walkability for children through the application of Geographic Information Systems. This was aimed at defining a novel Walkability for Children Index (WCI) through the analysis of a series of location-based open data about the city of Bologna (see Fig. 5). In particular, data analysis focused on the level of pedestrian friendliness of the city in terms of usefulness, comfort, safety, and attractiveness.

The results of the proposed GIS analysis revealed important insights about the possibility to assess the level of walkability for children. Our study found that neighborhoods with higher walkability scores tend to have more amenities, such as parks and playgrounds, which can encourage physical activity and outdoor play for children. These findings are

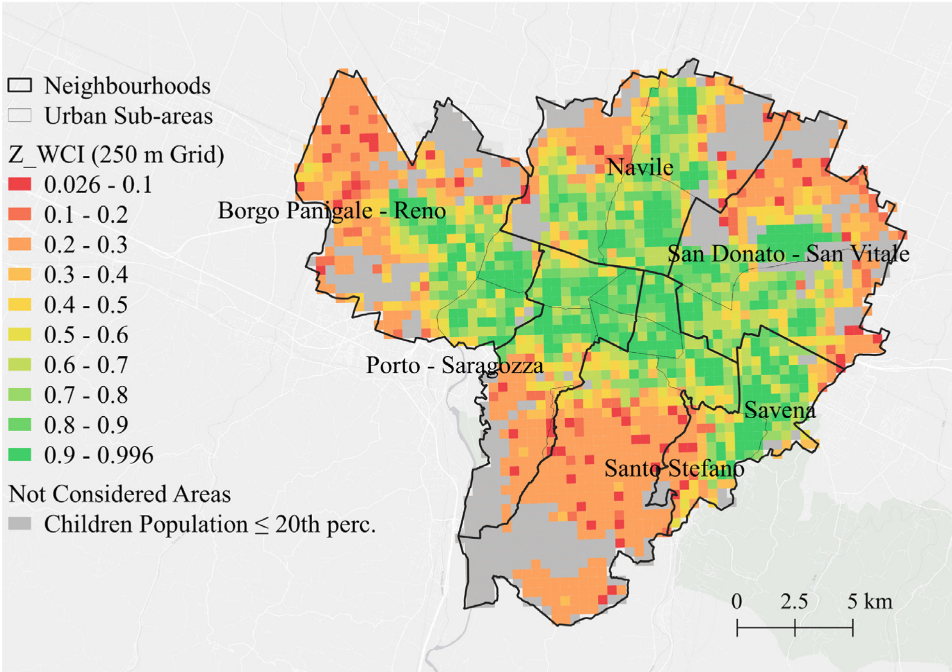

Fig. 5. Results of the Walkability for Children Index (WCI).

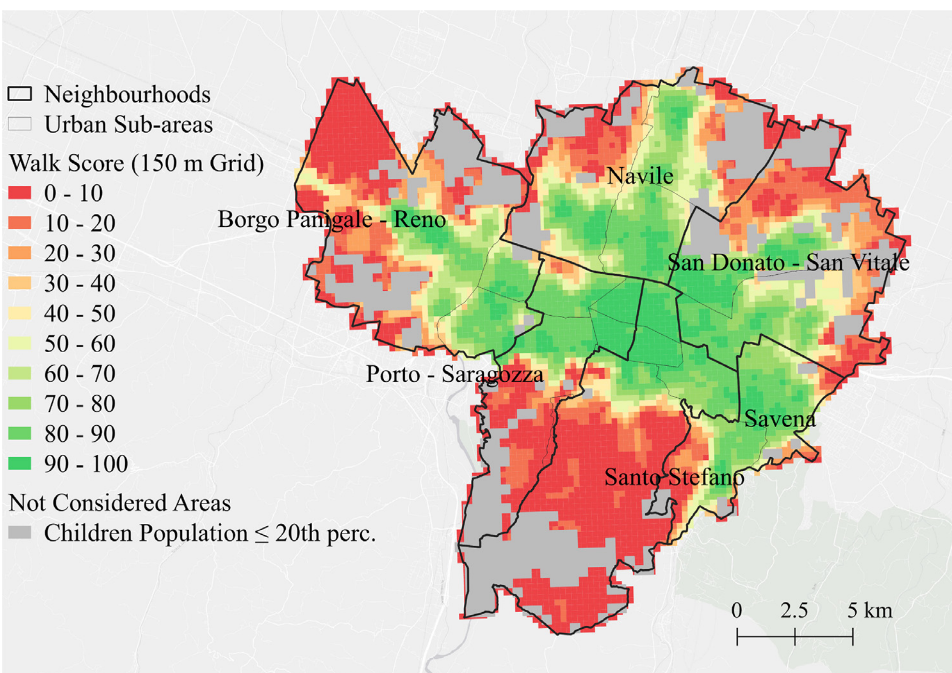

Fig. 6. Results of the Walk Score® analysis (< 60 poor, 60–80 moderate, > 80 high level).

consistent with previous research that has highlighted the importance of access to green spaces in promoting active lifestyles among children (Voce, 2018).

Moreover, our study found that neighborhoods with higher walkability scores tend to have lower traffic volumes and speed limits, which may contribute to safer pedestrian environments for children. This finding is particularly important given that pedestrian injuries are a leading cause of injury-related deaths among children (Evans and Norman, 2003; Rosenbloom et al., 2008). By identifying the characteristics of neighborhoods that support safe walking environments, our study can inform urban planning and policy efforts to create more child-friendly communities.

However, our study also highlighted disparities in walkability across different neighborhoods. Specifically, we found that neighborhoods with lower walkability scores tended to be located in peripheral and low-income areas. This finding is consistent with previous research that has shown that low-income and minority populations often face greater barriers to accessing safe and healthy environments (Gatrell et al., 2004). Thus, our study underscored the need for targeted interventions and policies that address these disparities and promote equitable access to walkable environments for all children.

Overall, this GIS analysis provided important insights into the walkability of neighborhoods for children, and highlights opportunities for improving the design and planning of child-friendly communities. By addressing disparities in walkability and promoting safe and accessible environments for all children, we can create healthier, more equitable communities that support the well-being and development of our youngest residents.

In particular, the final goal of the analysis was to identify and characterize a short list of suitable urban areas where to prioritize interventions to enhance the level of walkability for children (Peyton, 2019). This could be focused, for example, on innovative design elements for streets and public spaces focused on both the comfort and safety of children, and on differentiated urban planning strategies, such as: (*i*) inform decision makers and practitioners on the constraints and opportunities of the urban areas with regard to the street network and how it can attract or deter child pedestrian movements; (*ii*) offer insights on how the area can be optimised in its context regarding its viability, the design of sustainable development, and the creation of lively urban spaces; and (*iii*) test different strategic guidelines and design proposals.

The area identified by the Municipality of Bologna for the implementation of an interim public space was further investigated by the authors through onsite observations supported by video cameras and computer vision applications (Buch et al., 2011; Ceccarelli et al., 2023, *submitted*; Niu et al., 2022), aiming at producing *ex-ante* and *ex-post* intervention assessments related to level of comfort and safety for pedestrians. In particular, the analysis was aimed at producing behavioural maps by systematically noting specific pedestrians behaviours and movements occurring in the considered area (e.g., people counting and tracking, pedestrian flow patterns estimation, pedestrian-vehicle interactions, etc.), in order to support the iterative design process.

In conclusion, the research work represents a valuable example of the possibility to analyze digitally widespread open data sources to support decision-makers by unveiling specific target-users needs. According to the urban agenda for sustainability (e.g., SDG 11.2-Sustainable Transport for All, SDG 3.6-Reduced Road Deaths, Vision Zero Project, School Street Initiative, etc.), the presented results could be of notable interest for public institutions involved in the design of inclusive mobility strategies focused on the needs of children.

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.

CRediT authorship contribution statement

Andrea Gorrini: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Dante Presicce:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization. **Federico Messa:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Rawad Choubassi:** Conceptualization, Methodology, Investigation, Writing – review & editing.

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