Evaluation of the Compliance of Urban Functions in Sofia City with the 15-minute City Concept

Dessislava Petrova-Antonova[1], Bryan Monticelli[2], Sylvia Ilieva[1]

[1] Sofia University "St. Kliment Ohridski", GATE Institute, Sofia, Bulgaria
[2] Technology School Electronic Systems (TUES), Sofia, Bulgaria

Keywords: 15-minute City Concept, Importance, Fuzzy Logic, Proximity and Diversity of Urban Functions.

Abstract

The rapid growth of urbanisation has led to the expansion of cities, often resulting in reduced accessibility to essential services, particularly in peripheral areas. The "15-minute city" concept proposes a decentralised urban model where residents can access amenities within a 15-minute walk. While extensive research has explored the 15-minute city model, a standardised methodology for evaluating compliance remains absent. Existing studies predominantly rely on either survey-based assessments or algorithmic approaches, often overlooking the integration of both methods and the micro-scale walkability factors that impact accessibility.

This study presents a novel methodological framework for assessing urban alignment with the 15-minute city concept through an integrated qualitative and quantitative analysis. A 15-Minute City Compliance Index (15-MCCI) is introduced, comprising two components: 15-MCCI (Macro), which evaluates accessibility, and 15-MCCI (Micro), which assesses micro-scale walkability factors. The methodology utilises proximity analysis and fuzzy logic to determine compliance at the residential building level. A survey was conducted in the city of Sofia, Bulgaria, to establish key parameters such as amenity importance, preferred walking distance, and diversity thresholds. The framework was applied for the compliance assessment of the Lozenets district of the city, demonstrating spatial variations in compliance levels and the relationship between macro-scale accessibility and micro-scale walkability. Results indicate that established urban areas exhibit higher compliance due to greater amenity density and pedestrian-friendly infrastructure, whereas newly developed areas face accessibility challenges.

1. Introduction

The increasing urbanisation causes city expansion, but this growth often results in reduced connectivity and limited access to amenities, particularly in peripheral districts (Nilforoshan et al., 2023). The concept of the "15-minute city," introduced in 2016 by Carlos Moreno, envisions urban areas as a network of self-sufficient units where residents can access essential services within a 15-minute walk. This model aims to enhance urban living by reducing the time and effort required to reach daily services, thereby improving convenience for residents (Moreno et al., 2016; Allam et al., 2022). It is based on four criteria, including density, diversity, proximity, and digitalisation. Density refers to the number of citizens sustaining diversity of services. This increases activity, and decreases motor vehicle transportation, making the city more sustainable (Kesarovski and Hernández-Palacio, 2023; Lang et al., 2022). Diversity is related to the variety of amenities in a local area. It can be measured by counting the number of urban services near the residential building (Abdelfattah et al., 2022), Simpson's diversity index (Di Marino et al., 2022; Simpson, 1949) or by Shannon Entropy (Graells-Garrido et al., 2021). Proximity refers to the adjacency of the points of interest related to the residential buildings. This concept implies the redistribution of services so that they are optimally placed for the citizens. It directly impacts active mobility, the independence of disabled people and the reduction of the usage of motor vehicles (Barbarossa, 2020). Finally, digitalisation refers to using information technologies to improve compliance with the 15-minute city standard.

While the 15-minute city concept has garnered significant research interest, there is no universally agreed-upon framework for prioritising amenities based on their relative importance. Existing studies predominantly employ two methodological approaches: survey-based analyses and quantitative methods leveraging algorithms. Some studies integrate these approaches to achieve more comprehensive results (Papadopoulos et al., 2023).

A key element for planning the 15-minute city is analysing the walkability and its factors, considering increased accessibility to amenities (Zysk and Zalewska, 2024). Walkability is typically examined at two scales: macro-scale, assessing factors related to accessibility, and micro-scale, focusing on the walking environment, including sidewalk quality, pedestrian crossings, safety, and aesthetic appeal. Such factors can contribute to high levels of lifestyle physical activity since people living in neighbourhoods with higher residential density, a mixture of land use and grid-like street patterns with short block lengths are engaged more in walking and cycling (Saelens et al., 2003).

This study proposes a novel methodological framework for evaluating urban areas' alignment with the 15-minute city concept through an integrated qualitative and quantitative analysis. It addresses several common limitations identified in previous research, including the narrow focus on either survey-based or quantitative methods without combining both, the reliance on Boolean logic that can lead to inaccuracies in compliance assessment, the neglect of micro-scale walkability factors, and the arbitrary assignment of weights for urban function categories.

The rest of the paper is organised as follows. Section 2 describes the methodological framework of the study. Section 3 presents the results. Section 4 concludes the paper and provides directions for future work.

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1197-2025

2. Methodological Framework

The proposed methodological framework introduces the 15-Minute City Compliance Index (15-MCCI), which consists of two components: 15-MCCI (Macro) and 15-MCCI (Micro). These indices evaluate walkability for individual buildings, assigning a score from 0 to 100, representing the percentage of compliance with the 15-minute city concept. Since compliance varies across a city, the indices are applied at the building level.

2.1 Study Setup

The study is based on three datasets, including residential buildings, amenities and a pedestrian network. The pedestrian network is provided in a linear shapefile. The amenities are stored in a point shapefile, providing their location and type. Since the amenities in the initial dataset are classified into 50 different categories, some of the categories are merged to reduce their number to 20. The category reduction is performed based on the literature review and listed in Table 1 (Papadopoulos et al., 2023; Murgante et al., 2024). The number of amenities in each category is shown in Table 1. The residential buildings are stored in a polygon shapefile. All amenities that are more than 3000 meters away from a residential building are filtered, and tables with connections between residential buildings and amenities are created, including the distance between them over the pedestrian network. Walking is chosen as a primary mode of travel with a standard speed of 4.8 km/h, which corresponds to 5 minutes for 200 meters (Sdoukopoulos et al., 2024; Hosford et al., 2022; Staricco, 2022).

Amenity category	Number
Parks	1068
Primary Schools	51
Secondary Schools	115
Public Kindergartens	138
Private Kindergartens	66
Hospitals and Polyclinics	204
Public Transport	992
Cultural Objects	355
Sport Centers	1305
Courier Offices	154
Banks and ATMs	374
Grocery Stores	4902
Supermarkets	207
Restaurants	2468
Bars	582
Shopping Centers	11
Hairdressers	3016
Pharmacies	423
Children Playgrounds	936
Community Centres	84

Table 1. Categories and numerical distribution of amenities.

2.2 Conducting a Survey

Most of the walkability studies are aligned with the idea of creating an index to assess compliance with the 15-minute city model and use numerical weights to represent the importance of the different categories of amenities. Since they are, for the most part, subjective, a survey was conducted in Sofia to get the residents' insights into different aspects of the different amenities. Responses were collected from 90 participants across diverse districts. It included four sections: responder profiles, macro-scale walkability, micro-scale walkability, and feedback. The survey gathered key parameters for macro-scale analysis: (1) Importance (0–4 scale); (2) Preferred walking distance (3–30 minutes); and (3) Diversity (0–10 amenities within the preferred range). These parameters are based on the 4 criteria for the 15-minute model (Allam et al., 2022; Moreno et al., 2021) and other studies defining the importance of different amenities (Murgante et al., 2024; Papadopoulos et al., 2023). For micro-scale walkability assessment, factors such as sidewalk quality, noise, safety, and aesthetic appeal are evaluated equally (Otsuka et al., 2021; Van den Berg et al., 2017; Mitropoulos et al., 2023).

2.3 15-MCCI Calculation

A GIS-based proximity analysis is performed using Euclidean network distances to better reflect real-world walking paths. The analysis considers distances of a maximum of 2400 meters, which is equivalent to 30 minutes of walking. A macro-scale index is computed using fuzzy logic to assess amenities' proximity, importance, and diversity for each building. The importance is considered by splitting the maximum value for the index of 100 into 20 partitions, each representing an amenity category. Thus, the partitions have a value proportionate to the importance of a given category, called Maximum Partition Value (MPV), which is the maximum value the category can contribute to the index calculation.

Distance Fuzzy Coefficient (DFC) measures compliance based on proximity to amenities. It ranges from 0 to 1, where 1 means that the distance falls in the preferred range. Category Fuzzy Coefficient (CFC) assesses the diversity of amenities within the preferred range. Category Assessment Value (CAV) combines importance, DFC, and CFC for each category. The final macro-scale index is the sum of all CAVs across categories.

The micro-scale index is calculated based on the results from the survey. It evaluates factors like sidewalk quality, safety, and aesthetics, assigning values (0–1) based on survey responses. The values of the factors are summed and scaled to 0–100 for each response from the survey. Then, all responses are grouped based on the urban planning unit, and an average value is calculated for them, representing the micro-scale index. The overall 15-MCCI for each residential building is the average of the macro-scale and micro-scale indices for its corresponding urban planning unit.

2.4 Fuzzy Logic and Fuzzy Tree

Fuzzy logic is selected over other methods since it ensures nuanced evaluation by avoiding binary thresholds. Its simple, efficient and intuitive reasoning mechanism handles even concepts of increased complexity and ambiguity (The MathWorks, 2020). As a complex and multidimensional concept, the 15-minute city appears to be a suitable case for the application of a fuzzy logic approach, where diverse factors have to be considered, including population density, proximity to amenities, sidewalk quality, pedestrian crossings, safety, aesthetic appeal, etc. In addition, fuzzy logic handles data uncertainties, avoiding restrictions on the nature and structure of the input data (Phillis et al.,2011).

The fuzzy tree has two different Fuzzy Interference Systems (FIS), shown in Figure 1. The first FIS (FIS1) assesses proximity compliance by comparing actual distances to preferred ranges. Thus, it is used to determine how close the amenity is to the residential building.

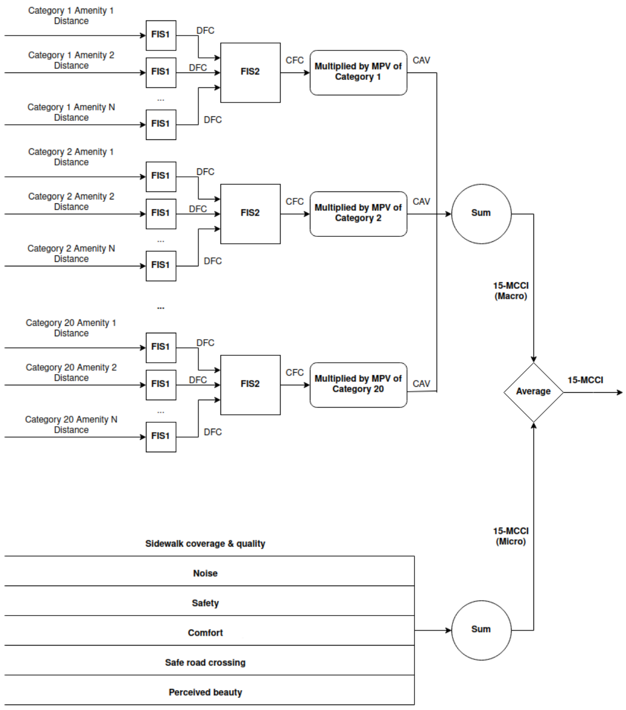


Figure 1. Fuzzy Tree.

The FIS1 incorporates FISs that correspond to the amenity categories. Each of these FIS takes two arguments: the maximum distance the residents should walk to the amenity of a specific category and the real distance to the amenity (see Figure 1). They produce as output an index that evaluates the proximity of the amenity in a range from 0 (low proximity) to 1 (high proximity).

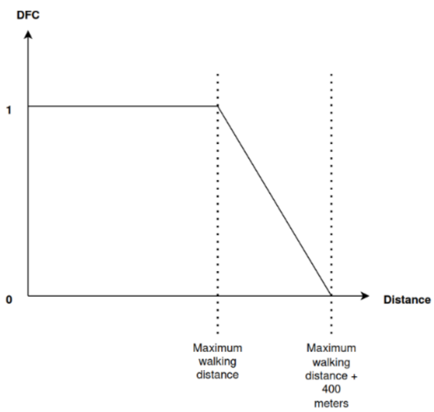


Figure 2. The first FIS.

The second FIS (FIS2) is used to determine if a given amenity category has enough diversity for a particular residential building. It incorporates FISs that take the sum of all DFC for the amenity category and compare it to the desired diversity (see Figure 3). As a result, a CFC is calculated for each amenity category, which in turn is used for the calculation of the CAV. The macro-scale index is a sum of all CAVs and input for the calculation of the overall 15-MCCI.

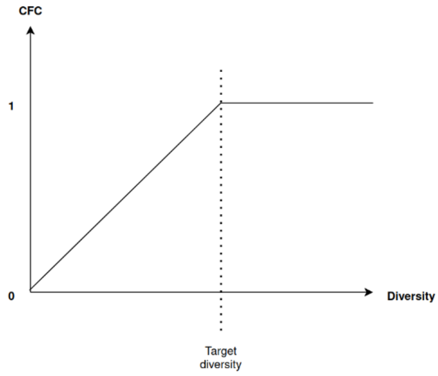


Figure 3. The second FIS.

Finally, Figure 1 shows the calculation of the overall 15-MCCI as an average of the macro-scale and micro-scale indices.

3. Results

To validate the feasibility of the proposed methodological framework, a pilot study is conducted in the Lozenets district of Sofia, Bulgaria, shown in Figure 4. To the best of our knowledge, this is the first attempt to combine macro- and micro-scale analysis. For instance, prior research employs Network Analysis to evaluate pedestrian accessibility to transportation stops and their corresponding service areas, taking into account the existing infrastructure (Karamitov and Petrova-Antonova, 2022). However, the study is conducted at a macro scale and does not incorporate critical micro-scale factors such as pavement conditions, safety, comfort, and the overall attractiveness of the urban environment, all of which significantly influence pedestrian route choice.

This area was chosen for its mix of established neighbourhoods and newer residential developments. The analysis utilised a pedestrian network comprising 125,001 segments, 5,710 residential buildings, and 17,451 amenities.

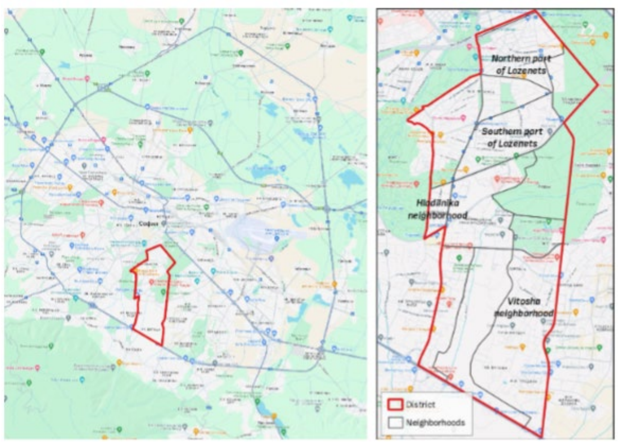
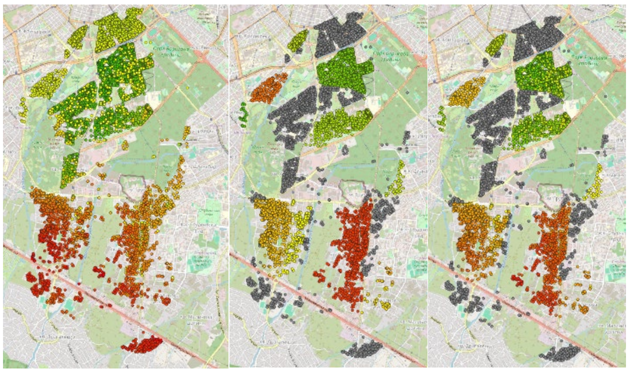


Figure 4. Pilot study area.

Figure 5a illustrates the geospatial 15-MCCI macro-scale distribution. Central neighbourhoods exhibit higher compliance with the 15-minute city model, likely due to better-established urban infrastructure, while peripheral areas, characterised by newer residential development, show lower compliance. Figure 5b shows the geospatial 15-MCCI micro-scale distribution. Neighbourhoods without survey responses are marked in green, as no micro-scale data is available. The similarity in distribution patterns between macro- and micro-scale indices suggests a correlation: neighbourhoods with strong connectivity and land-use diversity also tend to have favourable walking conditions. Figure 5c shows the alignment between the two indices, supporting the hypothesis that enhanced macro-scale connectivity correlates with improved micro-scale walkability.



(a) 15-MCCI (Macro) (b)15-MCCI (Micro) (c) 15-MCCI (Overall)

Figure 5. 15-MCCI distribution.

Figure 6, Figure 7 and Figure 8 shows chart diagrams of the 15-MCCI macro-scale, 15-MCCI micro-scale and overall 15-MCCI distribution, respectively. The colours range from red to green, indicating how much a building complies with the index, where red stands for lower compliance and green stands for higher compliance. The x-axis shows the index value for the corresponding amenity category, while the y-axis indicates the number of buildings corresponding to the given index value range.

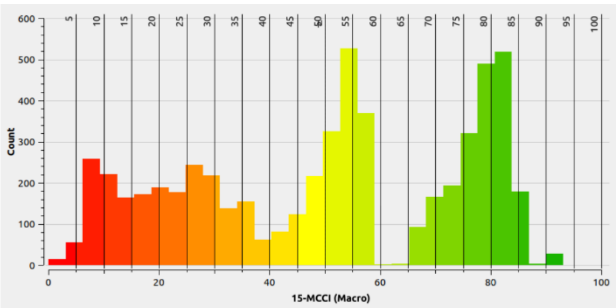


Figure 6. 15-MCCI (Macro) distribution.

As can be seen from Figure 6, there are three major clusters as follows. The green bars are related to the central part of the study area having a high macro walkability score. The northern part has moderate 15-minute compatibility, which is represented by the yellow bars. Finally, the southern neighbourhoods have low macro walkability scores, shown as the red bars in the diagram.

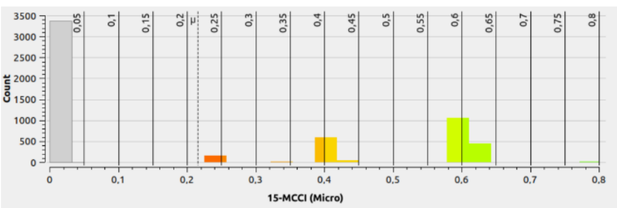


Figure 7. 15-MCCI (Micro) distribution.

The grey bar in Figure 7 indicates the missing data from the survey, so the 15-MCCI (Micro) can't be calculated, thus appearing also in the diagram of Figure 8 representing the overall 15-MCCI. It is the most prominent since approximately 60% of the buildings are situated in neighbourhoods without collected survey entries. The distribution of the 15-MCCI (Micro) closely resembles that of the overall 15-MCCI, exhibiting lower polarisation that results in fewer extremely high or low values.

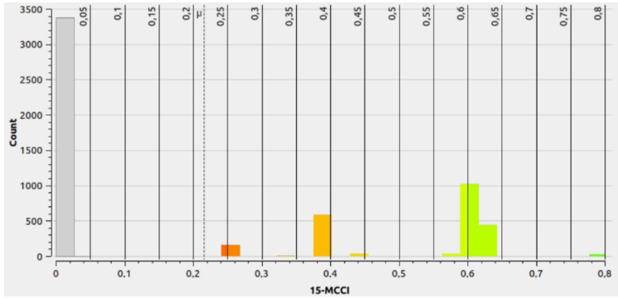


Figure 8. 15-MCCI (Overall) distribution.

Table 2 shows the results from the macro-scale analysis regarding the importance (I), proximity (P) and diversity (D) of amenity categories.

Amenity category	I	P (m)	D
Parks	3.18	1338	2.02
Primary Schools	2.14	1796	1.47
Secondary Schools	1.93	1964	1.31
Public Kindergartens	1.46	1716	1.58
Private Kindergartens	0.73	1716	1.58
Hospitals and Polyclinics	2.98	1418	1.78
Public Transport	3.42	756	3.61
Cultural Objects	1.84	2133	1.66
Sport Centers	2.86	1458	2.56
Courier Offices	2.53	1120	1.92
Banks and ATMs	2.70	1107	2.56
Grocery Stores	3.39	791	3.13
Supermarkets	3.16	1018	2.13
Restaurants	2.10	1653	2.61
Bars	1.79	1996	2.07
Shopping Centers	1.36	2160	1.30
Hairdressers	1.83	1516	2.02
Pharmacies	3.31	853	2.62
Children Playgrounds	2.34	1653	2.73
Community Centres	1.64	2178	1.39

Table 2. Macro-scale analysis results.

Figures 9, Figure 10, and Figure 11 illustrate the distributions of the amenities according to the three key factors, i.e. importance, proximity, and diversity, across amenity categories.

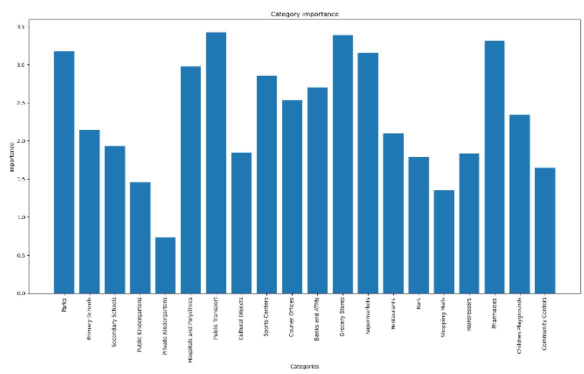


Figure 9. Importance distribution.

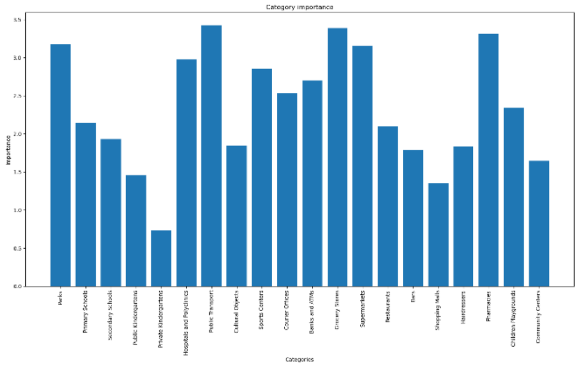


Figure 10. Maximum distance distribution.

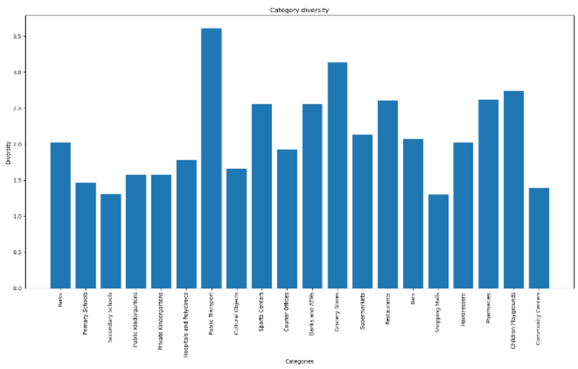


Figure 11. Diversity distribution.

The results indicate that the most important amenities are public transport, parks, grocery stores, supermarkets, and pharmacies. The amenities requiring the closest proximity to residences are pharmacies, grocery stores, and public transport, likely due to their frequent use or urgency of access. The most diverse amenities are public transport, grocery stores, playgrounds, sports centres, banks/ATMs, restaurants, and pharmacies, reflecting the need for variability within these categories (e.g., gyms vs. swimming pools or fast food vs. fine dining).

Figure 12 shows the correlation matrix between responders' profiles and the importance of amenity categories. Key correlations include: (1) Children-related amenities (schools, kindergartens, polyclinics, and community centres) correlating with responders who have children; (2) Public transport stops being more important for frequent public transport users; (3) Shopping malls correlating with responders' jobs; (4) Sports centres aligning with physical activity levels; (5) Cultural objects and pharmacies showing strong links to education and age; (6) Grocery store importance varying by gender.

4. Conclusion and Future Work

This study advances the existing literature by addressing a critical gap: the assessment of importance, maximum distance, and diversity for various amenity categories. It introduces a comprehensive framework for evaluating urban areas' compliance with the 15-minute city concept through a combined macro- and micro-scale analysis, aiming to enhance walkability and ensure equitable access to services. By integrating survey-based and quantitative methods, the proposed approach addresses several limitations found in existing research, such as the arbitrary weighting of urban function categories and the neglect of micro-scale walkability factors. The results demonstrate that well-established urban areas tend to have higher compliance due to their infrastructure and service distribution, while peripheral areas require targeted planning interventions to enhance accessibility.

A limitation of the study is the relatively small survey responses. Additionally, the framework does not account for variations in amenity significance. Future work will focus on expanding the application of the framework to a wider range of urban contexts, including cities with different spatial structures and socio-economic characteristics. Additionally, further research will investigate the role of digitalisation in improving access to urban services, incorporating real-time data on mobility patterns and user preferences. Enhancing the approach with predictive capabilities through machine learning techniques will also be explored to provide urban planners with more dynamic and adaptive tools for designing walkable cities. Finally, interdisciplinary collaborations with policymakers and urban designers will be essential in translating research findings into actionable strategies for sustainable urban development.

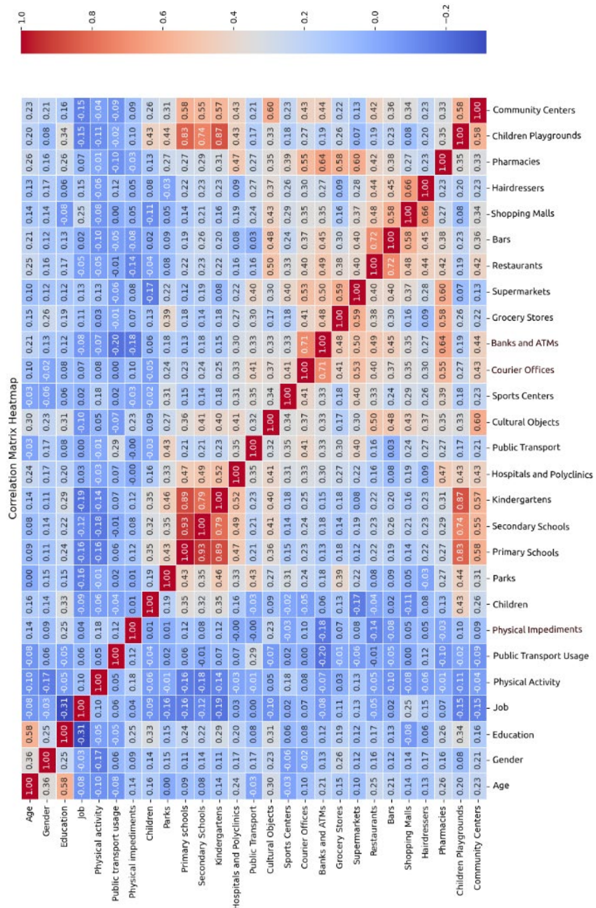


Figure 12. Correlation matrix between responders' profiles and amenity importance.

Acknowledgements

This research is part of the GATE project funded by the Horizon 2020 WIDESPREAD-2018-2020 TEAMING Phase 2 programme under grant agreement no. 857155 and the deployEMDS project, funded by Digital Europe Programme DIGITAL-2022-CLOUD-AI-03 under grant agreement no. 101123520.

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