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Theoretical framework to develop an urban health index using built environment variables: the case of Ferrara, Italy

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Abstract. The quality of our habitat strongly determines the well-being of both our society and us as individuals. The Urban Health (UH) index is an emerging tool for decision-makers to bridge the disparities in the quality of life in cities. Our study assesses the quality of the built environment as a proxy for urban health and proposes a theoretical framework for constructing a UH index. We first conducted a literature review and statistical analyses to select and screen a comprehensive array of urban health indicators, and then used Principal Component Analysis (PCA) to obtain the indicators' weights and build the UH index. On applying the framework on the city of Ferrara, Italy, we obtained promising results with four interpretable principal components explaining the contextual conditions. The autocorrelation of the UH index (Moran's I = 0. 795) demonstrated strong clustering, with very healthy urban census tracts located within the city centre and decreasing overall urban health in peripheral census tracts.

1. Introduction

In recent decades, the definition of health has expanded beyond the scope of biomedical science and healthcare to encompass the field of urbanism. The Health Map reinvented by Barton and Grant [1] visualized the relationship between human health and its trans-scaler interaction with physical, social, and economic factors. It theorized that determinants at different scales, ranging from global ecosystems and macroeconomics to medium-scale built environments, community micro-networks, and family lifestyles, all trickle down to affect human health [1].

Therefore, to gauge the disparity in the quality of built environment within or between cities, decision makers are increasingly relying on tools such as urban health index [2]. These tools provide comparative analyses between different spatial units based on their performance in urban health indicators [3]. A widely adopted methodology for constructing an Urban Health Index (UHI) is proposed by the World Health Organization [2] which uses a comprehensive list of indicators and a simple framework of standardization and geometric mean. Similarly, several governments have developed indices such as Healthy Places Index [4], Neighbourhood Quality of Life Index [5], and Livability Index [6, 7] to make decisions aimed at bridging urban disparities. Their methodologies to assess the physical environment often draw on the concepts from sustainable urbanism such as 15-minutes accessibility, walkability, affordability, and exposure to hazards [8–10].

Our study explores a different approach with context-specific selection and analysis of urban health indicators related to the built environment and apply them on the city of Ferrara, Italy. Commonly used in development of vulnerability index [11, 12], we employed Principal Component Analysis (PCA) that is a data reduction technique to group a large number of variables into interpretable *principal components* along with their respective weights to construct an urban health index [13].

This paper proceeds with the introduction to the study area and selection of urban health indicators based on its context (section 2 and 3), followed by the interpretation of results generated from the assessment of the urban health indicators using PCA (section 4). Section 5 concludes with the discussion of the limitation in the methodology and future research scope.

2. Urban context of Ferrara, Italy

With a population of 132,000 [14], Ferrara spans 405 km^2 in area. Over 20 % of its population resides in its city centre, within its historical walls known as *le mura di Ferrara* which now functions as a prominent 9 km long urban park. One railway station and a state highway SS-16 traversing Ferrara connect it to the rest of the country. Located in the Emilia-Romagna region of northern Italy in the Po River valley, Ferrara has been identified as one of the environmentally vulnerable areas of Italy [15]. The city faces a multitude of environmental challenges owing to the petrochemical industries clustered on its northern and southern periphery, its orographic situation, and specific meteorological conditions.

We used urban health index as a tool to assess these environmental exposure factors and urban determinants that impact human health and lifestyle in Ferrara.

3. Selection and filtering of urban health indicators

A total of 34 indicators to represent urban health were selected and grouped into five broad categories considering the context of southern European cities through literature review (Table 1). The predominant techniques for measurement were based on exposure, accessibility, and aggregation. In terms of exposure, the proximity to sources of air and noise pollution has been well-established as hazardous to human health [16–19]. Therefore, a weighted buffer technique was adopted, assuming decreasing exposure with increasing distance from the pollution sources. The buffer values for different pollution sources were determined through literature references [16, 19]. Likewise, accessibility to amenities and services ranging from food sources (e.g., supermarkets or weekly markets) to transportation services (e.g., bike parking stations or bus stops) was measured through network analysis of amenity or service points on a road network made suitable for pedestrians by excluding highways [20, 21]. Exposure to pollution, accessibility to amenities and services, and aggregation of other indicators such as land surface temperature, greenness of vegetation, and land use entropy were mapped on a hexagonal grid, and their normalized values were further aggregated on census tracts level (n = 1876). The aggregation of variables was done on census tracts for eventual scope of including demographic factors to this study.

As the index focuses on factors related to urban health, rural census tracts on the outskirts of Ferrara that could distort the distribution were excluded. As a result, we limited our subsequent analysis to urbanized census tracts (n = 1503) that met the selection criteria of having an impervious surface area greater than 30% of their total area. The resulting urbanized census tracts were consistent with the urbanized zones or *nuclei abitati* as defined by ISTAT [14].

Table 1. Urban health indicators from literature review

	Variables	Measures
	Environmental factors	
1	Proximity to industries	Weighted buffer (0 m - ≤ 300 m)
2	Proximity to major streets	Weighted buffer (0 m - ≤ 300 m)
3	Proximity to local airport (aeroclub)	Weighted buffer (0 km - ≤ 500 m)
4	Land surface temperature	Inverse of Land Surface Temperature
5	Area under tree canopy	Percent of tree cover per census tract
6	Quality of vegetation	Normalized Difference Vegetation Index NDVI
7	Proximity to water bodies	Weighted buffer (0 m - ≤ 100 m)
	Accessibility to food	
8	Supermarkets	10 mins accessibility
9	Local farm produce	15 mins accessibility

Table 1 *continued*. Urban health indicators from literature review

	Variables	**Measures**
10	Special food (bakery, meat shop, etc)	15 mins accessibility
11	Weekly farmers market	15 mins accessibility
12	Weekly market	15 mins accessibility
	Accessibility to amenities and services	
13	Kindergarten	10 mins accessibility
14	Schools	15 mins accessibility
15	Sports amenities	15 mins accessibility
16	Pharmacy	15 mins accessibility
17	Hospital services	15 mins accessibility
18	Cultural amenities	15 mins accessibility
19	Big parks	15 mins accessibility
20	Small parks	10 mins accessibility
21	Post offices	15 mins accessibility
22	Banks	15 mins accessibility
23	Toilets	15 mins accessibility
24	Benches	10 mins accessibility
25	Public water taps	15 mins accessibility
26	Water fountains	15 mins accessibility
	Mobility	
27	Bus stop	10 mins accessibility
28	Rail station	15 mins accessibility
29	Bike lane percent	Percent length of bike lane to total main roads
30	Bike parking	10 mins accessibility
31	Bike rent	15 mins accessibility
32	Bike repair	16 mins accessibility
	Built and land use	
33	Land use mix	Land use entropy index
34	Built volume	Average built volume per census unit

Spearman correlations were calculated between the standardized z-scores of all the indicators. Out of 34 variables, three statistically insignificant variables (p-value > 0.05) were removed. The correlation matrix also showed several variables with high correlation coefficients, indicating multicollinearity. This warranted the use of Principal Component Analysis for further analysis.

4. Results and discussion

During the development of the model using PCA, eight more variables were removed as they produced counterintuitive component loadings. The final model had a Kaiser–Meyer–Olkin (KMO) measure of 0.921 indicating that the sample size was more than adequate for the PCA [13]. The model generated four urban health components that we categorized as: 1) access to amenities and services, 2) health and wellbeing, 3) thermal comfort, and 4) local pollution (Figure 1). The first four principal components were selected because their eigen values were greater than 1 and they explained 76.7% of the total variance. The components were rotated using orthogonal rotation method, Varimax, wherein their component loadings (squared and normalized to a sum of 1) were used as weights for their respective components. These weights were then multiplied by the percentage variance explained (after normalization of 76.7% to a sum of 1) to obtain their overall weights. Table 2 shows that the final weights are in a range between 0.079 to 0.007, with access to amenities and services falling in the higher range and exposure to pollution in the lowest range. The urban health index was a combination of these four components factored in with their respective weights.

Table 2. Weights of the urban health indicators and their principal components

Selected urban health indicators	Access to amenities & services	Health and wellbeing	Thermal comfort	Local pollution	Urban health component weight x indicator weight
	Weights of urban health components				
	0.63	**0.17**	**0.12**	**0.09**	
Cultural amenities	0.08				0.079
Special food	0.08				0.077
Banks	0.08				0.074
Pharmacy	0.08				0.073
Weekly farmers market	0.08				0.071
Bike rent	0.08				0.071
Public water taps	0.08				0.069
Supermarkets	0.07				0.068
Water fountains	0.07				0.067
Weekly market	0.07				0.061
Bike parking	0.06				0.056
Post offices	0.06				0.055
Schools	0.05				0.046

Table 2 *continued.* Weights of the urban health indicators and their principal components

Toilets	0.05				0.042
Small parks		0.31			0.015
Sports amenities		0.27			0.014
Big parks		0.25			0.012
Hospitals		0.17			0.009
Land surface temperature			0.45		0.013
NDVI			0.36		0.010
Proximity to water bodies			0.19		0.005
Proximity to major streets				0.50	0.007
Proximity to industries				0.50	0.007
Total sum	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

The four urban health components (Figure 1) and the composite urban health index (Figure 2.1) evidently reflect the on-ground situation in Ferrara. In the first component of access to amenities and services, the higher values are concentrated at the center due to the higher density of amenities and services including mobility and food related points of interest in the city center. On the other hand, the access to places of health and wellbeing predominantly includes hospital, parks and sport amenities that

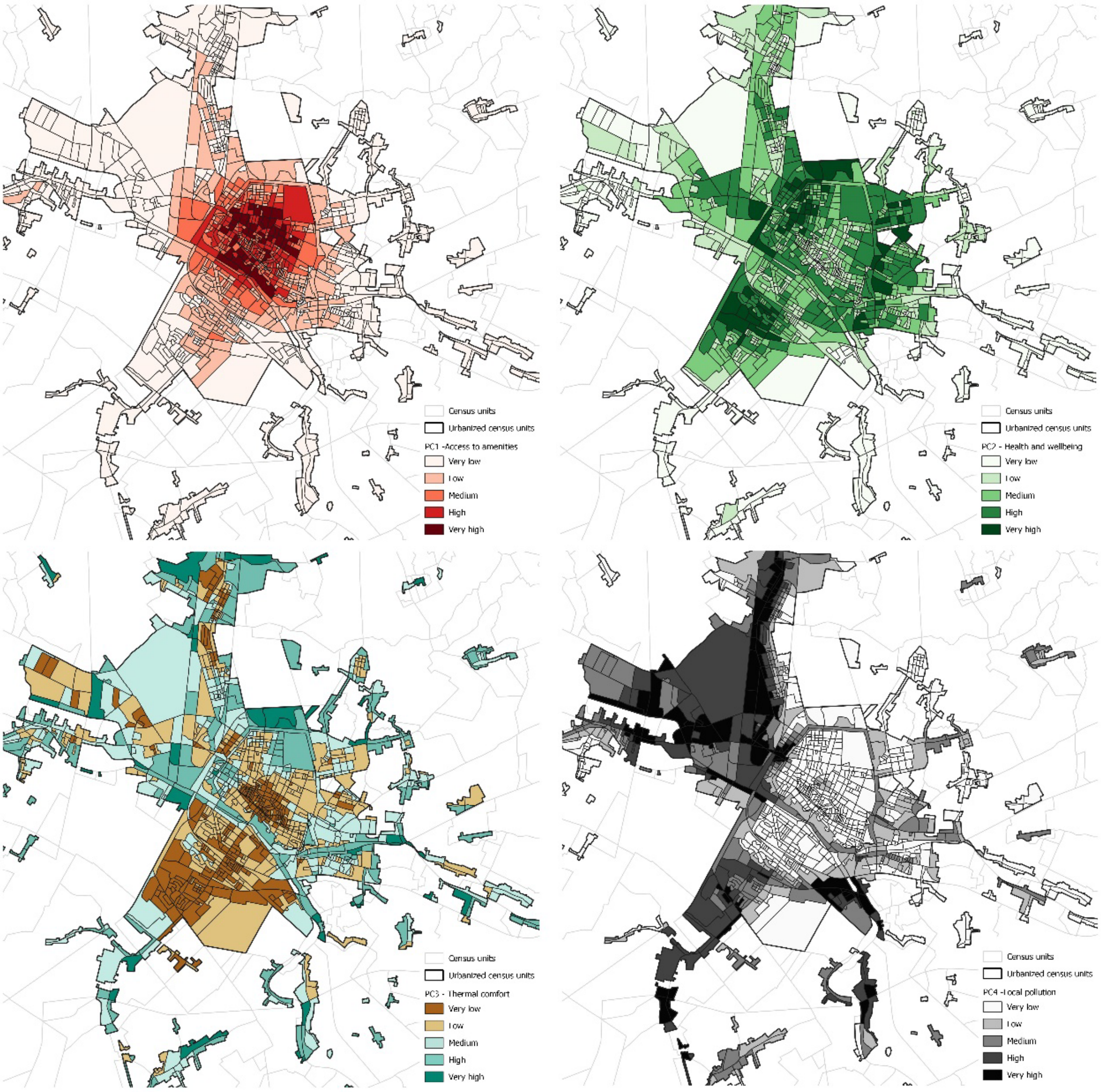

Figure 1. Principal components from top-left to bottom-right 1) Access to amenities and services 2) Health and wellbeing 3) Thermal comfort, and 4) Local pollution.

are in the periphery of the city, especially by virtue of *le mura di Ferrara* and *Parco Urbano Bassani* but are limited within the densely built city center.

The third component of thermal comfort, which includes exposure to average surface temperatures, presence of vegetation and proximity to the *Canale di Burana* highlights the southern part of city center and the neighbourhoods south of river experiencing thermal discomfort. Lastly, the fourth component of local pollution exhibits all the census tracts exposed to the pollution from major roads and industries. Figure 1.4 highlights the peripheral north-east neighbourhoods being in close proximity to the petrochemical compound and southern suburbs near the industrial estates and state highway SS-16.

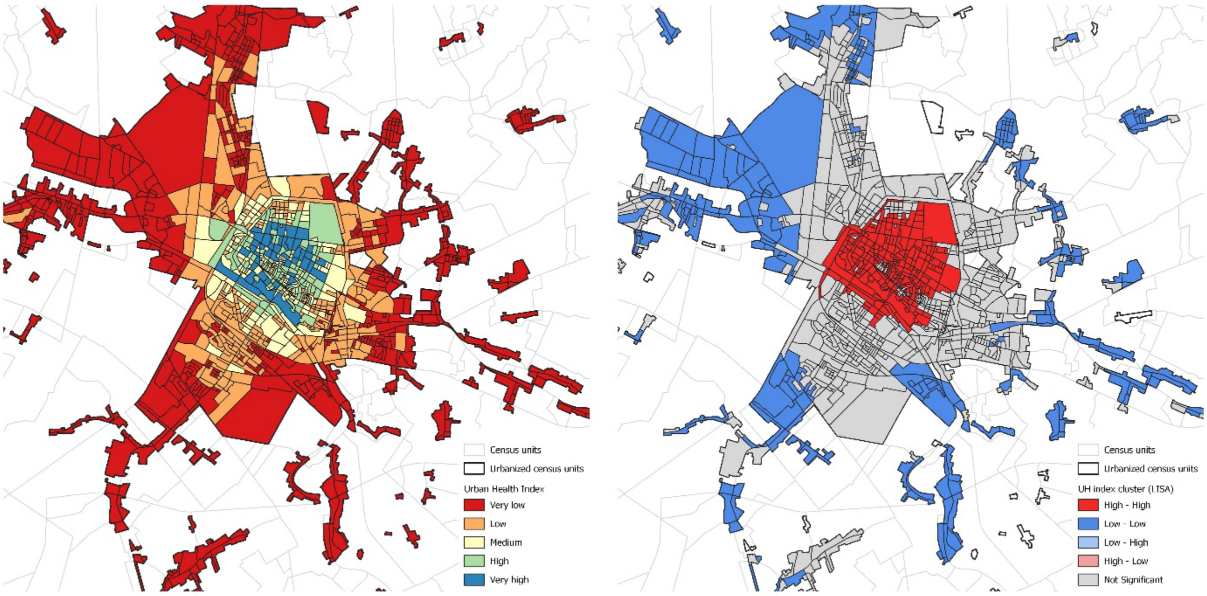

Figure 2. 1. Urban Health Index (left) and 2. its Local Indicator of Spatial Association (LISA) Moran's I (right)

The composite UH index (Figure 2.1) that factors in all the urban health components obtained from the PCA shows the overall urban health as defined by the quality of the built environment. The first evident observation is that neighbourhoods that scored highest in the UH index are all located within the city center. Neighbourhoods on both side of the historic city walls are either high or medium on the UH index score, whereas those on the periphery are either low or very low. The low scores of the peripheral census tracts could be attributed to the lack of access to more and diverse set of amenities and services, lack of soft-mobility infrastructure as well as proximity to pollution sources. The clustering of UH index was quantified by the Moran's I autocorrelation value which was 0.795 (Figure 3), implying positive spatial clustering of high-high and low-low values (Figure 2. 2).

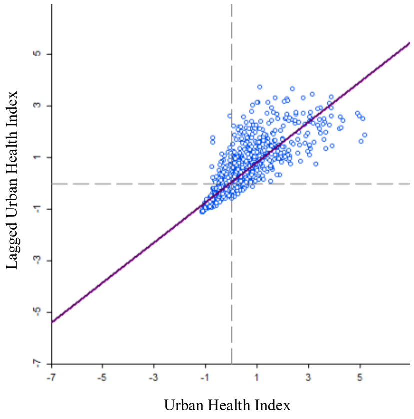

Figure 3. Moran's I indicating high-high significant tracts in quadrant I and low-low significant tracts in quadrant III

5. Conclusion and further research

The strength of the framework for constructing the UH index proposed by this study is that the choice of indicators is contextualized by the characteristics of the study area and the relationship of the indicators with one another. Moreover, the approach of grouping the indicators and generating their weights through PCA is useful in cases where the researchers do not have enough on-ground information about the study area but have access to adequate range of datasets at a finer resolution. This makes it replicable and flexible to adopt.

The next course of action for this study is the process of validation which was beyond the scope of this paper. The perception of citizens of the quality of life of their neighbourhood could be an important measure to validate the UH index results. A further interesting extension of this study could be to juxtapose the UH index with demographic vulnerability to understand the extent of environmental injustice and develop tools to map the risk of poor quality of life with varying accessibility in the city.

Author contributions

1. Amruta Umakant Mahakalkar: Conceptualization, Methodology, Supervision, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization
2. Eugenio Morello: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration, Funding acquisition
3. Farah Makki: Conceptualization, Methodology, Writing - Review & Editing, Supervision
4. Ahmed Hazem Eldesoky: Conceptualization, Methodology, Resources, Supervision
5. Enrico Caiani: Writing - Review & Editing, Supervision

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