A Topography-Adjusted Composite Walkability Index for Mountain Inner Areas: A GIS-Based Multi-Criteria Approach Applied to Premeno, Italy

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***Abstract*—This study proposes a composite walkability index specifically designed for hilly and mountainous contexts, where terrain morphology strongly constrains pedestrian mobility. The method is applied to the municipality of Premeno (Verbano-Cusio-Ossola, Italy) through a two-stage Multi-Criteria Decision Analysis framework on a 50 × 50 m regular grid, using open geospatial data and a high-resolution Digital Terrain Model. In the first stage, social-urban potential is estimated by combining street network connectivity and land-use diversity. In the second stage, a non-linear slope-based penalty is introduced to account for topographic friction and to correct the overestimation of pedestrian potential typically produced by conventional flat-environment walkability measures. The resulting spatial pattern shows a marked concentration of high walkability values in the central settlement area and near-zero values across steep peripheral zones. The proposed index provides a transferable and planning-oriented tool for assessing pedestrian potential in inner mountainous areas and offers a baseline spatial layer for agent-based simulations of pedestrian behaviour.**

***Index Terms*—walkability index, topographic friction,slope, inner areas, GIS.**

I. Introduction

Walkability research has expanded considerably over the past two decades. Many of the most influential walkability measures were developed and validated in urban contexts, primarily focusing on residential density, street connectivity, and land-use mix [1], [2], while topographic characteristics received comparatively limited attention. In alpine and sub-alpine inner areas, this assumption fails systematically: terrain morphology routinely constrains pedestrian mobility in ways that standard walkability measures cannot capture, leading to a systematic overestimation of pedestrian potential in hilly and mountainous contexts. This study addresses this gap by proposing a composite walkability index explicitly adapted to topographically complex settings, applied to the municipality of Premeno (Verbano-Cusio-Ossola, Italy), a small inner-area community characterised by steep terrain, limited services, and an ageing population. The index was constructed as a baseline spatial layer for agent-based simulation of pedestrian behaviour, providing a cell-level attractiveness score that grounds synthetic mobility patterns in objectively measured environmental conditions.

II. Index construction

The study area was tessellated into a regular grid at 50 × 50 m resolution. Each cell was assigned a composite walkability score through a two-stage Multi-Criteria Decision Analysis (MCDA) procedure, drawing on open geospatial data sources including OpenStreetMap, and a 5 m Digital Terrain Model (DTM) provided by the regional portal.

A. Stage 1 - Social-Urban Potential

Two dimensions of pedestrian environment quality were integrated: street network connectivity (CD) and land use diversity (LUM). Connectivity was operationalised as the density of street intersections with node degree ≥ 3 within a 250 m network buffer. This measure builds on GIS-based street connectivity indicators commonly used in walkability research [1], [3].Land-use diversity was measured through a normalised Shannon entropy index, a widely adopted approach for quantifying land-use mix in walkability research [1], [4], applied to the functional categories of Points of Interest (POIs) retrieved from the fused OSM dataset:

$$LUM = \frac{-\sum_{i=1}^{n} p_i \ln(p_i)}{\ln(n)} \quad (1)$$

where p_i is the proportion of POIs of category i within a 250 m buffer and n the number of distinct functional categories. Higher land-use diversity has been empirically associated with greater levels of physical activity and walkability-related behaviours [5]. Both components were standardised through Z-score normalisation and combined via a weighted linear combination:

$$W_{\text{SOCIAL}} = 2 \cdot z_{CD} + 1.5 \cdot z_{LUM} \quad (2)$$

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The weighting scheme prioritises street connectivity over land-use diversity, reflecting evidence that intersection density is a key environmental correlate of walking behaviour and pedestrian activity [1], [2]. The index was subsequently shifted to ensure non-negative values:

$$W_{\text{SOCIAL\_POS}} = W_{\text{SOCIAL}} - \min(W_{\text{SOCIAL}}) \tag{3}$$

B. Stage 2 - Topographic Friction and Normalisation

A non-linear penalty multiplier M was derived from DTM-based slope analysis and applied to each cell, where s denotes the terrain slope expressed as percentage rise over run:

$$M = \begin{cases} 1.0 & \text{if } s < 5\% \\ 0.7 & \text{if } 5\% \leq s < 8\% \\ 0.4 & \text{if } 8\% \leq s < 12\% \\ 0.1 & \text{if } s \geq 12\% \end{cases} \tag{4}$$

The 5% threshold reflects commonly adopted accessibility guidance for pedestrian environments and inclusive design, as reflected in ADA standards and EN 17210:2021 [6]–[8];the 8% threshold corresponds approximately to the ADA maximum ramp gradient. Gradients above this level were assigned stronger penalties because increasing physical effort has been shown to influence route choice behaviour among older pedestrians [6], [9]; the 12% threshold was selected to represent conditions under which walking performance becomes substantially more constrained, as significant changes in walking dynamics have been observed between gentle and steep walkway slopes across different age, gender, and body mass index groups [10], 12% threshold is also consistent with field observations reporting substantial reductions in pedestrian walking speed on gradients within the 10.5–12.5% range [11], Steep gradients have also been shown to generate substantial accessibility losses for individuals with declining mobility, highlighting how relatively limited portions of a pedestrian network can act as critical barriers to local accessibility [12]. The raw index is computed multiplicatively:

$$W_{IRAW} = W_{\text{SOCIAL POS}} \cdot M \tag{5}$$

and rescaled to [0, 100] via min-max normalisation:

$$WI = \frac{WI_{RAW} - \min(WI_{RAW})}{\max(WI_{RAW}) - \min(WI_{RAW})} \cdot 100 \tag{6}$$

III. Results and Discussion

The resulting walkability map reveals a strongly polarised spatial distribution, with high-scoring cells concentrated in the central village core, characterised by flat terrain, denser street networks, and proximity to services, and near-zero scores prevalent across the steep peripheral zones that constitute the majority of the municipal territory. The multiplicative structure of the index proves particularly effective in capturing this duality: cells with high social-urban potential are systematically suppressed by terrain conditions, a pattern that standard flat-environment indices would fail to detect. The model further demonstrates that even modest increases in service diversity or intersection density produce negligible walkability gains in cells where slope exceeds 12%, underscoring the primacy of topographic constraint in this context.

IV. Conclusions

This study proposes a transferable, open-data composite walkability index adapted to the specific conditions of mountainous and hilly inner areas, where terrain morphology constitutes the dominant constraint on pedestrian mobility. By integrating land use diversity, street connectivity, and topographic friction within a transparent MCDA framework, the index provides a spatially explicit and planning-actionable measure of pedestrian potential. Its application to Premeno demonstrates both the feasibility of the approach using freely available geospatial data and its sensitivity to the morphological conditions that standard indices systematically overlook. Future work will focus on empirical validation through GPS-tracked pedestrian surveys and on the integration of the index as a behavioural parameter in agent-based mobility simulations.

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