

“Social infrastructure accessibility and systemic spatial inequality: network evidence from Milan's 15-minute city”

Abstract

The 15-minute city model (Moreno et al., 2021) has gained considerable traction in urban planning research and policy, proposing that residents should be able to reach essential services within a short walk from home. This paper operationalizes this framework by examining pedestrian accessibility to non-commercial social infrastructure (Klinenberg, 2018) across Milan's 89 Neighborhoods of Local Identity (NIL), focusing on three amenity domains: care, educational, and cultural. OpenStreetMap point data are used to locate amenities, and shortest walking paths between population-weighted NIL centroids and each amenity are calculated by applying a 1km threshold as a proxy for 15-minute walkability. For each domain, a bipartite network links NIL nodes to reachable amenity nodes, from which two analytically distinct measures are derived: degree centrality, capturing internal accessibility, and weighted strength on the unimodal NIL×NIL projection, capturing how deeply each neighborhood is embedded in the city's shared service network. The results reveal substantial variation in accessibility across the city, with peripheral NILs underserved and not integrated in the urban fabric across all three domains. Principal Component Analysis shows a single dominant dimension accounting for 71.6% of variance across twelve network measures, and cluster analysis identifies three neighborhood types whose geography reproduces different stratification of accessibility and embeddedness between the center and the periphery. Spatial disadvantage appears as a single structural condition - hierarchically organized and operating simultaneously across care, education, and culture -

leaving a substantial share of Milan's neighborhoods outside the reach of the 15-minute city framework. In doing so, the paper contributes empirical evidence to the growing literature on spatial equity and walkable city models in European urban contexts, while demonstrating that separating internal accessibility from urban integration reveals structural positions that a measure of reachability alone cannot detect.

Introduction

The 15-minute city, a concept first articulated by Moreno in 2016 and subsequently formalized in academic literature (Moreno et al., 2021), has become the dominant frame through which urban equity is translated into a spatial standard: residents should be able to reach essential services within fifteen minutes on foot from home. Milan has formally adopted this principle as a strategic planning objective, committing to ensure that residents can access essential services within a 15-minute walk (Comune di Milano, 2020), and has dedicated municipal programs to its implementation, including a publicly funded initiative explicitly oriented toward the 15-minute city framework (Comune di Milano, 2022).

Access to services is not merely a logistical condition, but a social one. In fact, the physical space through which community life is sustained at the neighborhood scale - what Klinenberg (2018) calls social infrastructure - are the material preconditions for collective life: libraries, schools, clinics, cultural centers. Where they are absent or unreachable, the consequences could extend across multiple dimensions of social experience. Klinenberg's analysis of the 1995 Chicago heatwave showed that mortality varied with the density of local institutions, not just with income or race. The proximity of social infrastructure, in other words, is a sociological question and a

political one. But Klinenberg's argument carries a further implication: the value of social infrastructure is not exhausted by individual reachability. Libraries, schools, and cultural centers generate collective value precisely because they are shared - because they bring together residents from different streets, blocks, and neighborhoods, producing the cross-neighborhood exchange through which civic life is sustained. A service that is reachable by one neighborhood but shared with none of its neighbors contributes to individual access but not to that collective dimension. This distinction is what the projection captures formally, and what degree alone cannot see. Following this logic, according to Soja (2010), urban space is an active medium through which inequality is produced and reproduced. The geography of service provision reflects and reinforces existing patterns of stratification. This means that service deficits are not randomly distributed but they are clustered in specific areas across multiple domains simultaneously: a neighborhood without adequate healthcare is unlikely to be well-served by other central facilities such as educational or cultural ones, because the same structural forces that concentrate resources in wealthy central areas drive their withdrawal from the periphery. The sociological grounding for this claim comes from the neighborhood disadvantage literature. Wilson (1987) and Sampson (2012) showed that institutional withdrawal from poor neighborhoods is not domain-specific: it compounds across dimensions, and its effects on residents exceed what single-domain measure can capture. Putnam (2000) adds a further register to this argument: where civic institutions are thin or absent, the social networks that sustain trust and collective action erode - which means that the consequences of institutional withdrawal extend beyond individual service deprivation into the fabric of community life itself. Levy, Phillips, and Sampson (2020) push this further, arguing that a neighborhood's position depends not only on its own institutional density but on its connections to surrounding areas: isolation from better-served neighbors amplifies local disadvantage in ways

that aggregate scores cannot reveal. Taken together, these studies converge on the intuition that spatial disadvantage is simultaneously compound and structural, not a collection of independent domain-specific deficits.

Operationalizing this intuition, however, calls for an analytical framework that can hold the two dimensions apart. Conventional reachability-based accessibility analysis measures distance and coverage effectively, but it treats each neighborhood as an isolated origin point, producing a single score that counts what a neighborhood can reach without distinguishing whether that access is shared with adjacent neighborhoods or constitutes an isolated catchment. Two neighborhoods with identical reachability scores may connect entirely different sets of amenities; a single service point may be accessible from many neighborhoods or from very few. These asymmetries are structural features of how social infrastructure is organized across urban space, and they are invisible to measures that collapse accessibility into a single quantity. According to Batty (2008, 2012), cities are relational systems whose properties emerge from patterns of connection, not from the intrinsic attributes of individual places; understanding them requires that internal accessibility and structural integration in the urban fabric are treated as distinct analytical objects. Spatial science and network science have largely developed in parallel, but their integration opens analytical possibilities that neither tradition achieves alone (Ducruet & Beauguitte, 2014). Centrality measures, originally developed in structural sociology, can be transposed to geographic networks to reveal properties of urban systems that aggregate spatial measures cannot detect (Porta, Crucitti & Latora, 2006) - and this holds specifically for urban amenities, where network-based measures capture accessibility structure in ways that density-based approaches miss (Poudyal, Ghoshal & Kirkley, 2023).

This paper applies these logics to neighborhoods and services through a bipartite network framework that keeps the two analytical dimensions explicitly separate. A bipartite graph connects NIL nodes to reachable amenity nodes within 1 km; from this structure two analytically distinct measures are derived. Degree centrality counts what a neighborhood can reach - its internal accessibility. Strength on the unimodal NILxNIL projection measures how much of that access is shared with adjacent neighborhoods - its embeddedness in the urban service network. Everett and Borgatti (2022) established that degree on the bipartite graph and strength on the projection are non-redundant: together they preserve the full structural information of the two-mode network, each capturing what the other cannot. A neighborhood can score well on degree while sharing nothing with its neighbors, participating in no collective service catchment; conversely, integration without internal accessibility signals a different kind of structural position. Keeping the two dimensions separate is a precondition for making certain structural positions visible at all. Whether the two dimensions reinforce each other into a coherent pattern of structural disadvantage - simultaneously, across care, education, and culture - is the question this analysis addresses.

The central question this paper addresses is therefore: *Is spatial inequality in access to social infrastructure in Milan domain-specific, or does it constitute a unified structural condition operating simultaneously across care, education, and culture?*

Milan's 88 Nuclei di Identità Locale (NIL) provide the spatial units: sub-municipal areas defined by morphological and social coherence, adopted by the municipality as the reference framework for the 15-minute city strategy (Comune di Milano, 2020) and finer-grained than the nine administrative municipalities, making them well-suited to capturing the internal heterogeneity of a city that ranges from a dense, institutionally rich historic center to residential peripheries with

limited service provision. The city's concentric socioeconomic geography - high-income groups in the historic center, lower-income and foreign-born populations at the periphery (Musterd et al., 2017; Consolazio, Benassi & Russo, 2023) - makes Milan a fitting case for the argument this paper develops. If poorly served neighborhoods are also poorly connected, and if this holds simultaneously across care, education, and culture, spatial disadvantage in Milan is not a collection of isolated deficits but the expression of a single structural logic. The analytical distinction between internal accessibility and structural integration is what makes that logic legible - and what produces information about the structure of service provision that is directly relevant to how planning interventions might be targeted.

Data and methods

Data Sources

Street network and amenity data are sourced from OpenStreetMap (OSM), extracted via QuickOSM (Dumas et al., 2021) for the municipality of Milan. Three service domains are retained for analysis: care, education, and culture. The selection follows the social infrastructure framework established in the preceding section, which identifies non-commercial services delivered by public institutions or the third sector as the components of urban infrastructure most directly shaped by planning decisions. Commercial amenities are excluded on the grounds that their distribution follows market logic rather than planning allocation, and it is not demonstrated that their accessibility carries the same social infrastructure implications. An exception is made for pharmacies, which are included in the care domain: although formally commercial, pharmacies function as a primary point of contact for basic medical assistance and are regulated as essential

public health services under Italian law, making their distribution analytically closer to planned social infrastructure than to commercial supply. The full list of OSM tags retained per domain is reported in *Table 1*. Neighborhoods boundaries are drawn from the latest official Milan municipal dataset of 88 Nuclei di Identità Locale (Comune di Milano, 2021). Population data are from public ISTAT census (ISTAT, 2021).

Table 1 OSM amenity tags selected by category

Care	Education	Culture
clinic	college	arts_centre
doctor	kindergarten	cinema
hospital	library	community_centre
nursing_home	university	planetarium
social_facility	research_institute	social_centre
	school	theatre

It is acknowledged that OSM coverage is not geographically uniform. Some NIL may appear underserved due to incomplete mapping rather than an actual absence of facilities. This constitutes a known limitation of Volunteered Geographic Information (VGI) datasets (Haklay, 2010), and it is discussed further in the limitations.

Geospatial Data Preparation

Three point-of-interest (POI) layers - one per domain - were created in QGIS via QuickOSM plugin. All layers were then projected to EPSG:25832 (ETRS89 / UTM Zone 32N), a coordinate

reference system (CRS) metric appropriate for distance calculations in northern Italy. OSM returns POI both as point geometries and as polygon geometries, depending on how individual contributors have mapped each facility. To ensure a homogeneous point-based representation, polygon features were converted to their geometric centroid and merged with the point layer for each domain.

A methodological challenge arises from the Modifiable Areal Unit Problem (MAUP; Openshaw, 1984): using the geometric centroid of a NIL polygon as its representative point may misrepresent accessibility for large or irregularly shaped zones, where the geometric center may be poorly connected to the actual population distribution. To address this, a population-weighted centroid was computed for each NIL by spatially joining population of census sections (ISTAT, 2021) to their containing NIL and computing the weighted mean coordinate using resident population as the weight. In this way, the resulting representative point reflects the internal spatial distribution of residents rather than the geometric center of the NIL. Weighted centroids were subsequently snapped to the nearest edge of the OSM road network to ensure valid routing origins. Pedestrian travel costs between NIL centroids and amenity points were then computed using the QNEAT3 OD Matrix tool in QGIS, which calculates shortest-path distances along the street network for all origin-destination pairs – a more realistic representation of actual walking behavior than Euclidean distance, which ignores the constraints imposed by the road network topology.

The result is three origin-destination matrices - one per domain - each containing all NIL–amenity pairs, filtered in R with a threshold of 1 km to retain only reachable pairs: at an average pedestrian speed of 4-5 km/h, 1 km corresponds to approximately 12-15 minutes of walking, consistent with thresholds adopted in the empirical 15-minute city literature (Mouratidis, 2025; Caselli et al., 2021). Pairs for which QNEAT3 returned no path - approximately 2% of all pairs across all three

domains, distributed uniformly and attributed to minor topological discontinuities in the OSM network - were excluded. NIL-amenity pairs exceeding this threshold are treated as structurally inaccessible - those are not a data artefact, but a substantive result reflecting the pedestrian network's actual constraints, indicating the absence of walkable access to the specific category of service. For this reason, they are included in the analysis.

Bipartite and projected graph construction

Each origin-destination matrix is translated into a bipartite graph connecting two disjoint node sets: NIL nodes (origins) and amenity nodes (destinations). An edge exists between a NIL and an amenity if and only if the amenity is reachable within 1 km on foot. The graphs are undirected, as reachability is non-directional. This produces three bipartite graphs, one for each domain.

NILs that appear in the NIL layer but not in any origin-destination pair within threshold receive degree zero and are reintegrated into all subsequent measures as isolated nodes.

Network measures

Four measures are derived from each bipartite graph, yielding a total of twelve variables across the three domains. The selection is motivated by the paper's central analytical distinction: internal accessibility captures what a neighborhood can reach on its own; structural integration captures how that access is positioned within the broader service network of the city.

Degree centrality on NIL nodes counts the number of amenities reachable within 1 km - the most direct operationalization of internal accessibility. A NIL with high degree can reach many services on foot; a NIL with degree zero is structurally excluded from pedestrian access in that domain.

Betweenness centrality on NIL nodes measures the extent to which a NIL lies on shortest paths between other nodes in the bipartite graph (POI), identifying whether a NIL occupies a bridging position that connects amenities reached by few or no other NILs. Betweenness is normalized to allow comparison across domains.

Unimodal projection strength. The bipartite graph is projected onto the NIL layer: two NILs are connected in the projection if they share at least one reachable amenity, with edge weight equal to the number of shared amenities. The weighted degree - strength - of each NIL node in this projection measures urban integration: the total shared service catchment between a NIL and all its neighbors. A NIL with high strength is embedded in a dense network of shared access; a NIL with low strength, even if internally accessible, is spatially isolated from the rest of the city's service network. This is the measure that a reachability-only approach cannot produce: it requires the relational structure of the bipartite graph to be formalized as an analytical object.

Betweenness centrality on the projection measures the extent to which a NIL lies on shortest paths between other NILs in the projected network. This identifies neighborhoods that serve as structural bridges in the inter-NIL connectivity graph. Edge weights are inverted for this calculation, so that a higher number of shared amenities corresponds to a shorter effective distance rather than a longer one, consistent with the interpretation of shared catchment as proximity. Betweenness is normalized.

Principal Component Analysis (PCA)

The twelve measures - four per each domain - are assembled into an 88×12 matrix. Principal component analysis is applied to the standardized matrix: components are extracted from the

correlation matrix, and retention is guided jointly by the cumulative variance criterion ($\geq 70\%$) and the Kaiser criterion (eigenvalue > 1). Correlation loadings - the correlation between each original variable and each component - are used for interpretation in preference to raw weights, as they express the substantive relationship between variables and dimensions in a more directly interpretable metric. PCA in this case serves a specific inferential function: it tests whether the twelve domain-specific measures collapse onto a single underlying dimension. If they do, this constitutes empirical evidence that spatial disadvantage in Milan is not a set of independent domain-specific conditions but a single structural condition manifesting simultaneously across care, education, and culture - which is precisely what the research question asks.

Cluster analysis

Cluster analysis is performed on the standardized original variables rather than on PCA scores, following the rationale that dimensionality reduction may distort cluster structure by discarding variance that is substantively meaningful. Agglomerative hierarchical clustering uses the Agnes algorithm with complete linkage, which produces compact and well-separated clusters suited to urban accessibility data where distinct spatial types are theoretically expected. K-means clustering is run in parallel for $k=2$ to 8, with 25 random initializations per solution to reduce dependence on starting conditions.

The optimal number of clusters is selected by joint inspection of the Within-Group Sum of Squares (WGSS) elbow and the Average Silhouette Width (ASW), the latter providing a direct measure of cluster cohesion and separation (Rousseeuw, 1987). Concordance between hierarchical and k-means solutions at the selected k is reported as a robustness check: high agreement across methods

indicates that the cluster structure reflects genuine patterning in the data rather than algorithmic artefact.

Results

The results are presented in five steps, moving from domain-specific descriptions to a structural interpretation of the city as a whole. First, the domain-specific distributions of internal accessibility and urban integration establish the extent and shape of inequality within each domain. Second, having established the domain-specific distributions of both measures, the question is how strongly and consistently the two dimensions covary within each domain - and whether there are domains that tell different stories. Third, the cross-domain correlation structure tests whether domain-specific inequalities are independent or reflect a shared underlying pattern. Fourth, PCA provides the formal test of whether that pattern reduces to a single structural dimension. Fifth, cluster analysis translates the distribution along dimensions into a discrete neighborhood typology.

Domain-specific accessibility: internal accessibility and urban integration

The three bipartite graphs differ substantially in density and coverage, reflecting the uneven spatial distribution of social infrastructure across Milan's territory (*Table 2*). The care graph is the most extensive, connecting 80 NILs to 627 service points through 896 edges; the educational graph connects 76 NILs to 582 points through 707 edges; the cultural graph is markedly sparser, connecting only 67 NILs to 200 points through 278 edges. The NILs absent from each graph - those with no reachable service within 1 km - number 8 in care, 12 in education, and 21 in culture. These are not missing data: they are neighborhoods structurally excluded from pedestrian access in that domain, and their count signals a gradient of exclusion that intensifies from care to education to culture.

Table 2: *Bipartite graph structure by domain*

Domain	NILs	POI	Edges	NIL with no access
Educational	76	582	707	12
Care	80	627	896	8
Cultural	67	200	278	21

Note: NIL in graph = neighborhoods with at least one reachable POI within 1 km. NIL with degree = 0 = structurally excluded neighborhoods, reintegrated in subsequent analyses with degree zero.

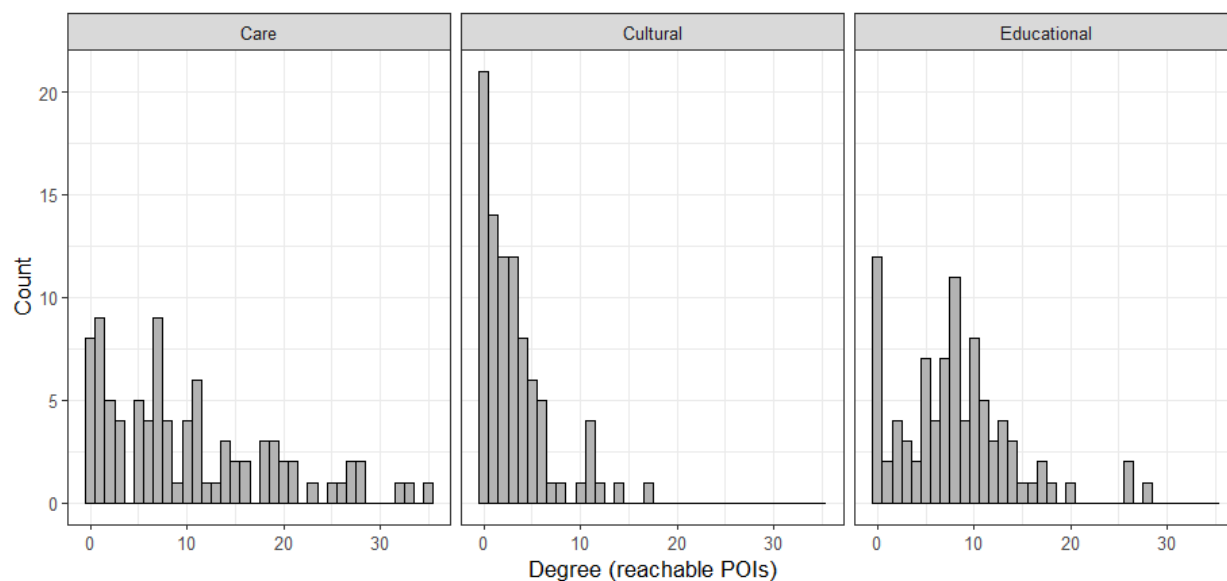
Degree distributions confirm and sharpen this picture (*Table 3; Figure 1*). In all three domains, distributions are right-skewed: a small number of centrally located NILs concentrate access, while the majority of neighborhoods present low values. Care degree ranges from 0 to 35 (mean=10.18, median=7.5); educational degree from 0 to 28 (mean=8.03, median=8); cultural degree from 0 to 17 (mean=3.16, median=2). The cultural domain is not only the most compressed in range but also the most exclusionary in structure: 21 NILs - nearly one quarter of the total - record zero reachable cultural amenities within 1 km, more than double the figure for care. The right-skewed shape of all three distributions points to the same underlying dynamic: access is unequal and structurally concentrated, with a small central core holding a disproportionate share of the city's reachable services.

Table 3: *Bipartite degree distribution by domain (88 NIL)*

Domain	NIL	NIL = 0	Mean	Max
Educational	88	12	8.03	28
Care	88	8	10.18	35
Cultural	88	21	3.16	17

Note: Degree = number of POI reachable within 1 km on the pedestrian network. NIL zero = neighbourhoods with no reachable POI in that domain.

Figure 1: Degree distribution by domain – histograms



The unimodal NIL×NIL projection adds a second, distinct analytical layer to the results of the bipartite networks. Where degree measures what a neighborhood can reach internally, projection strength measures how much it shares with its neighbors - the extent to which its accessible services overlap with those of adjacent NILs. This distinction matters precisely because the two can diverge: a neighborhood can score reasonably well on degree while remaining structurally isolated in the projection if its accessible services are not shared with any other NIL; conversely, a well-integrated neighborhood is one whose catchment is woven into the broader service fabric of the city, contributing to urban integration. NILs with strength zero - those sharing no reachable amenity with any neighbor - number 25 in care, 29 in education, and 43 in culture (*Table 4*). In the cultural domain, nearly half of all NILs are not merely poorly served internally: they are structurally disconnected from the rest of the city's cultural service network. The care projection,

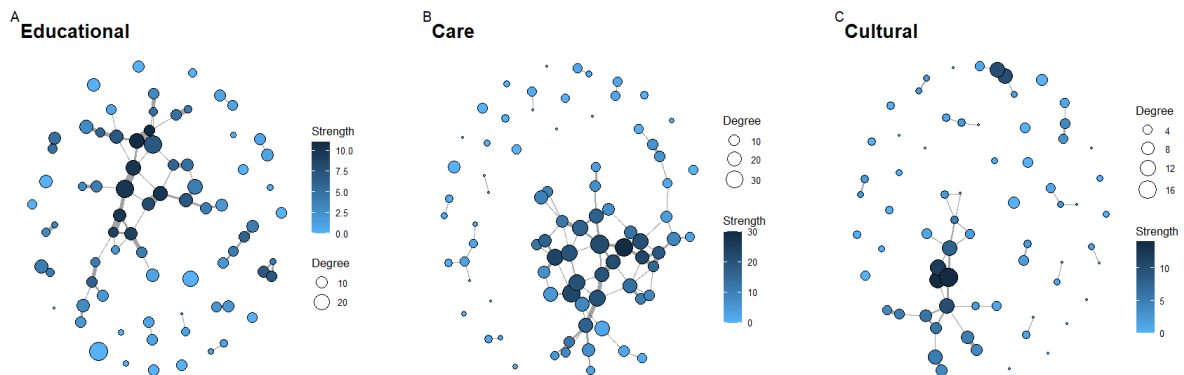
by contrast, is denser and more interconnected, with a mean strength of 6.57 and a maximum of 30, reflecting the more spatially continuous distribution of healthcare and welfare facilities across the city.

Table 4: Unimodal NIL×NIL projection structure and strength distribution ($N = 88$ NIL)

Domain	NIL conn.	Edges	NIL isolated	Mean strength	Max strength
Educational	59	58	29	2.95	11
Care	63	83	25	6.57	30
Cultural	45	40	43	1.91	14

Note: NIL conn. = NIL with at least one shared POI with a neighbour. NIL strength = 0 and mean/max strength computed on all 88 NIL (zeros reintegrated).

Figure 2: Projection network plots (degree taken from the bipartite)



Intra-domain relationship between internal accessibility and urban integration

Having established the domain-specific distributions of both measures, a natural question follows: do internal accessibility and urban integration covary within each domain, or do they capture genuinely independent information about a neighborhood's position in the service network?

The Pearson correlations between bipartite degree and projection strength are positive and highly significant in all three domains but vary substantially in magnitude (*Table 5; Figure 3*). The association is strongest in culture ($r = 0.894$, $p < 0.001$) and care ($r = 0.875$, $p < 0.001$), and considerably weaker in education ($r = 0.502$, $p < 0.001$). In care and culture, the two dimensions are tightly coupled: a NIL that is internally accessible tends almost without exception to be well-integrated in the projection, and one that is poorly served internally tends to be isolated. The near-linear relationships visible in the scatterplots for these two domains reflect a service geography in which proximity and shared catchment are structurally aligned - reaching more services means sharing more of them with neighbors. Educational domain tells a slightly different story. Twenty-nine NILs reach at least one educational facility within 1 km - they are not, by a degree-based measure, educationally deprived. Yet they share none of those facilities with any neighbor: their catchments do not overlap with those of adjacent NILs. A reachability-only measure would classify these NILs as adequately served; the projection reveals that they are formally accessible but structurally isolated from the shared educational landscape of the city. This is consistent with the planning logic of educational provision, where coverage obligations distribute schools and kindergartens across residential areas in ways that may reduce spatial overlap between adjacent NILs even as they raise individual degree scores. The implication is that a NIL assessment based on degree alone would overstate effective educational integration for dispersed neighborhoods: they reach facilities, but they do so in isolation from the rest of the city's educational network, contributing nothing to the cross-neighborhood exchange through which social infrastructure generates collective value beyond individual reachability.

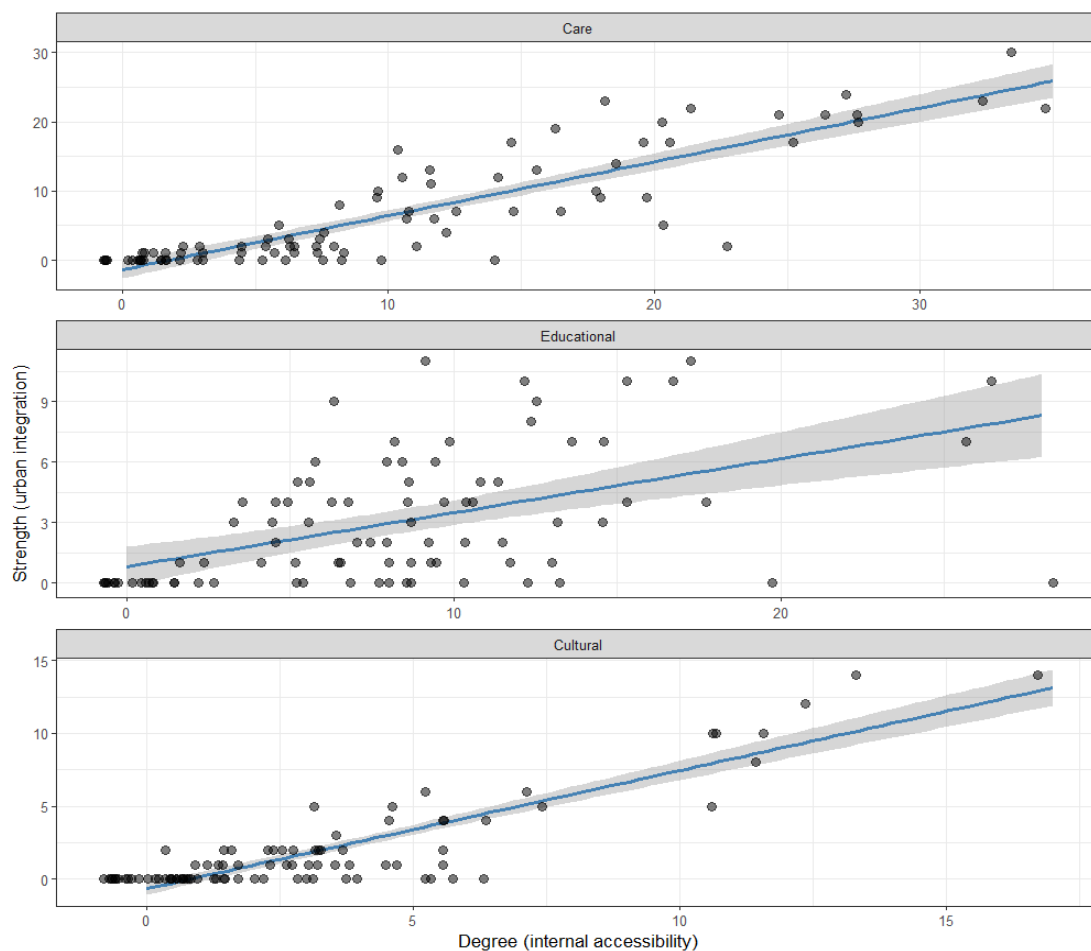
Across all three domains, however, the direction of the relationship is unambiguous. No domain shows a negative association, and none shows independence. Neighborhoods with higher internal accessibility are systematically better integrated into the shared service network - the two dimensions of the analytical framework move together, even if not always at the same rate.

Table 5: Pearson correlation between bipartite degree and projection strength, by domain

Domain	r	95% C.I.	t	p
Educational	0.502	[0.327, 0.644]	5.39	<.001
Care	0.875	[0.815, 0.916]	16.8	<.001
Cultural	0.894	[0.842, 0.929]	18.5	<.001

Note: Intra-domain association between internal accessibility (degree) and urban integration (strength). N = 88 NIL.

Figure 3: scatterplot degree x strength by domain

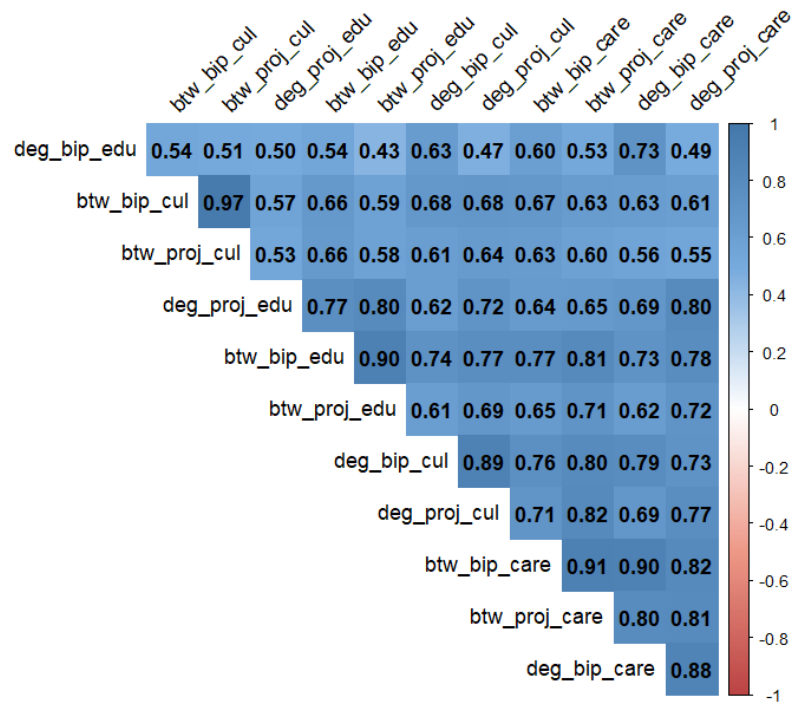


Cross-domain correlation structure

The domain-specific analyses establish that inequality exists within each domain and that the two analytical dimensions are non-redundant. The question that now follows is whether the inequalities documented within each domain are independent of each other - so that a NIL disadvantaged in care might be well-served in culture - or whether they reflect a single underlying structure of spatial advantage and disadvantage operating simultaneously across all three domains.

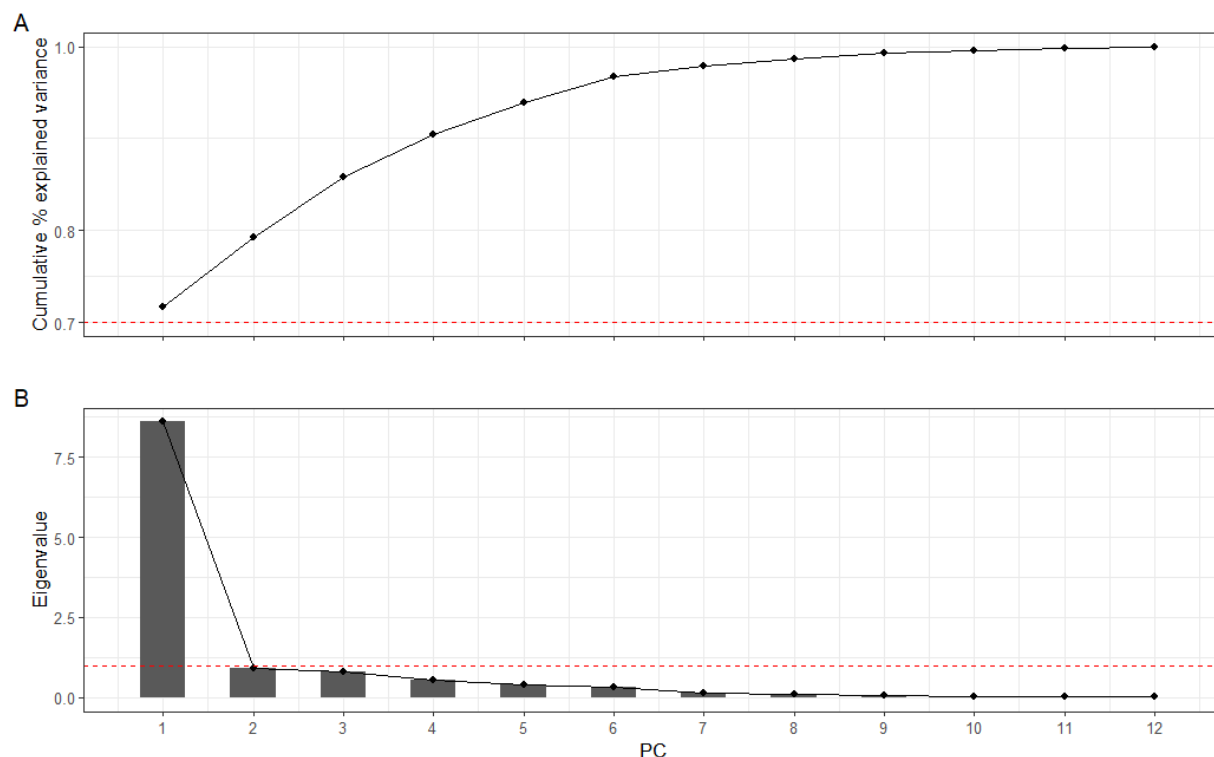
The correlation matrix of the 12 network measures provides the first answer. All correlations are positive and statistically significant at $p < 0.01$, with no exception. The range extends from 0.434 to 0.967. The strongest associations occur within measurement type: cultural bipartite betweenness and cultural projection betweenness share $r = 0.967$; care bipartite betweenness and care projection betweenness $r = 0.910$. What is theoretically significant, however, is the magnitude of the cross-domain correlations: educational degree correlates 0.729 with care degree and 0.631 with cultural degree; care degree correlates 0.787 with cultural degree. Even the weakest correlation in the matrix - 0.434 between educational bipartite degree and educational projection betweenness, coherent with the patterns identified so far - is positive and highly significant. A NIL that is well-served in one domain tends to be well-served in all others; one that is poorly served in one domain tends to be poorly served across the board. The pervasive positive correlation structure rules out the domain-specific deprivation scenario and points toward a single underlying dimension of structural spatial advantage and disadvantage. Whether that dimension is empirically recoverable as a single latent construct is what the next step addresses.

Figure 4: Correlation matrix (12 measures)



Principal Component Analysis

PCA on the standardised 12-variable matrix provides the formal answer. As reported in *figure 5*, PC1 has an eigenvalue of 8.60 and explains 71.6% of total variance - already satisfying the 70% cumulative threshold with a single component. PC2 has an eigenvalue of 0.91, falling below the Kaiser criterion of 1, and explains a further 7.6%. The scree plot shows a marked drop after PC1, with all subsequent components falling well below the eigenvalue threshold. Both cumulative variance and Kaiser criteria converge on PC1 as the only component warranting substantive interpretation.

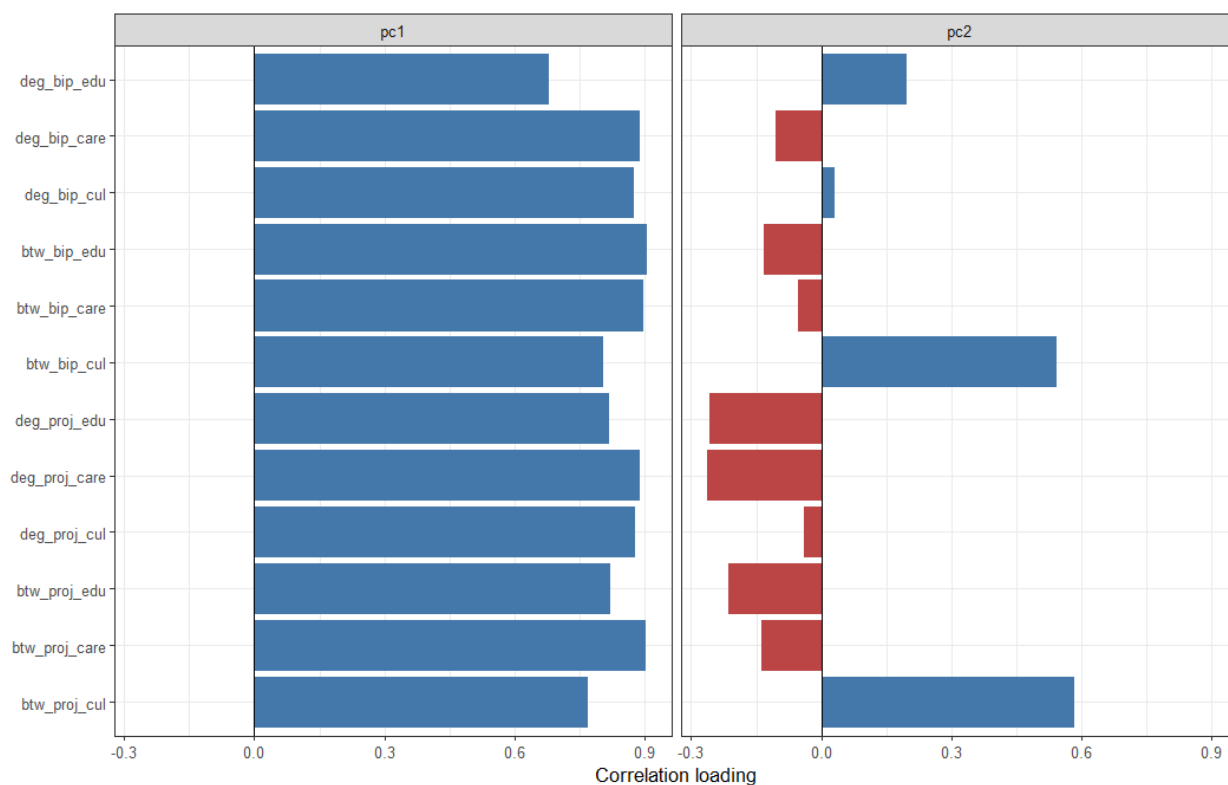
Figure 5: *A = Cumulative explained variance; B = Eigenvalue*

The loading plot makes the structure of PC1 explicit (*Figure 6*). All 12 loadings on PC1 are positive and high, ranging from 0.68 (educational bipartite degree) to 0.90 (educational bipartite betweenness), with no variable pulling in a different direction. PC1 is a general dimension of cumulative service accessibility: a NIL's score on this axis reflects its simultaneous standing across all three domains and all four measure types. High-scoring NILs are internally accessible and well-integrated across care, education, and culture; low-scoring NILs are excluded or marginal across all dimensions simultaneously. The collapse of 12 conceptually distinct indicators onto a single dominant dimension is the empirical answer to the research question: spatial deprivation in Milan is not a collection of independent domain-specific condition; it is a single structural condition that manifests across domains simultaneously.

PC2, retained for visualization despite its eigenvalue is <1 , captures a secondary dimension of cultural betweenness: high positive loadings from cultural bipartite betweenness (0.543) and cultural projection

betweenness (0.584), alongside negative loadings from educational and care projection measures. NILs scoring high on PC2 - Guastalla (5.97), Duomo (2.19), Magenta-S.Vittore (1.00) - combine very high overall accessibility with an anomalously strong bridging position in the cultural network. NILs scoring low on PC2 - Garibaldi Repubblica (-2.35), Tre Torri (-2.05), Sarpi (-1.91), Parco Sempione (-1.87) - are well-connected in care and education but peripheral in cultural betweenness. This secondary axis qualifies the main finding without contradicting it: within the small group of well-served central NILs, there is a further internal differentiation based on structural position in the cultural network - a form of positional advantage in the network that betweenness on the projection makes visible. The large majority of NILs, however, cluster in the negative half of PC1 with near-zero PC2 scores - a visual confirmation that peripheral disadvantage is the dominant structure in the data (*Figure 9*).

Figure 6: Loadings on *pc1* and *pc2*

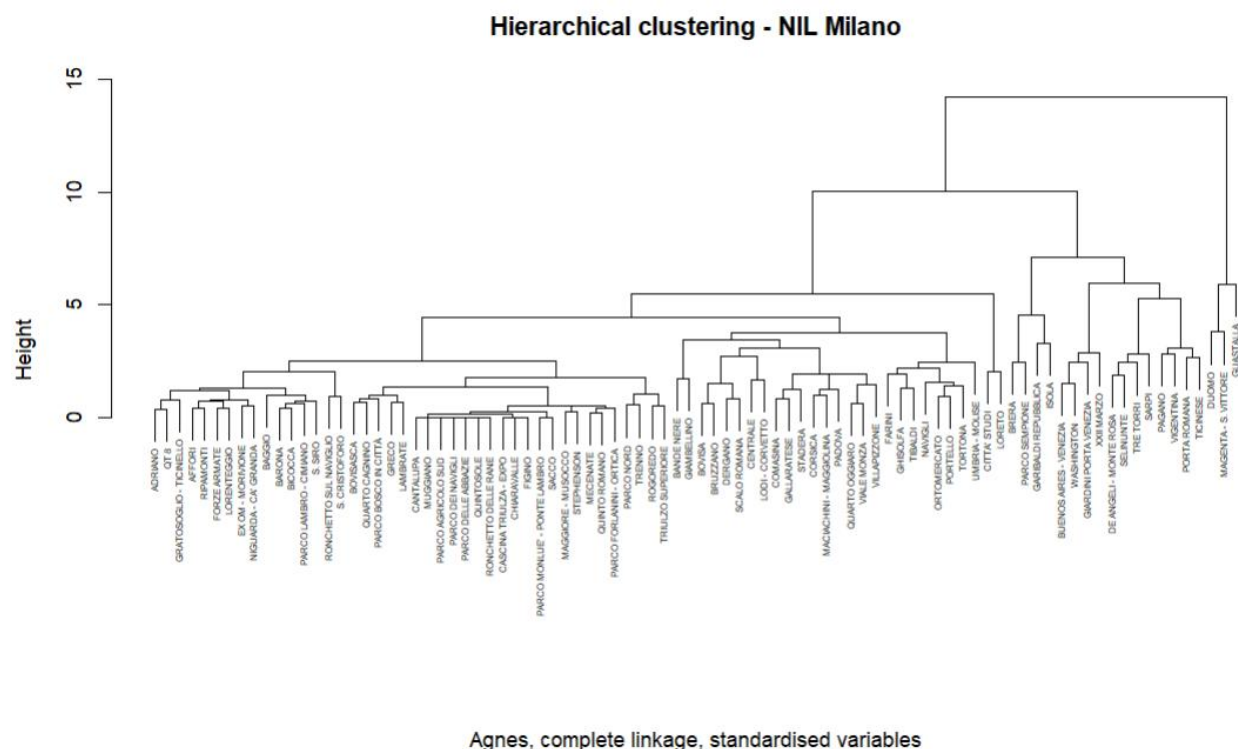


Cluster analysis and neighborhood typology

PCA has shown that the 12 measures are reduced to a single dominant dimension along which NILs are distributed. Cluster analysis asks whether this distribution contains discrete groups of neighborhoods.

Agglomerative hierarchical clustering with complete linkage produces a dendrogram (*Figure 7*) whose height profile indicates three natural groupings: a large peripheral cluster that merges at low heights, a smaller intermediate cluster, and a tight group of three extreme central NILs that merge last and at a much greater distance from the rest. The large jump in merge height between the third and the remaining clusters provides a visual signature of discontinuity in the data.

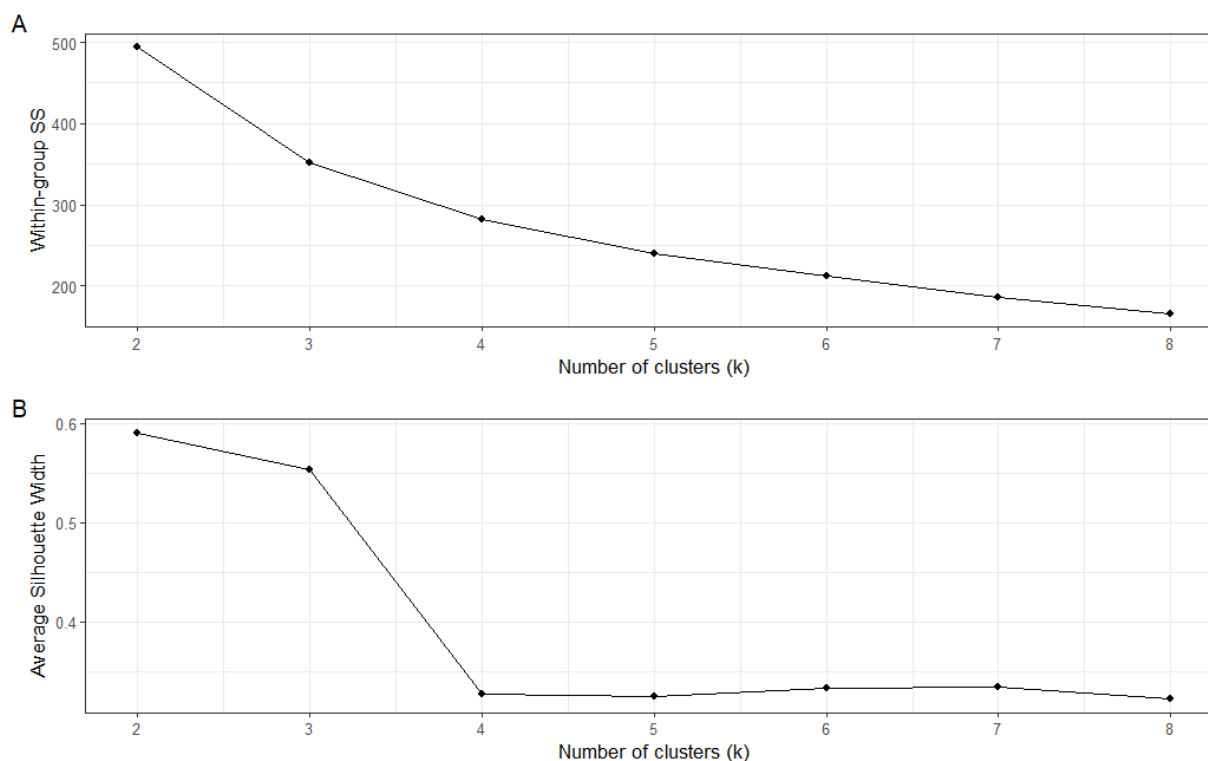
Figure 7: Dendrogram; Hierarchical agglomerative clustering; Agnes, complete linkage.



K-means clustering on the standardized 12-variable matrix is run in parallel for $k = 2$ to 8, with both the WGSS elbow and the average silhouette width used to select the optimal solution (*Figure 8*). The ASW is

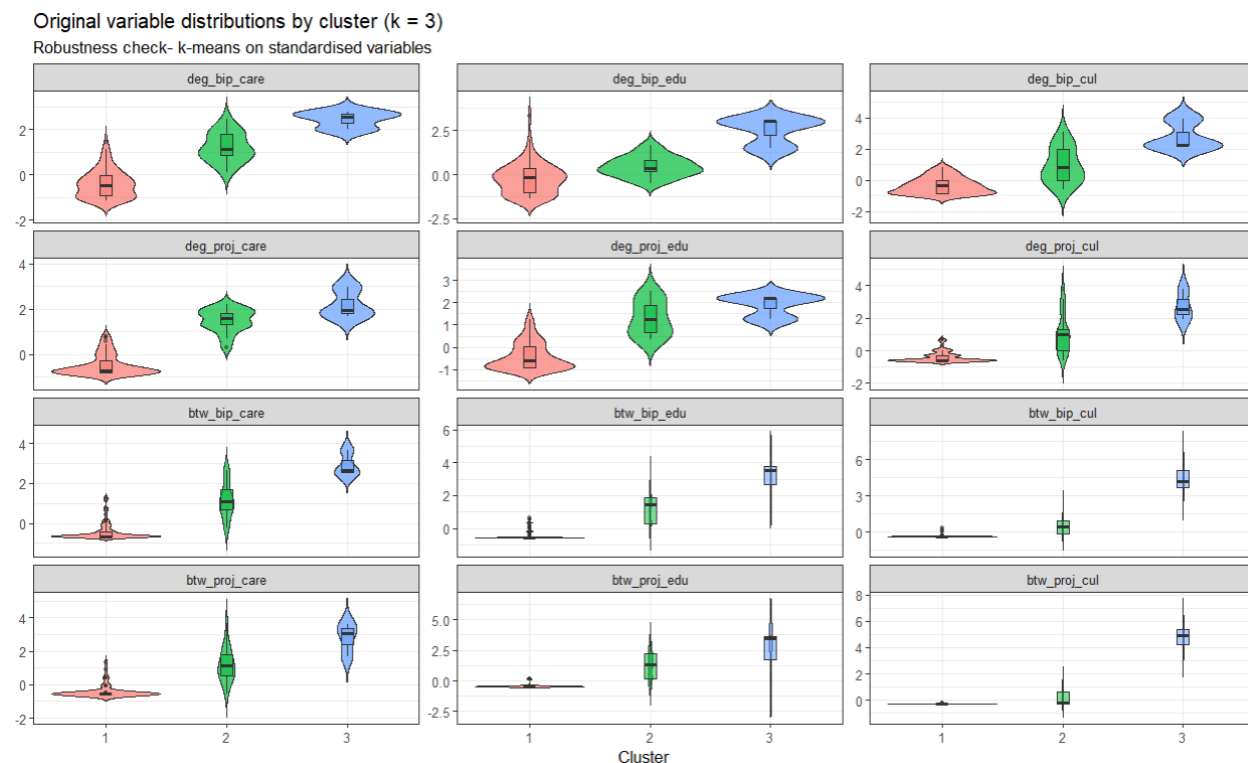
highest at $k = 2$ (0.591), drops to 0.553 at $k = 3$, and falls to 0.328 at $k = 4$. The WGSS elbow falls between $k = 2$ and $k = 3$. On purely metric grounds, $k = 2$ has a marginally higher silhouette score and would represent the statistically supported solution. However, the three-cluster solution is preferred for substantive reasons. At $k = 2$, the algorithm merges two structurally distinct groups into a single peripheral majority: NILs with near-zero accessibility across all domains, and NILs that are moderately well-served and centrally located but fall short of the extreme values of the core. These two groups occupy different positions in the $PC1 \times PC2$ space (*Figure 9*) and differ systematically across all 12 measures: collapsing them into a single cluster loses structural information that is relevant. The three-cluster solution recovers this distinction at a modest cost in silhouette score, a trade-off that is justified by the substantive interpretability of the resulting typology. With both quantitative criteria and substantive considerations being taken together, $k = 3$ is the preferred solution.

Figure 8: *K*-means; WGSS elbow and average silhouette width by *k*.



The violin plots of all 12 standardized measures by cluster confirm that the separation is consistent across every variable in the matrix and it's not driven by a subset of measures (*Figure 10*). For every measure, the three clusters are ordered in the expected direction - cluster 3 highest, cluster 1 lowest - with no variable showing a reversal or a collapse of the distinction. This consistency across 12 conceptually distinct measures further validates the three-type structure as a genuine feature of the data rather than an artefact of the clustering algorithm or arbitrary choice.

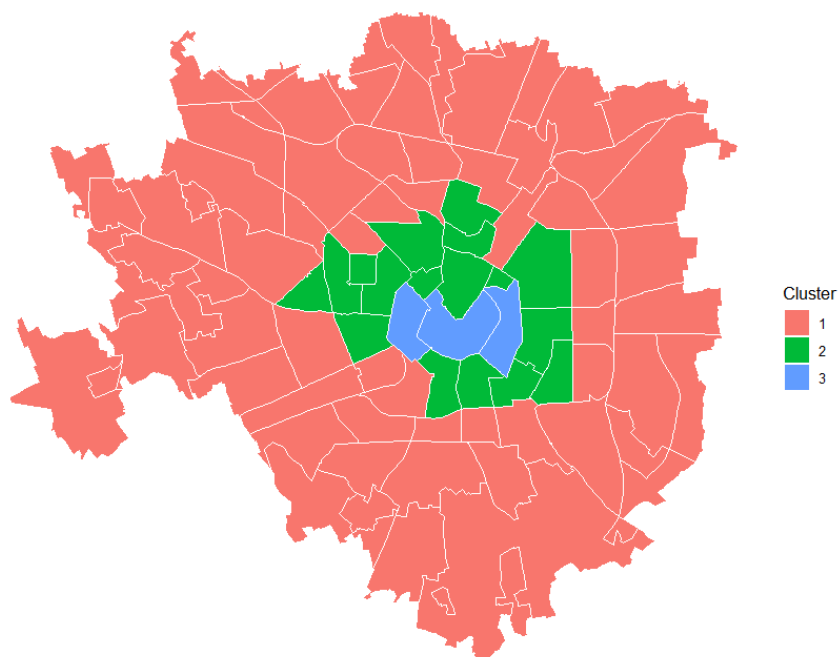
Figure 10: *Violin plots of standardised variables by cluster*



Projected onto the map of Milan, the three clusters reproduce with clarity the concentric spatial logic that the theoretical framework anticipated (*Figure 11*): cluster 3 occupies the historic center, cluster 2 forms a discontinuous inner ring of relatively well-served neighborhoods, and cluster 1 covers the majority of the city's surface area - including all peripheral and peri-central NILs.

Figure 11: *Map of Milan; 3 clusters visualization*

Urban accessibility clusters - Milano (k = 3)
K-means on 12 standardised measures



Discussion

The results of this analysis converge on a clear answer to the research question: spatial disadvantage in access to social infrastructure in Milan is not a domain-specific phenomenon but a structural one. The single dominant component extracted by PCA - accounting for 71.6% of variance across 12 analytically distinct measures - is the empirical expression of a structural condition that operates simultaneously across care, education, and culture, along both the internal accessibility and urban integration dimensions. NILs that are well-served in one domain tend to be well-served in all others; NILs that are structurally isolated in the cultural network tend also to be peripheral in the care and educational networks. The geography of access in Milan is the expression of a single organizing logic, spatially distributed along the city's concentric axis from center to periphery. According to Klinenberg (2018), social infrastructure functions as an integrated

material condition for community life - which implies that its absence should manifest as compound deficit, not isolated gaps. The results presented here support that claim at the neighborhood scale, and extend it: the bipartite network framework adds a formal demonstration of the compounding mechanism that Klinenberg's largely ethnographic account could partially provide, showing not only which neighborhoods lack access but how their structural position in the service network reproduces and amplifies that lack across domains simultaneously. The PCA result - a single dimension absorbing 71.6% of variance across twelve measures - is the formal counterpart to Klinenberg's qualitative argument.

The concentric cluster structure documented here gives precise empirical form to Soja's (2010) argument that urban space does not merely reflect social inequality but actively produces it. The three neighborhood types are not the product of random variation in service supply: they reproduce a spatially organized logic of resource concentration that has accumulated in Milan's urban fabric over time. In fact, the discontinuity breaks in the three clusters is evident: three NILs - Duomo, Guastalla, and Magenta-S.Vittore - record values across all 12 measures that are qualitatively different from those of the semi-central ring, let alone the structural periphery. This is not just a matter of degree but also of structural position. The spatial logic of this structure suggests that the city's social infrastructure has organized itself around a center whose conditions of access are structurally reproduced, while the periphery inherits a position of compound disconnection that no single-domain intervention is likely to address. The cultural domain is where this logic is most legible - and most consequential. Twenty-one NILs have no reachable cultural amenity within 1 km, and nearly half the city is structurally isolated in the cultural projection. This is not simply a quantitative difference from care and education: it reflects a qualitatively different logic of infrastructure allocation. Unlike schools and health facilities, whose distribution is shaped by planning obligations and minimum coverage norms, cultural infrastructure in Milan follows logics of prestige, institutional history, and real estate value that concentrate it in areas already rich in other forms of social infrastructure. Wilson (1987) and Sampson (2012) argue that the concentration of disadvantages produces effects that exceed the sum of individual deficits - that the withdrawal of institutions from peripheral areas cascades across

domains of social life. The cultural domain illustrates this cascading logic clearly: it is precisely the domain most associated with civic life, shared identity, and the production of urban belonging that is most thoroughly organized around the reproduction of central advantage, and whose absence from the periphery therefore carries the heaviest social cost.

The projection dimension of the analytical framework reveals a form of disadvantage that internal accessibility measures cannot capture. Twenty-nine NILs reach at least one educational facility within 1 km - they are not, by a degree-based measure, educationally deprived. Yet they share none of those facilities with any neighbor: their catchments do not overlap with those of adjacent NILs, which means they are structurally absent from the network of shared educational access through which proximity to resources is collectively reproduced. In Klinenberg's terms, these neighborhoods have access to institutions but are excluded from the exchange those institutions make possible. Similarly, Levy et al. argue that a neighborhood's well-being depends not only on its own conditions but on the structure of its connections to surrounding areas - that isolation from better-served neighbors' compounds local disadvantage in ways that individual-level measures cannot capture. This is what the projection makes visible: a NIL in this position is excluded from the relational infrastructure that makes neighborhood-level access to education more than the sum of individual reachability scores. In a city where educational provision is distributed widely enough to give most NILs some degree of formal access, the projection reveals a second-order inequality that degree alone cannot see: the difference between reaching a school and being part of a connected educational landscape. This distinction could have implications for how policy is designed: a NIL with high degree and near-zero strength does not need more services, it needs interventions that create catchment overlap with neighboring NILs. Conversely, NIL with degree zero needs services before integration can even be addressed. The two conditions may require qualitatively different responses.

Betweenness centrality adds a further dimension. Where degree counts what a neighborhood reaches and strength measures how much it shares, betweenness identifies whether a neighborhood occupies a

structurally bridging position - whether it lies on the paths through which other nodes access the system. If we look at the results of PCA, NILs scoring high on PC2 - Guastalla, Duomo, Magenta-S.Vittore - combine strong overall accessibility with relatively high betweenness in the cultural network specifically, occupying bridging positions in a domain where the projection is sparse and structural intermediaries are few. NILs scoring low on PC2 - Garibaldi Repubblica, Tre Torri, Sarpi - are well-connected in the educational and care networks but record near-zero cultural betweenness, absent from the relational structure of cultural access entirely. PC2 therefore could capture a secondary axis of structural differentiation within the well-served core: whether it mediates cultural connectivity for others - a form of positional privilege that degree and strength alone cannot reveal.

Limitations

The main limitation of this study concerns the OSM data infrastructure. Volunteered Geographic Information datasets are known to exhibit systematic geographic bias, with coverage quality positively correlated with population density and negatively correlated with peripheral location (Haklay, 2010). In the context of this analysis, this means that the degree of underservice documented for peripheral NILs may be partly attributable to incomplete mapping rather than to an actual absence of facilities. This aspect could be further investigated with cross-validation against official administrative registers. The cultural domain is particularly exposed to this limitation, given that smaller or informal cultural venues are less systematically represented in OSM than schools or hospitals. Another limitation concerns the 1 km threshold: while grounded in the pedestrian accessibility literature and consistent with the 15-minute city operationalization, it is a binary cutoff. A facility at 950 meters is treated identically to one at 50 meters, while one at 1,050 meters is entirely excluded. Sensitivity analyses using distance-decay weighting or alternative thresholds would provide a more complete account of how the results depend on this analytical choice, and are a natural direction for further development. A final limitation concerns the descriptive nature of the analysis: it documents the current structure of spatial stratification but does not model its causes, its dynamics over time, or its relationship to socioeconomic characteristics of the resident population.

Connecting the network-based accessibility typology to demographic and income data at the NIL level - and eventually to longitudinal records of service investment and disinvestment - would allow the structural patterns documented here to be situated within a fuller account of how spatial inequality is produced and reproduced in Milan's urban periphery.

Conclusion

This paper has examined pedestrian accessibility to non-commercial social infrastructure across Milan's 88 NIL, combining GIS-based shortest-path routing with bipartite network analysis to characterise the structure of access along two analytically distinct dimensions - internal accessibility and urban integration - across three service domains simultaneously. In doing so, it contributes empirical evidence to the growing literature on spatial equity and the 15-minute city model in European urban contexts, while demonstrating that network-based measures reveal structural features of service geographies that reachability-based approaches alone cannot detect.

The central finding is that spatial disadvantage in Milan is not domain-specific. A single dominant dimension accounts for 71.6% of variance across 12 network measures, all correlations among those measures are positive and significant, and cluster analysis identifies three structurally distinct neighborhood types whose geography reproduces the concentric logic of the city's socioeconomic organization. The structural periphery - comprising 77% of Milan's NIL - faces simultaneously low internal accessibility and near-complete isolation in the urban integration dimension across all three domains. Three NILs in the historic center occupy a position so structurally distant from the rest of the city that the gap between them and the semi-central ring exceeds the gap between the semi-central ring and the periphery. Taken together, the analyses presented here suggest that the 15-minute city, in Milan, is not a city-wide condition. It is a central privilege.

The paper also shows that this structure is not fully visible to a measure of internal reachability alone. Separating degree from projection strength reveals neighborhood positions - formally accessible but isolated from the shared service network - that a single aggregate score would misclassify as adequately served. In the educational domain, 29 NILs fall into precisely this position: they reach facilities, but they do so outside the cross-neighborhood exchange through which social infrastructure generates collective value. The distinction between reaching a service and being part of a connected service landscape is one that reachability-based measures cannot make.

These findings also carry implications for how accessibility-oriented planning frameworks are designed and evaluated. A policy approach that targets one service domain at a time, or that relies on aggregate reachability scores, may not capture the structural dimension of disadvantage documented here - precisely because that disadvantage is simultaneous across domains and relational in character. The framework developed in this paper makes legible a city in which the distance between centre and periphery runs deeper than geography: it is structural, consistent across every domain of access, and silent in any measure that does not look for it.

Appendix

Appendix Table a1: Descriptive statistics for the 12 network measures (N = 88 NIL)

<u>Variable</u>	<u>Min</u>	<u>Q1</u>	<u>Median</u>	<u>Mean</u>	<u>Q3</u>	<u>Max</u>
Bipartite degree (internal accessibility)						
<u>deg_bip_edu</u>	0.00	4.00	8.00	8.03	11.00	28.00
<u>deg_bip_care</u>	0.00	2.75	7.50	10.18	15.25	35.00
<u>deg_bip_cul</u>	0.00	1.00	2.00	3.16	4.00	17.00
Bipartite betweenness (normalised)						
<u>btw_bip_edu</u>	0.0000	0.0000	0.0004	0.0131	0.0166	0.1079
<u>btw_bip_care</u>	0.0000	0.0000	0.0056	0.0297	0.0424	0.1963
<u>btw_bip_cul</u>	0.0000	0.0000	0.0001	0.0060	0.0008	0.1095
Projection strength (urban integration)						
<u>deg_proj_edu</u>	0.00	0.00	2.00	2.96	5.00	11.00
<u>deg_proj_care</u>	0.00	0.00	2.00	6.57	11.25	30.00
<u>deg_proj_cul</u>	0.00	0.00	1.00	1.91	2.00	14.00
Projection betweenness (normalised)						
<u>btw_proj_edu</u>	0.0000	0.0000	0.0000	0.0086	0.0032	0.0776
<u>btw_proj_care</u>	0.0000	0.0000	0.0000	0.0157	0.0249	0.1198
<u>btw_proj_cul</u>	0.0000	0.0000	0.0000	0.0026	0.0000	0.0550

Appendix Table a2: NIL with highest and lowest PC2 scores: selection on betweenness.

NIL <chr>	pc1 <dbl>	pc2 <dbl>	btw_bip_cul <dbl>	btw_proj_cul <dbl>	btw_bip_edu <dbl>	btw_bip_care <dbl>
1 GUASTALLA	8.64	5.97	0.110	0.0550	0.0553	0.143
2 DUOMO	11.5	2.19	0.0776	0.0466	0.108	0.196
3 MAGENTA - S. VITTORE	10.0	1.00	0.0612	0.0345	0.0944	0.150
4 CITTA' STUDI	0.197	0.783	0.000284	0	0.00175	0.0369
5 VIALE MONZA	-1.25	0.645	0.000284	0	0.000362	0.000113

NIL <chr>	pc1 <dbl>	pc2 <dbl>	btw_bip_cul <dbl>	btw_proj_cul <dbl>	btw_bip_edu <dbl>	btw_bip_care <dbl>
1 GARIBALDI REPUBBLICA	5.91	-2.35	0.00241	0.000932	0.0566	0.150
2 TRE TORRI	1.62	-2.05	0	0	0.0585	0.0202
3 SARPI	2.93	-1.91	0.000766	0	0.0619	0.106
4 PARCO SEMPIONE	5.14	-1.87	0.0136	0	0.0513	0.0654
5 DE ANGELI - MONTE ROSA	1.96	-1.60	0.00610	0	0.0531	0.0509

Bibliography

Batty, M. (2008). Whither network science? *Environment and Planning B: Planning and Design*, 35(6), 987–991.

Batty, M. (2012). Building a science of cities. *Cities*, 29(Supplement 1), S9–S16.

Borgatti, S. P., Everett, M. G., Johnson, J. C., & Agneessens, F. (2022). *Analyzing Social Networks Using R* (1st edition). SAGE Publications Ltd.

Browning, C. R., & Calder, C. A. (2017). Ecological networks and neighborhood social organization. *American Journal of Sociology*, 122(6), 1939-1988.

Caselli, B., Carra, M., Rossetti, S., & Zazzi, M. (2021). From urban planning techniques to 15-minute neighbourhoods: A GIS-based analysis of pedestrian accessibility. *Environmental Technology*, 42(85).

Comune di Milano. (2021). *Nuclei di Identità Locale (NIL) - dataset ufficiale*. Open Data Comune di Milano.

Comune di Milano. (2020). Milano 2020. Strategia di adattamento. Comune di Milano. https://partecipazione.comune.milano.it/uploads/decidim/attachment/file/2/Milano_2020._Strategia_di_adattamento.pdf

Comune di Milano. (2022). Mi15 – Spazi e servizi per Milano a 15 minuti: Avviso pubblico (PON Città Metropolitane 2014-2020, MI6.2.1.b). Comune di Milano. <https://servizi.comune.milano.it/documents/20121/38425738/Avviso+pubblico+FESR+Mi15+Spazi+e+Servizi+per+Milano+a+15+minuti.pdf>

Consolazio, D., Benassi, D., & Russo, A. G. (2023). Ethnic residential segregation in the city of Milan at the interplay between social class, housing and labour market. *Urban Studies*, 60(10), 1853-1874.

Ducruet, C., & Beauguitte, L. (2014). Spatial science and network science: Review and outcomes of a complex relationship. *Networks and Spatial Economics*, 14(3-4), 297–316.

Dumas, M., Goyal, N., & Lacroix, P. (2021). *QuickOSM QGIS plugin* (Version 2.0).

Fraser, T., Feeley, O., Ridge, A., Cervini, A., Rago, V., Gilmore, K., Worthington, G., Berliavsky, I. (2024). How far I'll go: Social infrastructure accessibility and proximity in urban neighborhoods. *Landscape and Urban Planning*, 241, Article 104922.

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and Planning B: Planning and Design*, 37(4), 682–703.

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2), 73–76.

ISTAT. (2021). *15° Censimento generale della popolazione e delle abitazioni*. Istituto Nazionale di Statistica.

Klinenberg, E. (2018). *Palaces for the people: How social infrastructure can help fight inequality, polarization, and the decline of civic life*. Crown.

Levy, B. L., Phillips, N. E., & Sampson, R. J. (2020). Triple disadvantage: Neighborhood networks of everyday urban mobility and violence in U.S. cities. *American Sociological Review*, 85(6), 925–956.

Moreno, C. (2021). Introducing the "15-minute city": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities*, 4(1), 93–111.

Mouratidis, K. (2025). The 15-minute city revisited: A GIS approach to measuring, visualizing, and analyzing accessibility by proximity and by public transport supply. *Travel Behaviour and Society*, 51, Article 101283.

Musterd, S., Marcińczak, S., van Ham, M., & Tammaru, T. (2017). Socioeconomic segregation in European capital cities: Increasing separation between poor and rich. *Urban Geography*, 38(7), 1062–1083.

Neutens, T. (2015). Accessibility, equity and health care: Review and research directions for transport geographers. *Journal of Transport Geography*, 43, 14–27.

Openshaw, S. (1984). *The modifiable areal unit problem*. Geo Books.

Porta, S., Crucitti, P., & Latora, V. (2006). The network analysis of urban streets: A dual approach. *Physica A: Statistical Mechanics and its Applications*, 369(2), 853–866.

Poudyal, B., Ghoshal, G., & Kirkley, A. (2023). Characterizing network circuitry among heterogeneous urban amenities. *Journal of the Royal Society Interface*, 20(208), Article 20230296.

Putnam, R. D. (2000). *Bowling alone: The collapse and revival of American community*. Simon & Schuster.

Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, 20, 53–65.

Sampson, R. J. (2012). *Great American city: Chicago and the enduring neighborhood effect*. University of Chicago Press.

Soja, E. W. (2010). *Seeking spatial justice*. University of Minnesota Press.

Wilson, W. J. (1987). *The truly disadvantaged: The inner city, the underclass, and public policy*. University of Chicago Press.