Supplementary material

PLOT MORPHOLOGY AND RETAIL PATTERNS: A MORPHOLOGICAL ASSESSMENT OF PERIPHERAL RETAIL CLUSTERS

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Retail structure in three capital cities

Ankara, Türkiye

Ankara's retail landscape reflects liberal market reforms, fragmented spatial strategies, and the rapid expansion of shopping malls since the late 1980s. Corridor development in the 1990s shifted retail activity toward western and southwestern districts along major roads, producing auto-oriented strips where block-based development replaced traditional neighborhood centers. The absence of coherent retail policy, combined with weak zoning enforcement, leaves micro-businesses vulnerable to chain stores and shopping malls (Erkip & Özüduru, 2015). Without overarching planning guidance, commercial activities cluster along the most accessible roads. Although SMEs remain dominant, accounting for 88% of retail employment in 2023, large enterprises have expanded their share from 5% to 12% between 2009 and 2023 (Turkish Statistical Institute, 2025).

Helsinki Metropolitan Area (HMA), Finland

The HMA represents a highly regulated retail environment dominated by strong domestic chains, with the three largest groups accounting for 87% of market share (Santasalo & Koskela, 2008). Strict land-use controls limit retail development and reinforce established formats, while post-1950s suburban expansion created large peripheral plots that diminished the role of individual plots in retail structuring (Efeoglu et al., 2024). The result is a compact-center model, often transit-oriented, where planning constraints and plot capacity concentrate retail into planned nodes. Between 2018 and 2023, employment continued to shift toward large enterprises, with the share of small firms declining from 52% to 49% (Statistics Finland, 2025), reflecting the gradual erosion of independent street retail in suburban areas dominated by big-box formats.

Vilnius, Lithuania

Vilnius represents a post-Soviet transitional context in which the retail sector shifted rapidly from central planning to competitive market economy following the early 1990s. EU accession in 2004 accelerated modernization and the introduction of large retail formats. By 2009, the top four retail companies controlled 73% of turnover (Sekliuckiene & Langviniene, 2012), though subsequent regulatory frameworks were introduced to protect small retailers. Many micro-businesses remain located within or near residential areas, often occupying ground floors of Soviet-era estate buildings, reinforcing a compact, node-based retail pattern. Between 2000 and 2023, employment in large enterprises expanded from 9% to 27%, while the share of small firms declined from 71% to 54% (Lithuanian Official Statistics Portal [OSP], 2025).

Table S1. Percentage change in retail businesses* per 1,000 people

City	2018	2023	Change (%)
Ankara	18.30	20.89	+14.15%
Vilnius	10.36	10.76	+3.86%
Helsinki	9.09	8.99	-1.10%

Note: *Retail trade: G47 and Food & beverages service activities: I56

Between 2018 and 2023, Ankara experienced the most notable retail growth, with businesses per 1,000 residents increasing by 14.15% (TUIK, 2025). Vilnius recorded a modest rise of 3.86% (OSP, 2025), while Helsinki experienced a slight contraction of 1.10% when adjusted for population (Statistics Finland, 2025; Table S1). These diverging trajectories reflect structurally different retail development paths. Helsinki and Vilnius, through regulation and estate-based plot capacity, tend toward compact retail clusters anchored in planned or inherited node structures. Ankara's market-led dynamics and corridor infrastructure favor linear retail formations along integrated roads. These differences provide the contextual background within which the MAF results are interpreted.

Density based spatial clustering of retail units



Figure S1. A city-specific nearest-neighbor threshold distances and results of DBSCAN for each city (colors indicate different clusters and are arbitrary)

DBSCAN requires two parameters: the minimum number of points required to form a cluster (minPts) and the neighborhood radius (ε). minPts was set to five retail units, including the core point itself. Because DBSCAN with this setting also identifies small groups of shops, only clusters containing more than 10 retail units were retained for further analysis, so that the identified clusters represent substantial retail concentrations rather than incidental groupings.

The value of ε was determined for each city from its k-distance graph, in which the distance from every retail unit to its k-th nearest neighbor is sorted in ascending order (Figure S1). The point of maximum curvature on this curve, identified using the Kneedle algorithm (Satopää et al., 2011), marks the transition from densely clustered to sparsely distributed retail units and was used as the city-specific threshold.

DBSCAN was then applied with the selected thresholds (ε = 120 m for Ankara, 200 m for Helsinki, and 216 m for Vilnius). The method groups retail units into clusters of any shape without pre-specifying the number of clusters; units that do not meet the density criterion remain unclustered. The robustness of the selected thresholds was assessed through a sensitivity analysis repeating the clustering at all three thresholds in each city (Table S2).

Table S2 reports the clustering results at 120, 200, and 216 m for all three cities. The selected thresholds, 120 m

for Ankara (94 clusters), 200 m for Helsinki (58 clusters), and 216 m for Vilnius (49 clusters), correspond to the maximum curvature of each city's k-distance curve and capture the main retail concentrations while limiting both fragmentation and excessive merging.

The combined index integrates the three locational attributes, normalized within each city to a 0–1 scale, so that higher values indicate clusters located farther from the CBD, in areas of lower population density, and with higher numbers of retail units. Clusters with an index value above 0.75, corresponding to the upper quarter of the index range, were retained as the peripheral retail concentrations of each city (Figure 2). Because the index is normalized within each city, the threshold identifies clusters that occupy comparable positions within their respective urban systems, without favoring larger or denser cities. This yielded 7 clusters in Ankara, 5 in Helsinki, and 7 in Vilnius out of 94, 58, and 49 identified clusters, respectively.

Table S2. Sensitivity of retail clustering to the DBSCAN distance threshold (minPts = 5; only clusters with more than 10 retail units; cluster size is measured as the number of retail units)

City	ε	Clusters	Avg. Size	Median	Max.	Units in clusters
Ankara	120 m	94	98.21	30.5	2,784	9,232
	200 m	50	202.52	39	6,115	10,126
	216 m	44	231.70	40	6,479	10,195
Helsinki	120 m	62	90.05	20	3,039	5,583
	200 m	58	105.43	23.5	3,500	6,115
	216 m	59	105.02	24	3,510	6,196
Vilnius	120 m	77	43.18	17	811	3,325
	200 m	59	71.27	23	1,272	4,205
	216 m	49	87.59	27	2,304	4,292

Table S3. Locational attributes

1. Population density (number of people per hectare)

$PD_{RA} = \frac{\sum_{i=1}^{n} PD_i}{n}$ where,

PD: Average population density of the RA (Retail Area)

P_i: Population of the i^{th} neighborhood

A_i: Total area of the i^{th} neighborhood in hectares

n: Number of neighborhoods intersecting with the RC

2. Distance to CBD

$D_{CBD} = \min\left(\sum_{j=1}^{m} L_j\right)$ where,

D_{CBD}: Shortest network distance from the RA to the CBD.

m: Number of road segments in the shortest path.

L_j: Length of the j^{th} road segment in the path.

3. Number of retail units

$R_k = n_k$ where,

R_k: Total number of retail stores in the k-th cluster.

n_k: Number of retail stores in the k-th cluster.

Combined Index $= D'_{CBD} + \left(1 - PD'_{RA}\right) * R_k'$

where,

D'_{CBD} : Normalized distance to CBD

PD'_{RA} : Normalized population density

Rk' : Normalized retail intensity

4. Shape index

$S = \frac{4\pi A}{P^2}$ where,

S: Compactness ratio (Circularity ratio)

A: Area of the std. deviational ellipse generated by retail points

P: Perimeter of the ellipse

Table S4. NACE division groups based on OSM and places API

NACE Division-groups						
47.1	47.2	47.4	47.5	47.6	47.7	56
Retail sale in non-specialised stores	Retail sale of food, beverages and tobacco in specialised stores	Retail sale of information and communication equipment in specialised stores	Retail sale of other household equipment in specialised stores	Retail sale of cultural and recreation goods in specialised stores	Retail sale of other goods in specialised stores	Food and beverage service activities
Openstreetmap – OSM values:						
OSM tag: shop OSM values: • beverages • supermarkets • grocery • convenience • department store • mall • variety store • kiosks • general	OSM tag: shop OSM values: • alcohol • bakery • butcher • cheese • chocolate • coffee • confectionery • delicatessen • dairy • farm • frozen food • health food • tobacco • greengrocer • pasta • pastry • seafood • spices • tea • wine • water	OSM tag: shop OSM values: • computer • electronics • hifi (audio components) • mobile phone • radiotechnics • video games • electrical	OSM tag: shop OSM values: • appliance • bathroom furnishing • do it yourself • fireplace • garden furniture • hardware • houseware • paint • security • musical instruments • bed • candles • carpet • curtain • doors • window blind • furniture • tiles • interior decoration • kitchen • lighting	OSM tag: shop OSM values: • anime • books • newsagent • stationery • music • video • copyshop • toys • bicycle • boat • fishing • art • hunting • outdoor • sports • swimming pool	OSM tag: shop OSM values: • baby goods • bag • beauty • butcher • clothes • fabric • fashion accessories • jewellery • shoes • watches • chemist • cosmetics • hairdresser supply • florist • nutrition supplements • medical supply • pet • florist • garden center • tailor • gift • second hand	OSM tag: amenity OSM values: • restaurant • pub • bubble tea • food court • fast food • cafe • biergarten • bar • ice cream
Google Places – Place types:						
convenience_store, department_store, shopping_mall, supermarket,	bakery, liquor_ store	electronics_store electrician	furniture_store, hardware_store, home_goods_store painter	art_gallery, bicycle_store, book_store aquarium, bowling_alley, movie_rental	clothing_store, jewelry_store, shoe_store, pet_store, florist, pharmacy, drugstore, beauty_salon hair_care veterinary_care	restaurant, cafe, bar, meal_takeaway, meal_delivery

Retail units were collected in 2025 from Google Maps Platform (Places API) and OpenStreetMap. Each point was classified into one of seven NACE division groups (G47.1 - G47.7 and I56) based on its OpenStreetMap tag or Google place type, following the correspondence in Table S4. Points without a tag or place type corresponding to one of these groups were excluded, so that no point was classified manually or by inference. Points sharing the same name within 5 meters were considered as duplicates between the two sources and retained once. Individual establishments within shopping malls were retained as separate units, as each represents an independent retail activity, often operated by a different business and belonging to a different NACE division group. Aggregating a mall into a single point would underestimate both retail density and retail diversity, and would treat mall-based and street-based retail inconsistently. After cleaning, the dataset comprised 10570 retail units in Ankara, 7519 in Helsinki, and 5013 in Vilnius.

Because the coverage of both platforms may vary between countries, combining the two sources was intended to reduce source-specific gaps. Moreover, all analyses were conducted within each city, and morphological and retail variables were standardized within each city; differences in overall data coverage between countries therefore affect the absolute level of retail metrics, but not the within-city associations on which the results are based, unless coverage varies systematically within a city.

Table S5. Compositional and Configurational Indicators

Compositional Indicator
(Structural Morphological Character)

$$S_{comp}^{(i,Y)} = \sum_{n \in C} \beta_n^{(Y)} \cdot z_n^{(i)}$$

where,
$Y \in$ {Density, Agglomeration, Diversity}: dependent variable

- $S_{comp}^{(i,Y)}$: compositional indicator of plot i for retail metric Y
- $z_n^{(i)}$: value of variable n for plot i, standardized within the city (z-score: (x − city mean) / city standard deviation)
- $\beta_n^{(Y)}$: mean of the statistically significant local MGWR coefficients of variable n for retail metric Y, estimated separately for each city; β = 0 where no local coefficient is significant
- C: index set for compositional variables {Plot Area, GAR, Building Frontage, Plot Frontage}

Configurational Indicator
(Contextual Morphological Character)

$$S_{conf}^{(i,Y)} = \sum_{n \in K} \beta_n^{(Y)} \cdot z_n^{(i)}$$

where,

- $Y \in$ {Density, Agglomeration, Diversity}: dependent variable
- $S_{conf}^{(i,Y)}$: configurational indicator of plot *i* for retail metric *Y*
- $z_n^{(i)}$: value of configurational variable *n* for plot *i*, standardized within the city (*z*-score: (*x* − city mean) / city standard deviation)
- $\beta_n^{(Y)}$: mean of the statistically significant local MGWR coefficients of variable n for retail metric Y, estimated separately for each city; β = 0 where no local coefficient is significant
- K: index set for configurational variables {Plot Frequency, Connectivity, Local Integr., Global Integr.}

Note: Because variables are standardized within each city, an indicator value of 0 corresponds to the city mean.

Table S6. Summary statistics for MGWR coefficient values for retail density

Variable	City	Mean	SD	Min	Median	Max	Bandwidth	ENP_j	Adj t-val (95%)	DoD_j
Plot area	Ankara	0.010	0.002	0.007	0.010	0.021	3400	1.633	2.163	0.940
	Helsinki	0.139	0.454	–1.317	0.145	0.943	73	15.522	2.957	0.573
	Vilnius	–0.050	0.050	–0.125	–0.016	–0.013	830	2.120	2.267	0.892
Ground area ratio	Ankara	0.017	0.005	0.013	0.014	0.026	3400	1.649	2.167	0.938
	Helsinki	0.227	0.324	–0.173	0.085	1.236	47	26.041	3.116	0.492
	Vilnius	0.095	0.087	0.017	0.128	0.431	588	3.695	2.474	0.812
Building frontage ratio	Ankara	–0.013	0.007	–0.027	–0.009	–0.007	3400	1.634	2.163	0.940
	Helsinki	0.031	0.293	–0.541	0.033	0.770	62	18.596	3.014	0.545
	Vilnius	–0.013	0.069	–0.122	0.032	0.037	1017	1.907	2.226	0.907
Plot frontage ratio	Ankara	–0.005	0.001	–0.007	–0.004	0.002	3400	1.702	2.179	0.935
	Helsinki	0.027	0.130	–0.189	–0.004	0.367	111	10.832	2.843	0.629
	Vilnius	–0.016	0.025	–0.137	–0.011	0.011	801	2.537	2.335	0.866
Plot frequency	Ankara	0.149	0.346	–1.157	0.069	1.709	158	54.973	3.320	0.507
	Helsinki	–0.089	0.059	–0.148	–0.109	0.037	478	2.250	2.292	0.874
	Vilnius	–0.106	0.004	–0.113	–0.104	–0.102	1051	2.070	2.258	0.895
Local connectivity	Ankara	–0.039	0.005	–0.047	–0.041	–0.032	3400	1.190	2.034	0.979
	Helsinki	0.134	0.011	0.118	0.143	0.144	612	1.567	2.151	0.930
	Vilnius	0.238	0.221	0.087	0.088	0.589	816	2.239	2.288	0.884
Local integration	Ankara	0.041	0.163	–0.129	–0.020	0.439	835	5.073	2.582	0.800
	Helsinki	0.044	0.236	–0.532	0.066	0.692	55	20.562	3.044	0.529
	Vilnius	–0.098	0.107	–0.267	–0.030	–0.024	1007	1.861	2.217	0.911
Global integration	Ankara	0.528	0.812	–0.072	0.171	2.889	400	14.613	2.929	0.670
	Helsinki	0.047	0.407	–0.512	–0.090	0.814	123	6.499	2.674	0.708
	Vilnius	0.054	0.071	–0.081	0.018	0.165	975	2.440	2.321	0.872

Table S7. Summary statistics for MGWR coefficient values for retail agglomeration

Variable	City	Mean	SD	Min	Median	Max	Bandwidth	ENP_j	Adj t-val (95%)	DoD_j
Plot area	Ankara	–0.126	0.191	–0.639	–0.042	0.073	364	16.614	2.969	0.654
	Helsinki	0.006	0.020	–0.032	0.013	0.045	492	2.620	2.350	0.850
	Vilnius	0.086	0.261	–0.224	0.007	0.849	79	24.204	3.088	0.542
Ground area ratio	Ankara	0.015	0.001	0.013	0.016	0.017	3400	1.368	2.091	0.961
	Helsinki	0.069	0.024	0.046	0.049	0.103	499	1.639	2.169	0.923
	Vilnius	–0.031	0.012	–0.048	–0.028	0.014	727	2.217	2.284	0.886
Building frontage ratio	Ankara	–0.003	0.012	–0.022	–0.006	0.059	862	7.658	2.722	0.750
	Helsinki	–0.005	0.222	–0.698	–0.003	0.873	44	27.672	3.134	0.483
	Vilnius	0.045	0.056	–0.164	0.043	0.302	132	15.434	2.951	0.607
Plot frontage ratio	Ankara	–0.004	0.025	–0.121	–0.003	0.153	444	16.783	2.972	0.653
	Helsinki	0.016	0.005	0.005	0.018	0.020	612	1.806	2.207	0.908
	Vilnius	0.025	0.102	–0.168	0.008	0.307	127	16.006	2.962	0.601
Plot frequency	Ankara	0.106	0.554	–1.328	0.007	1.387	44	118.011	3.528	0.413
	Helsinki	–0.321	0.610	–2.011	–0.234	1.267	43	21.133	3.053	0.525
	Vilnius	–0.222	0.331	–1.164	–0.207	1.132	43	37.637	3.218	0.479
Local connectivity	Ankara	0.392	0.384	–0.202	0.257	1.662	96	39.963	3.230	0.546
	Helsinki	0.206	0.265	–0.257	0.167	1.065	43	24.038	3.092	0.505
	Vilnius	0.550	0.443	–0.146	0.431	2.029	43	45.905	3.275	0.450
Local integration	Ankara	0.029	0.752	–2.775	0.120	2.364	44	112.673	3.516	0.419
	Helsinki	0.470	0.598	–0.427	0.258	1.725	43	20.238	3.040	0.531
	Vilnius	–0.093	0.304	–0.785	–0.080	0.812	77	18.518	3.007	0.581
Global integration	Ankara	0.084	0.433	–1.245	0.099	1.996	156	17.952	2.993	0.645
	Helsinki	0.251	0.863	–1.171	–0.012	2.231	43	16.549	2.977	0.563
	Vilnius	0.022	0.611	–2.084	–0.023	1.244	43	36.817	3.212	0.482

Table S8. Summary statistics for MGWR coefficient values for retail diversity

Variable	City	Mean	SD	Min	Median	Max	Bandwidth	ENP_j	Adj t-val (95%)	DoD_j
Plot area	Ankara	–0.029	0.594	–1.928	0.007	3.852	44	104.200	3.495	0.429
	Helsinki	0.087	0.115	–0.125	0.134	0.278	312	3.857	2.492	0.790
	Vilnius	–0.008	0.061	–0.156	0.023	0.084	302	6.771	2.684	0.725
Ground area ratio	Ankara	0.003	0.069	–0.303	0.008	0.918	70	99.350	3.482	0.435
	Helsinki	0.038	0.038	–0.005	0.017	0.106	494	1.911	2.229	0.899
	Vilnius	–0.006	0.022	–0.020	–0.006	0.106	755	2.324	2.302	0.879
Building frontage Ratio	Ankara	–0.003	0.001	–0.005	–0.004	–0.002	3400	1.293	2.068	0.968
	Helsinki	0.036	0.131	–0.397	–0.011	0.199	274	4.136	2.517	0.779
	Vilnius	–0.011	0.008	–0.026	–0.015	0.001	1051	1.725	2.187	0.922
Plot frontage ratio	Ankara	0.007	0.044	–0.103	0.002	0.243	226	31.736	3.163	0.575
	Helsinki	–0.025	0.120	–0.256	–0.019	0.414	118	8.722	2.772	0.663
	Vilnius	0.020	0.015	0.007	0.011	0.045	1004	1.992	2.243	0.901
Plot frequency	Ankara	–0.007	0.619	–2.112	–0.003	1.492	44	84.809	3.440	0.454
	Helsinki	0.032	0.015	0.013	0.042	0.050	612	1.527	2.140	0.934
	Vilnius	–0.391	0.322	–1.178	–0.373	0.539	43	39.626	3.233	0.471
Local connectivity	Ankara	0.121	0.389	–2.088	0.087	2.428	44	99.253	3.482	0.435
	Helsinki	0.042	0.057	–0.010	–0.004	0.128	494	1.912	2.229	0.899
	Vilnius	0.550	0.310	–0.202	0.496	1.514	43	46.644	3.280	0.448
Local integration	Ankara	0.222	0.535	–1.338	0.206	2.542	44	82.406	3.432	0.458
	Helsinki	0.156	0.204	–0.023	0.061	0.565	283	3.661	2.473	0.798
	Vilnius	0.007	0.427	–0.927	0.067	1.105	43	40.449	3.239	0.468
Global integration	Ankara	–0.005	0.742	–1.538	–0.019	2.310	44	82.533	3.432	0.457
	Helsinki	0.028	0.730	–2.600	0.013	3.540	43	30.499	3.163	0.468
	Vilnius	0.178	0.644	–0.926	0.002	1.887	90	13.524	2.909	0.626

Across all three dependent variables, the Multiscale Geographically Weighted Regression (MGWR) model consistently outperforms the global Ordinary Least Squares (OLS) regression. As shown in Table S9, MGWR yields higher R^2 and adjusted R^2 values, lower Residual Sum of Squares (RSS), and lower corrected Akaike Information Criterion (AICc) scores in all cities. These criteria indicate that MGWR provides a better fit than OLS and captures the context–specific associations between morphological metrics and retail density, agglomeration, and diversity more accurately.

Table S9. Model diagnostics for OLS and MGWR

	City	Model	Log-likelihood	AICc	R^2	Adj. R^2	RSS
Retail density	Ankara	OLS	–4775.95	9571.97	0.03	0.02	3300.98
		MGWR	–4587.18	9347.81	0.13	0.11	2954.25
	Helsinki	OLS	–773.92	1568.22	0.26	0.25	448.33
		MGWR	–591.87	1447.59	0.59	0.51	247.53
	Vilnius	OLS	–1470.62	2961.46	0.04	0.03	1008.71
		MGWR	–1437.85	2920.22	0.09	0.08	947.80
Retail agglomeration	Ankara	OLS	–4462.33	8944.73	0.19	0.19	2745.18
		MGWR	–72.77	1164.50	0.93	0.93	207.89
	Helsinki	OLS	–835.36	1691.08	0.10	0.09	547.82
		MGWR	–203.66	752.03	0.88	0.85	69.75
	Vilnius	OLS	–1342.56	2705.32	0.24	0.24	790.73
		MGWR	–407.40	1414.66	0.87	0.83	133.63
Retail diversity	Ankara	OLS	–3928.44	7876.94	0.41	0.40	2005.66
		MGWR	–173.13	1987.98	0.93	0.92	220.53
	Helsinki	OLS	–835.03	1690.42	0.10	0.09	547.24
		MGWR	–566.18	1264.12	0.62	0.58	227.63
	Vilnius	OLS	–1211.39	2443.00	0.41	0.41	616.22
		MGWR	–558.16	1592.85	0.83	0.79	177.99

Table S10. Data sources

Cities	Data sources	Website
Helsinki Metropolitan Area, Finland	HSY Open geographic interface	https://www.hsy.fi/en/environmental-information/geographic-information/geographic-information-interfaces/open-geographic-information-interfaces/
	Open data service for municipalities	https://hri.fi/en_gb
Vilnius, Lithuania	Spatial Information Portal of Lithuania	https://www.geoportal.lt/geoportal/web/en
Ankara, Türkiye	Maps & Plans Documentation Unit	https://crp.metu.edu.tr/en/maps-and-plans-archive

Table S11. Cluster-level Spearman correlations between morphological indicators and the shape index of retail clusters (n = 19) p-values from permutation tests (10000 permutations)

	Compositional ρ [95% CI]	p	Configurational ρ [95% CI]	p
Retail density	−0.20 [−0.60, 0.33]	0.41	0.32 [−0.27, 0.75]	0.18
Retail agglomeration	0.11 [−0.48, 0.57]	0.65	0.36 [−0.17, 0.73]	0.14
Retail diversity	0.01 [−0.43, 0.43]	0.97	0.37 [−0.17, 0.73]	0.12

Table S11 reports the association between the morphological character of retail clusters and their form. Because the shape index is defined at the cluster level, clusters were used as the unit of analysis (n = 19), with the median compositional and configurational indicators of each cluster related to its shape index using Spearman's rank correlations, bootstrap 95% confidence intervals (5000 resamples), and permutation-based p-values (10000 permutations). As higher shape index values indicate more compact clusters, a positive coefficient indicates that clusters with higher indicator values tend to be more compact, and a negative coefficient that they tend to be more elongated. None of the associations is statistically significant (p = 0.12–0.97), and all confidence intervals include zero.

The configurational coefficients are consistently positive (ρ = 0.32–0.37), but given the small number of clusters, the analysis does not provide evidence that cluster form varies with the morphological character of plots within clusters. The differences in cluster form are therefore interpreted as a contrast between cities rather than as a relationship at the level of individual clusters.

Table S12. Pearson correlation between compositional and configurational indicators, by retail metric and city

	All plots	Ankara	Helsinki	Vilnius
Retail density	0.05*	–	0.17*	0.18*
Retail agglomeration	0.28*	0.30*	0.21*	0.34*
Retail diversity	−0.04*	−0.15*	0.08	−0.03

Note: *p < 0.05.

Table S12 reports the correlation between the compositional and configurational indicators for each retail metric, by city and for all plots combined. Within cities, the two indicators are weakly positively associated for retail density and agglomeration, and largely unrelated or weakly negatively associated for retail diversity (−0.15 to 0.08), indicating that the two morphological dimensions do not operate in opposition at the plot level.

Table S13. Linear mixed-effects models of each retail metric (standardized within city) on the compositional and configurational indicators, with city as a fixed effect and a random intercept for retail cluster (n = 19 clusters; 5064 plots for density, agglomeration and diversity)

	Compositional β [95% CI]	Configurational β [95% CI]
Retail density	0.94 [0.79, 1.09]*	0.19 [0.12, 0.25]*
Retail agglomeration	0.27 [0.12, 0.41]*	0.66 [0.59, 0.72]*
Retail diversity	0.55 [0.29, 0.82]*	0.64 [0.59, 0.69]*

Notes: *p < 0.05. Coefficients indicate direction and significance; because the indicators are weighted sums with different variances, their magnitudes are not directly comparable across indicators.

Because plots are nested within retail clusters, plot-level observations within the same cluster are not fully independent, which may inflate the statistical significance of plot-level correlations. To account for this, linear mixed-effects models were estimated for each retail metric, with the compositional and configurational indicators as predictors, city as a fixed effect, and a random intercept for retail cluster. Retail metrics were standardized within each city. Both indicators retained positive and statistically significant coefficients for all three retail metrics (Table S13), indicating that the associations reported in Tables 3–5 are not an artifact of the nesting of plots within clusters.

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Table S14. Weights used to construct the compositional and configurational indicators (mean of statistically significant local MGWR coefficients). Den. = retail density; Agg. = retail agglomeration; Div. = retail diversity. – = no statistically significant local coefficient (weight = 0)

	Ankara			Helsinki			Vilnius		
	Den.	Agg.	Div.	Den.	Agg.	Div.	Den.	Agg.	Div.
Compositional									
Plot area	–	−0.209	−0.011	0.146	–	0.141	−0.091	0.161	−0.071
Ground area ratio	–	–	−0.031	0.352	0.033	0.090	0.117	–	0.052
Building frontage ratio	–	−0.021	0.060	0.140	–	−0.036	–	0.037	–
Plot frontage ratio	–	0.032	–	−0.004	−0.013	0.090	–	0.085	–
Configurational									
Plot frequency	0.268	0.168	0.001	–	−0.222	–	−0.081	−0.192	−0.332
Node connectivity	–	0.422	0.411	0.071	0.122	0.092	0.396	0.371	0.339
Local integration	0.193	−0.006	0.331	0.019	0.309	0.491	−0.194	−0.076	0.070
Global integration	0.539	0.142	0.155	0.267	0.301	0.061	0.120	0.077	0.137