

Consumption at what cost? Neighbourhood complexity and heat hazard

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Urban heat hazards are unevenly distributed across cities, yet their relationship with the geography of urban consumption remains poorly understood. In this study, we propose a relational reading of urban heat hazard, arguing that thermal exposure is shaped not only by residential surroundings but also by the characteristics of urban destinations. We measure the attractiveness of places using a Neighbourhood Complexity measure, which captures the structural diversity and specialisation of local urban economies, and relate it to pedestrian heat hazard in Milan. We characterise neighbourhood thermal environments to capture the intensity, mitigation and internal heterogeneity of local heat conditions. Results reveal a tension between urban vitality and heat hazard: highly complex neighbourhoods concentrate both destination mobility and elevated thermal hazard, while also offering greater opportunities for passive mitigation through urban form.

Keywords: Heat Hazard, Spatial Complexity, Urban Form, Consumption

JEL Classifications: O18, R12, R22, R31

Introduction

Contemporary cities, now home to a majority of the global population (United Nations, 2019), are confronting an ever-increasing exposure to the impacts of climate change (Bai et al., 2018). Among these impacts, urban heat hazard is of particular concern, as extreme temperatures are becoming more frequent and intense in many metropolitan regions (McCarthy et al., 2010). Urban environments tend to amplify heat hazard due to the absorption and retention of solar radiation by buildings, pavements and other impervious surfaces, combined with reduced ventilation and limited vegetation (Oke, 1973). The health consequences are severe, with studies indicating that heat exposure contributes substantially to excess mortality in cities (Vicedo-Cabrera et al., 2021). Yet, heat hazard within cities is not spatially uniform: urban areas are patchworks of microclimates, with variations in local heat conditions (Stewart & Oke, 2012).

Despite growing recognition that urban mobility patterns mediate thermal exposure (Huang et al., 2024), the structural forces that organise those destination patterns

remain under-theorised in the urban climate literature. Existing dynamic hazard studies have largely focused on *where* people move through thermal environments, while leaving largely unaddressed the question of *why* people converge on particular urban destinations in the first place. This raises a key question: how does the geography of consumption (Mansvelt, 2005) intersect with the spatial distribution of urban heat hazards?

We posit that consumption patterns offer a critical framework for this analysis. In commodified cities, where urban growth increasingly hinges on amenity-driven ‘consumer city’ dynamics (Glaeser et al., 2001), consumption practices play a central role in structuring everyday life, as individuals’ destinations are influenced by the concentration of job opportunities, retail, leisure and service amenities. Neighbourhoods rich in amenities embody both the ‘place of consumption’, through infrastructures designed to facilitate retail and leisure, and the ‘consumption of place’ as their symbolic, aesthetic and cultural qualities themselves become commodities (Lefebvre, 1967; Zukin, 2002). These spaces generate vitality, but they may also

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amplify environmental stress, concentrating flows of people and activities (Choi et al., 2025). We argue that heat hazard is not a fixed attribute of place but a relational condition shaped by the attractiveness of urban destinations and the thermal environments they embody. To investigate whether urban morphologies and forms that sustain economic vitality and cultural life are associated with local heat hazard, we apply the Neighbourhood Complexity Index (NCI), a constructed proxy derived from economic complexity methods (Hidalgo & Hausmann, 2009). By quantifying the structural diversity and specialisation of urban amenities, the NCI serves to capture the sophistication and attractiveness of neighbourhood consumption geographies, reflecting the distinctive functional character of each area. To ground this measure empirically, we validate the NCI against an origin-destination matrix of daily commuting flows derived from census data, testing whether neighbourhoods with higher amenity complexity attract greater volumes of intra-urban mobility. This validation step is important as it establishes that the NCI does not merely describe the morphological composition of neighbourhoods in the abstract, but captures their actual capacity to concentrate people's daily movements. To articulate the economic-environmental relationship under study, we link the Neighbourhood Complexity Index to simulated pedestrian thermal hazard. Specifically, we model Mean Radiant Temperature (MRT), defined as the uniform temperature of an imaginary enclosure that would produce the same net radiant heat exchange as the actual surrounding environment (Lindberg et al., 2018), and use it as a physically grounded indicator of human heat stress in outdoor space. MRT is simulated at 1 m spatial resolution across the whole city by integrating meteorological conditions with urban-form characteristics during a representative hot summer day; the analysis is then restricted to paved areas to better approximate hazard along everyday pedestrian environments.

At this detailed scale it becomes possible to distinguish the thermal micro-environments that pedestrians actually navigate, as within a single neighbourhood the contrast between a sun-drenched intersection and a narrow shaded street canyon can vary substantially. Field measurements, for example, document T_{mrt} reductions of 28.1°C under tree shade and 28.8°C under building shade compared to fully sunlit surfaces, while air temperature across the same environments drops by only 1–2°C (Du et al., 2020). Accounting for this intra-neighbourhood variability therefore calls for a multi-dimensional approach to thermal exposure. Rather than relying on a single aggregate indicator, we characterise each neighbourhood along three complementary dimensions: the intensity of peak radiant load, the degree of shadow protection afforded by its morphology, and the internal thermal contrast between its hottest and coolest micro-environments. Together, these dimensions allow us to describe not just how hot or cold a neigh-

bourhood is on average, but how its thermal structure is organised across space and how it evolves over the course of the day in relation to the complexity of neighbourhood.

This paper contributes to the literature on urban economics and climate hazard by examining how the geography of consumption intersects with patterns of urban heat at the neighbourhood scale. More broadly, the results point to the importance of integrating urban climate adaptation strategies with the spatial organisation of consumption and destination, considering not only the physical characteristics of the built environment but also the functional role that neighbourhoods play within the urban system. The paper proceeds as follows. We first outline the theoretical background, then present the empirical analysis of the city of Milan, and finally discuss the implications of our findings for the study of urban climate and consumption geographies.

Theoretical background

Heat hazard and urban thermal hazard of destinations

Heat intensification in urban environments has become one of the most pressing public health challenges of the twenty-first century (Santamouris, 2015). Cities increasingly concentrate the conditions that intensify thermal stress, producing persistent temperature differentials relative to surrounding rural areas and contributing directly to excess morbidity and mortality (Gould et al., 2025). Italy illustrates the severity of this challenge, as during the 2022 summer heatwave the country recorded the highest number of heat-related deaths in Europe (Ballester et al., 2023), highlighting both the acute vulnerability of urban populations to extreme heat and the urgent need to understand how thermal exposure is distributed across the urban fabric.

Traditional assessments of thermal hazard and vulnerability primarily rely on residential location as a proxy for individuals' heat hazard (Eugenio Pappalardo et al., 2023; Hsu et al., 2021). Residence-based approaches have been effective in revealing important socio-spatial patterns of heat hazard. However, focusing exclusively on residential environments may underestimate destination hazard. In particular, urban economics has long highlighted the strong pull of the central business district, where employment opportunities concentrate (Fujita et al., 1999) and daily commuting flows bring large shares of the population into potentially different thermal environments. Consequently, when mobility is taken into account, patterns of heat exposure may diverge significantly from those suggested by residence-based assessments alone (Li et al., 2025).

In this paper we focus on this emerging perspective, here referred to as urban thermal hazard of destinations, that tries to incorporate how destination patterns shape

individuals' interaction with urban thermal environments. Rather than treating hazard as a static condition tied solely to residential location, this approach emphasises that individuals move across the city. As a result, thermal hazard is understood as a outcome shaped not only by where individuals live, but also by where they work, study, and spend their leisure time. This perspective is particularly relevant in urban environments where pedestrian activity constitutes a substantial share of daily mobility, exposing individuals directly to outdoor thermal conditions and microclimatic variations at street level (Johansson et al., 2014; Kántor & Unger, 2011; Nikolopoulou & Lykoudis, 2006). Because pedestrians experience heat through direct interaction with urban surfaces, shading conditions, and airflow patterns, their thermal hazard is strongly influenced by local urban morphology and microclimate dynamics (Middel & Krayerhoff, 2019). In this regard, the geography of consumption offers a useful conceptual lens for understanding urban destination patterns. This perspective examines how the spatial distribution of services, economic activities, and commercial third places (Oldenburg, 1999) structures the organisation of urban amenities and the circulation of people within cities. Amenities facilitate urban consumption practices by concentrating pedestrian flows toward highly attractive areas such as business and leisure districts, historic centres, and retail corridors. Unlike air temperature, which captures only the convective component of the thermal environment, mean radiant temperature integrates shortwave solar radiation—both direct and diffuse—together with longwave radiation emitted by surrounding surfaces, making it the dominant driver of perceived outdoor heat stress during summer conditions (Höppe, 1999; Matzarakis et al., 2007). Its spatial distribution across a city is fundamentally shaped by urban morphology: street canyon geometry, sky-view factor (SVF), and surface albedo jointly determine how much solar radiation reaches the pedestrian level and how much longwave energy is trapped and re-emitted at street level (Ali-Toudert & Mayer, 2007; Lindberg et al., 2008). In this sense, MRT is not simply a meteorological variable but also a morphological one—it encodes, in a single scalar, the thermal consequences of how a city is built. This property makes it particularly suitable for our analysis, as it allows us to capture how variations in urban form and spatial structure translate into differences in pedestrian-level thermal hazard across the city. Narrow, shaded canyons with low SVF can reduce MRT relative to open, sun-exposed surfaces during peak solar hours (Johansson, 2006), a difference large enough to shift the thermal environment from physiological stress to near-comfort conditions (Nikolopoulou & Lykoudis, 2006).

Given the pronounced morphological heterogeneity of dense urban environments, characterising pedestrian thermal hazard through a single summary temperature would obscure much of the variation that is most consequen-

tial for human health and behaviour. To focus specifically on the conditions experienced by pedestrians, we restrict the analysis to paved surfaces. Moreover, because thermal conditions vary substantially over the course of the day, the analysis considers hourly conditions across a representative summer day, allowing us to capture the diurnal heat hazard. Within this framework, three complementary dimensions of the thermal environment are considered. First, the upper tail of the temperature distribution across paved surfaces within each spatial unit which provides a measure of extreme radiant burden. This metric reflects the conditions experienced by the most exposed pedestrians (Middel & Krayerhoff, 2019). Second, particular attention must be given to the role of passive morphological mitigation through shading. Urban canyon geometry and vegetation canopy intercept incoming short wave radiation before it reaches street level, substantially altering the radiant environment experienced by pedestrians. Empirical studies have consistently shown that well-shaded urban canyons can maintain T_{mrt} values tens of degrees lower than those observed on adjacent open surfaces, effectively functioning as low-cost and infrastructure-free thermal refuges accessible to all pedestrians (Bernatzky, 1982; Tan et al., 2013). Third, beyond extreme radiant exposure and the mitigating effects of shading, the internal thermal contrast within neighbourhoods—captured as the modal gap between average sunlit and shaded surface temperatures within the same spatial unit—provides a measure of the degree to which high-burden and low-burden environments are simultaneously available. This dimension is particularly relevant for adaptive capacity, as the presence of proximate thermal alternatives enables spontaneous behavioural thermoregulation, allowing pedestrians to adjust their trajectories and activities in response to local heat conditions (Harlan et al., 2006).

Spatial organization of urban amenities and neighbourhood complexity

The spatial positioning of economic activity has long been a central theme within regional economics and economic geography. Early foundational theories, such as Weber (1909)'s model, analysed firm location through a cost-minimization framework based on resource inputs and product outputs. Subsequently, Marshall (1919) addressed the concentration of activities and the resulting external benefits, particularly in the context of urban development. This concept was systematically advanced by Christaller (1933) and Lösch (1954) through the development of central place theory.

Christaller introduced the idea of the thresholds, the minimum population necessary to sustain a particular activity, thereby explaining why certain goods and services are only viable in larger settlements. Lösch later expanded this approach by emphasizing profit-maximizing

behaviour of firms, providing a more flexible account of how multi-product economies and their spatial interrelationships produce a system of locations. Hence, the location of economic activity is revealed to be non-random, but rather arranged according to a distinct hierarchy. This structure is considered as a logical outcome of a series of profit-maximizing decisions by firms, a process that generates clusters and identifies 'central places' as locations capable of offering both high- and low-order goods.

In cities, the formation of urban amenity clusters can be influenced by both broader locational factors and inter-amenity relationships. On the one hand, a cluster may succeed because it benefits from deliberate, top-down planning decisions, such as proximity to transit access (Cervero & Kockelman, 1997). On the other hand, the way amenities interact with each other within the cluster is equally important. Similar amenities group together to form competitive clusters, where co-location reduces risks for businesses and makes it easier for customers to compare options (Hotelling, 1929). Alternatively, clusters may be built around complementary activities, offering a variety of options in one place and encouraging people to combine different kinds of consumption in a single trip (Thill & Thomas, 1987).

More recently, the principle of relatedness, which emphasizes that new economic activities tend to emerge and develop in locations where related capabilities already exist (Hidalgo et al., 2018; Neffke et al., 2011), has been used to explain the spatial patterns of urban amenities at the neighbourhood level (Hidalgo et al., 2020). This proposition posits that urban amenities are more likely to emerge in locations that already possess the capabilities associated with related activities, offering a robust statistical account of the spontaneous formation of distinct amenity clusters within cities. Building on this principle, the concept of economic complexity (Hidalgo & Hausmann, 2009) provides a method to quantify the sophisticated productive structure that emerges from these dynamics.

Initially developed for national economies, economic complexity methods have since adapted across multiple geographical scales (Balland & Rigby, 2017). Recently this framework has been extended to the intra-urban level to quantify the sophistication of local amenity supply in the urban areas (Choi et al., 2025; Juhász et al., 2023; Magalhães et al., 2023; Robertson et al., 2023). The original framework is founded on the recursive relationship between two interconnected indices: the Product Complexity Index (PCI) and the Economic Complexity Index (ECI) to measure the productive capabilities of national economies. The PCI ranks products based on the capabilities required for their production, while the ECI assesses a nation's productive capabilities by evaluating the diversity and sophistication of its export portfolio. A country's economic complexity (ECI) is determined by the collective complexity (PCI) of the products it exports. In turn, a product's

complexity is inversely related to the number of countries that can produce it competitively, as such more complex products are produced by fewer locations. Therefore, a high ECI score indicates that an economy possesses a rare and extensive network of capabilities necessary to produce high-PCI goods. Moving at an urban scale, this framework posits that urban neighbourhoods, much like national economies, can be characterised by the diversity and exclusivity of their amenity portfolio, as many of these amenities function as third places (Oldenburg, 1999), structuring everyday patterns of visitation and social interaction. A neighbourhood has high economic complexity when it combines high diversity (many amenity types) with high exclusivity (amenity types that are less ubiquitous across neighbourhoods). This indicates a highly developed and sophisticated local market. Thus complexity is defined by the concentration of higher-order functions, reflecting the ability to support non-ubiquitous amenities that most other urban areas cannot sustain (Kim et al., 2024; Van Meeteren & Poorthuis, 2018).

This concentration of diverse and specialised amenities relates to the broader concept of urban vitality. Maas (1984) defines vitality as the synergy generated by distinctive commercial and entertainment opportunities sustained by a dense and socially heterogeneous pedestrian population, where the size and diversity of social groups create demand, attract visitors and contribute to a city's distinctive *genius loci*. While the presence of commercial activities signals a degree of urban activity, vitality refers to a wider urban condition encompassing the intensity, diversity and social quality of urban life, emerging from the interaction between built form, land-use diversity and the flows of people that animate urban space (Montgomery, 1998).

Rather than being only a social characteristic, vitality also has a structural dimension. At the morphological level, neighbourhoods with a richer mix of uses tend to exhibit higher built density (Cervero & Kockelman, 1997). These urban configurations may, in turn, facilitate the co-existence and accessibility of amenities while also shaping pedestrian radiant heat exposure. At the same time, amenity concentration both attracts and depends on human presence: the density of economic and social opportunities can influence destination choice, pedestrian concentration, length of stay and the timing of urban occupation, thereby contributing to the sustained flows that characterize vital urban areas (Robertson et al., 2023). Building on Jane Jacobs's conception of urban complexity as the diversity and spatial mixture of functions, research further emphasises how functional diversity sustains vibrant urban environments by supporting continuous social interaction and heterogeneous patterns of use across the urban fabric (De Nadai et al., 2016; Dogan & Lee, 2024). In this regard, neighbourhood complexity is best treated not as an exogenous driver, but as an emergent feature of urban configura-

tion that captures centrality, density and amenity composition. The empirical relationship between complexity and thermal hazard therefore reflects broader socio-spatial organisation rather than a direct causal effect.

Data Research context

To understand how the urban geography of consumption relates to heat hazard, we develop our case study around the city of Milan. Located in northern Italy, Milan is the country's main financial and cultural hub, generating approximately 10% of national GDP while hosting only 2.3% of the population. The city is home to the Italian Stock Exchange and a large labour market that attracts nearly two million daily commuters. Beyond its economic centrality, Milan accounts for 12% of Italy's total cultural expenditure¹, reflecting its national role in retail, entertainment, and cultural consumption. These features make Milan a compelling case study because of its socially heterogeneous population, including workers, consumers, and students. Its dense commercial corridors, business districts and layered historical urban fabric channel intense pedestrian flows, while also shaping uneven patterns of heat hazard exposure across urban destinations, making Milan especially suitable for examining the link between neighbourhood complexity and urban destination hazard.

Climate and urban data

Climate forcing data and morphology parameters are integrated to drive a high-resolution radiative simulation of outdoor thermal conditions. A 1m Digital Surface Model (DSM) and Digital Terrain Model (DTM) are acquired from the Banca Dati del Piano Straordinario di Telerilevamento (PST), while tree-location data and land-use/land-cover (LULC) layers are retrieved from the Geoportal of the City of Milan. The tree dataset is paired with the DTM to derive a Tree Canopy Digital Model (CDM), and LULC classes are used to assign surface radiative properties, including SOLWEIG default values for dark asphalt (albedo = 0.18, emissivity = 0.95) and walls (albedo = 0.20, emissivity = 0.90). We implement SOLWEIG-GPU (Kamath et al., 2026; Lindberg et al., 2018) and forced the model with ERA5 meteorological variables required for MRT computation as well as incoming shortwave radiation, incoming longwave radiation. Simulations are performed for 4 July 2025—selected as one of the hottest days of the summer 2025 season—from 08:00 to 20:00 local time (UTC + 2), producing hourly rasters of T_{mrt} at 1 m resolution alongside sky-view factor (SVF) grids derived from the urban digital surface model. The analysis prioritises T_{mrt} since it is the physically direct radiative state variable that most directly encodes the effects of urban geometry, surface shading and material albedo at street scale (Lindberg & Grimmond, 2011). While UTCI includes T_{mrt} —and tends to

be strongly correlated with T_{mrt} under summer daytime conditions (Bröde et al., 2012)—its additional physiological and behavioural parametrisations introduce assumptions about metabolic rate, clothing, and activity level that are not relevant to a morphology-focused spatial analysis. Using T_{mrt} directly therefore preserves the interpretive link between the observed thermal signal and its structural urban determinants, without embedding more confounding assumptions (Thorsson et al., 2014). To focus specifically on pedestrian-scale hazard, we clipped the T_{mrt} rasters using the paved land-use class, thereby isolating paved thermal fields and thus preserving the within-street heat gradients.

Urban data are built from two complementary sources. First, urban amenity information is retrieved from OpenStreetMap (OSM), an open, collaboratively maintained geospatial database. Amenities are classified by functional type and spatially matched to neighbourhood units. While OSM data can suffer from selective reporting and uneven completeness, this limitation is likely less severe in Milan, where a high population and extensive mapping activity generally improve coverage relative to smaller or less connected contexts. Second, destination data are retrieved from the Geoportal of the City of Milan and originate from the ISTAT 15th General Census of Population and Housing. This origin-destination dataset contains roughly half a million observations of daily commuting flows within Milan and is used as an external validation for our measure of complexity, testing whether more complex neighbourhoods are associated with stronger attraction and movement patterns.

Methods Neighbourhood complexity Index

The functional character of an urban neighbourhood is intrinsically linked to the practices it facilitates. Urban amenities provide the physical stage for the enactment of diverse opportunities and patterns of consumption. As discussed earlier, urban theory suggests that they cluster to form specialised districts based on principles of agglomeration, market demand and relatedness. Specialisation is determined by neighbourhood amenity categories and its relative concentration compared to the city-wide average, reflecting the dominant consumption patterns that define the neighbourhood's character. The Revealed Comparative Advantage (RCA) is the metric that evaluates a neighbourhood's specialisation in each specific amenity category relative to its prevalence across the entire city. It is calculated by comparing two key ratios, the local share of the amenity within the neighbourhood and its city-wide share. For a given city, let A and N be the total number of amenity categories and the total number of neighbourhoods, respectively. The index RCA is defined in the following way:

$$RCA_{n,a} = \frac{x_{n,a}/X_n}{X_a/X}$$

where $x_{n,a}$ accounts for the specific number of amenities in category a at the neighbourhood level n . The terms $X_n = \sum_{a=1}^A x_{n,a}$ is the total amount of amenities in the neighbourhood n , $X_a = \sum_{n=1}^N x_{n,a}$ is the total quantity of amenities in category a across the entire city and X is the sum of all amenities of all types across all neighbourhoods in the entire city.

We then construct a bipartite network between neighbourhoods and amenities from the binary presence matrix, where:

$$M_{n,a} = \begin{cases} 1, & \text{if } RCA_{n,a} \geq 1 \\ 0, & \text{otherwise} \end{cases}$$

From the geographical matrix $\mathbf{M}$, two initial metrics are computed. The diversity of a neighbourhood n , denoted $k_{n,0}$ defined as the number of amenities in which the neighbourhood specialises, computed as the sum of the elements in corresponding row:

$$k_{n,0} = \sum_{a=1}^A M_{n,a}$$

Similarly, the ubiquity of amenity a , denoted $k_{a,0}$, is the number of neighbourhoods specialising in that amenity, given by the sum of elements in the corresponding column:

$$k_{a,0} = \sum_{n=1}^N M_{n,a}$$

These initial values represent simple counts of diversity and ubiquity. Then, the algorithm iteratively updates the complexity scores for neighbourhoods and amenities. At iteration B , the complexity $k_{a,B}$ of an amenity a is calculated as the average complexity of the neighbourhoods specialising in it, weighted by their diversity scores from the previous iteration:

$$k_{a,B} = \frac{1}{k_{a,0}} \sum_{n=1}^N M_{n,a} \cdot k_{n,B-1}$$

Conversely, the complexity $k_{n,B}$ of a neighbourhood n is determined as the average complexity of the amenities it hosts, weighted by their ubiquity from the previous iteration:

$$k_{n,B} = \frac{1}{k_{n,0}} \sum_{a=1}^A M_{n,a} \cdot k_{a,B-1}$$

The iterative process continues until the values converge, yielding stable complexity scores. Mathematically, this iterative procedure corresponds to computing the components of the eigenvector associated with the second largest eigenvalue of a matrix derived from $\mathbf{M}$ (Caldarelli et al., 2012). This eigenvector captures the latent structure of the bipartite network linking neighbourhoods and amenities, providing a principled measure of complexity

that reflects both diversity and ubiquity. The final Neighbourhood Complexity Index (NCI) corresponds to the converged vector k_n . Similarly, the Amenity Complexity Index (ACI) is given by the converged vector k_a , indicating the distinctiveness of each amenity category. Together, these two indexes position each neighbourhood within the city's consumption geography. A neighbourhood with a high NCI score hosts a wide array of specialised, non-ubiquitous amenities, reflecting its specialisation in higher-order urban functions. The ACI measures the (dis)similarity between amenity categories relying on the principal components that best explains differences in their co-location patterns across neighbourhoods, using a binarised matrix of presence/absence. Importantly, the principal component is agnostic about what it represents in real-world terms. It is a purely data-driven dimension extracted from the structural relationships in the amenity-neighbourhood network. The ACI ranks amenity categories based on their ubiquity and higher ACI values identify less ubiquitous amenities that tend to co-occur with other rare amenities in high-complexity setting.

Thermal and destination metrics

Thermal metrics are selected to capture three complementary dimensions of heat hazard that are directly relevant to urban vitality and local economic activity: intensity, protection, and intra-neighbourhood thermal inequality. We use the street level 95th percentile of T_{mrt} as our primary measure of thermal intensity, as it is more robust than simple maxima, less sensitive to isolated outliers, and better captures the upper-tail heat conditions experienced during periods of thermal stress. Across the study area, the overall mean of hourly means is 56.90°C ($sd = 15.44^\circ\text{C}$). Secondly, to represent protection from direct radiative load, we include shadow share, defined as the proportion of shaded street pixels per neighbourhood and hour. This metric captures the morphological buffering role of buildings and trees and complements the intensity metric by identifying where hazard is mitigated (Lindberg & Grimmond, 2011). Across hours, mean shadow share is 30.88%, with a minimum at 2:00 pm (8.9%), while the largest values occur at day margins, around 61% at 8:00 am and 64.2% at 20:00, consistent with longer cast shadows under low sun angles. Finally, to quantify within-neighbourhood thermal structure, we adopt a two-mode approach: for each hour, we fit a two-component Gaussian Mixture Model (GMM) to pixel temperatures. GMM allows a probabilistic decomposition of the urban thermal field into a cool mode (proxy for shaded or thermally protected micro-environments) and a hot mode (proxy for exposed paved and built surfaces); from these two densities, we compute a Bayesian decision boundary, i.e., the temperature at which a pixel has equal posterior probability of belonging to either mode, and use that threshold to define a local mode-gap as the difference

between mean temperatures above and below the boundary, providing a neighbourhood-scale measure of hot-cold thermal contrast. Mode-gap dynamics show a pronounced diurnal pattern. The temperature difference between the two modes increases sharply during the morning, rising from 5.4°C at 8:00 am to 29.6°C at 11:00 am. This surge likely reflects the rapid warming of sun-exposed surfaces, while many streets and building façades remain partially shaded, temporarily maximizing the thermal contrast between hot and cool areas before solar illumination becomes more spatially uniform around midday. After this peak, the gap progressively narrows, decreasing to 23.3°C at 1:00 pm and falls to 2.4°C by 8:00 pm. Together, these indicators provide a framework to captures extreme burden, passive mitigation, and the thermal fragmentation within the same urban fabric (Figure 1).

To validate the NCI as a meaningful proxy for the functional attractiveness of urban neighbourhoods, we aggregate inbound flows from the origin–destination matrix to the neighbourhoods and compute the Pearson correlation between arrival intensity and NCI scores. To further characterise the nature of this relationship, neighbourhoods are partitioned into two classes—high and low complexity—using the sample median NCI as the threshold. This binary split yields a 2×2 transition matrix to examine not only whether high-complexity neighbourhoods draw flows from a broader and more spatially dispersed set of origins, but also whether mobility preferentially occurs between districts of similar complexity—pointing to a structured, complexity-sorting logic in urban movement.

Spatial strategy

Our spatial strategy examines how neighbourhood complexity is associated with heat hazard over the course of the day by estimating, at each hour, three separate SAR-lag models for the standardized measures of high-temperature intensity, shadow share, and local temperature gap, with NCI included as the normalised dependent variable to ensure comparability across hourly specifications. Neighbourhoods are operationalised as 520 hexagonal grid units with a side length of 500 m, a resolution that balances interpretability at the sub-urban scale with sufficient observation counts for stable spatial modelling. By construction, NCI is time-invariant—it encodes the structural diversity and specialisation of the amenity supply within each hexagon and does not vary across hours. The hourly variation in the estimated associations therefore reflects changes in the thermal environment alone, not in neighbourhood composition, allowing us to observe how the same spatial structure of urban complexity relates to systematically different thermal conditions as solar geometry and shadow patterns shift throughout the day. To address spatial dependence, we adopt a Spatial Autoregressive lag framework rather than assuming independent

hexagons, allowing outcomes in one spatial unit to be influenced by outcomes in neighbouring cells through a spatial weights structure. Neighbourhood relations are defined with a row-standardised k -nearest-neighbour matrix, with k adjusted to sample size to preserve connectivity at each hour; the choice of a spatial model is guided by Lagrange Multiplier diagnostics run against an OLS baseline. All models are estimated by Maximum Likelihood, and adequacy is verified with permutation-based residual Moran diagnostics ($n = 499$). To assess whether the association between NCI and thermal hazard is spatially stationary or varies across the city, we additionally estimate a Geographically Weighted Regression (GWR) for each hour, examining whether local coefficients exhibit systematic spatial patterning that the global SAR-lag model would otherwise mask. Finally, to evaluate the robustness of the estimates to the choice of spatial unit, the full modelling pipeline is replicated under alternative hexagon sizes of 400 m (784 units) and 600 m (373 units), allowing us to assess whether the direction, magnitude, and significance of the reported associations are sensitive to the scale of aggregation.

Results

Urban complexity

Our results for the Amenity Complexity Index (ACI) and Neighbourhood Complexity Index (NCI) reveal marked intra-urban variation in Milan's geography of consumption. At the amenity level, the highest ACI values are associated with luxury-oriented activities and cultural or artistic venues, which tend to co-locate with other distinctive functions in the city's most complex neighbourhoods (Figure A1). By contrast, lower ACI values characterise more ubiquitous everyday amenities, such as cafés, supermarkets, restaurants, and pharmacies, whose distribution is more diffuse across the urban fabric. This pattern is consistent with evidence from Paris and Seoul, suggesting that although the specific mix of amenities differs across cities, the underlying logic of urban complexity remains stable: specialised and higher-order functions concentrate in a limited number of selective districts, while routine services are distributed more evenly across space (Kim et al., 2024; Robertson et al., 2023).

When scaled to the neighbourhood level, the Neighbourhood Complexity Index reveals a sharply differentiated urban geography (Figure 2A), with central areas such as Brera and the Duomo emerging as some of the most complex parts of Milan. These neighbourhoods are characterised by dense combinations of specialised retail and cultural amenities, alongside the symbolic capital and aesthetic qualities that make place itself an object of consumption (Lefebvre, 1967). NCI therefore captures not only the diversity of amenities present in a neighbourhood, but also the extent to which they form a distinctive and selective consumption environment.

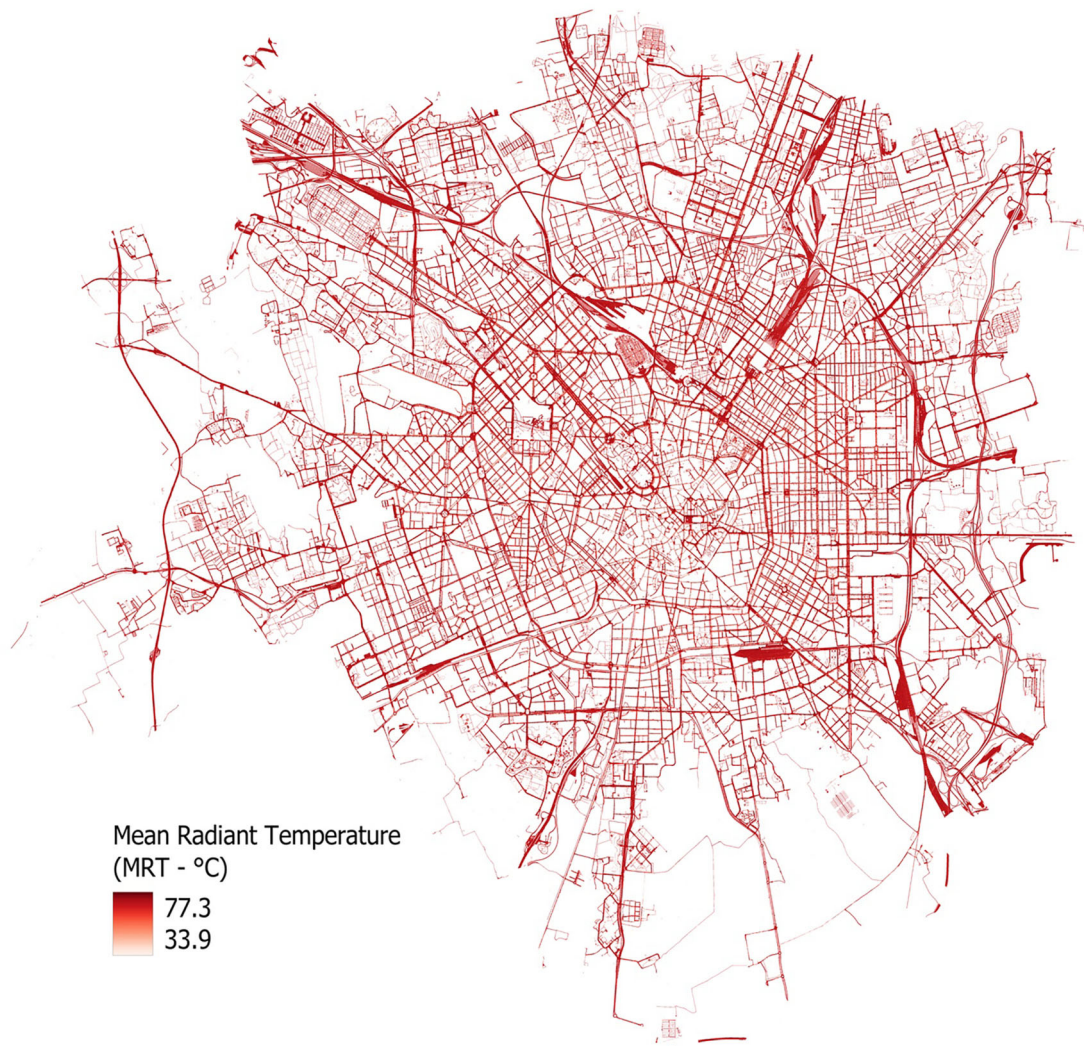


Figure 1 Paved surface mean radiant temperature (MRT) at 1:00 pm, at 1×1 meter resolution.

Importantly, NCI is positively correlated with arrivals derived from intra-urban destination flows ($r = 0.72$), as shown in Figure 2B. This is not a marginal relationship as it indicates that neighbourhoods with more complex amenity structures attract more people. In other words, complexity is not simply an abstract descriptor of urban form, but a reliable predictor of where people choose to go within the city. If more complex neighbourhoods attract larger volumes of visitors, workers, and consumers, then their thermal conditions are likely to affect a population that extends well beyond local residents. To investigate this destination gradient, we descriptively partitioned neighbourhoods at the median NCI, creating a binary classification of Low and High Complexity districts

(Figure 3). Four distinct regimes emerge: (A) Low-to-High transit (25.09% of all trips), one-quarter of all commuting originates in low-complexity peripheral areas and terminates in high-complexity cores; (B) High-to-High circulation (54.04% of all trips), more than half of all commuting movements occur entirely within high-complexity neighbourhoods; (C) High-to-Low circulation (10.37% of all trips), representative of movements flowing from complex to low-complexity districts, corroborating the structural centrality of complex places as the primary poles of daily mobility, consumption, and service access across the urban system; (D) Low-to-Low (10.50% of all trips), suggesting that peripheral neighbourhoods generate relatively little internal demand for destination. These flow regimes reflect the

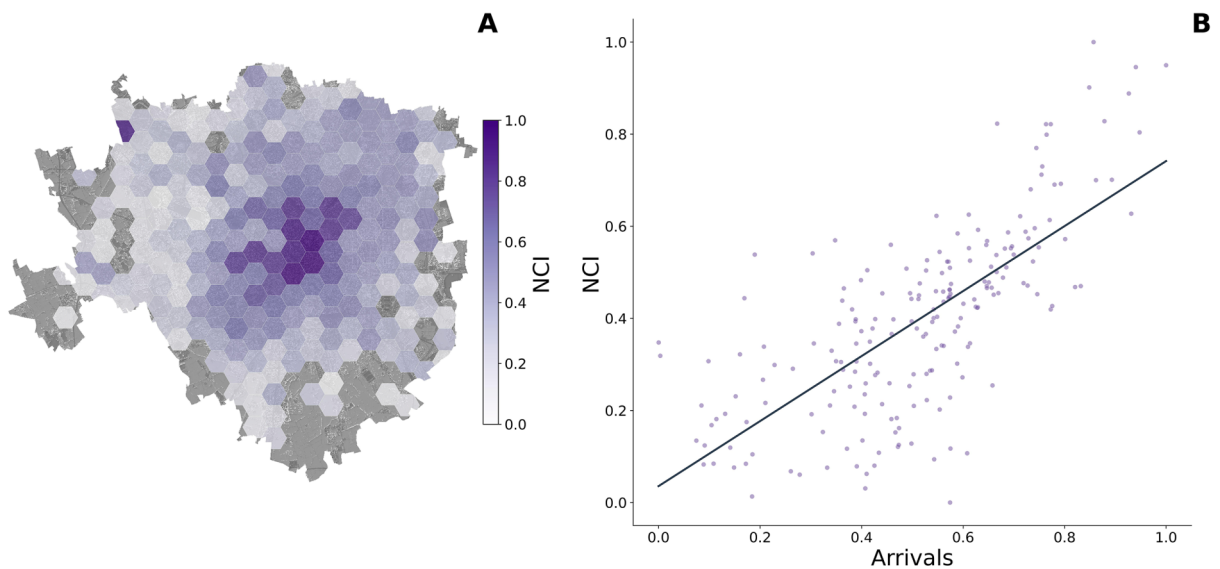


Figure 2 Panel A: spatial distribution of neighbourhood complexity index. Panel B: scatter plot of NCI and arrivals from the origin destination matrix.

higher-order functional status of high-complexity neighbourhoods as higher-order central places, concentrating a sufficient range and threshold of goods, opportunities and services to sustain demand not only from their resident population but from a wider urban population

Thermal environment in complex neighbourhoods

Across the hourly SAR models, the three indicators display distinct temporal patterns in their association with neighbourhood complexity. For the 95th percentile of T_{mrt} , which we interpret as an upper-tail radiant heat burden, the estimated coefficient is significantly negative in the early morning (08:00 am–09:00 am), becomes positive and significant around midday (12:00 pm–2:00 pm), weakens through the afternoon, and turns positive again in the evening (7:00 pm–8:00 pm) (Tab. A1). This changing sign indicates that the relationship between neighbourhood complexity and extreme thermal hazard is not stable over the day, but varies with the hourly configuration of solar exposure and urban form (Figure 4A). To test for local spatial heterogeneity in this association, we additionally estimated a Geographically Weighted Regression (GWR) for each hour; the local coefficients are broadly consistent with those recovered by the SAR-lag specification, and a comparison of information criteria indicates that the SAR-lag model achieves a marginally better fit in the majority of hourly models, supporting the use of the global spatial lag framework as the primary estimator.

The appropriateness of the SAR specification over a standard OLS baseline is further corroborated by Robust Lagrange Multiplier diagnostics applied to the OLS residuals, which reject the hypothesis of no spatial lag dependence, with very few exceptions, confirming that the spatial lag model is appropriate for the data-generating process at hand.

Shadow shows the clearest and most consistent pattern (Figure 4B). The coefficient remains positive throughout the day and is statistically significant at all hours, with the largest magnitudes around midday and early afternoon. Empirically, this means that neighbourhoods with higher complexity tend also to display higher shares of shaded paved surfaces, and that this association is especially visible during the hours of strongest radiative stress (Table A2).

The local mode gap should be read differently (Figure 4C). This indicator does not measure heat intensity directly, but the difference between the hot mean and the cold mean within each neighbourhood, that is, the internal thermal separation between warmer and cooler conditions inside the same environment. In that sense, it captures the degree of within-neighbourhood thermal contrast. Its coefficient is mostly positive, but less stable than that of shadow: it becomes significant in the late morning and around noon, weakens in mid-afternoon, and rises again in the evening. Thus, what we observe is that more complex neighbourhoods tend to combine greater shade provision, higher temperatures, and sharper hot–cold microclimatic contrasts, indicating that condi-

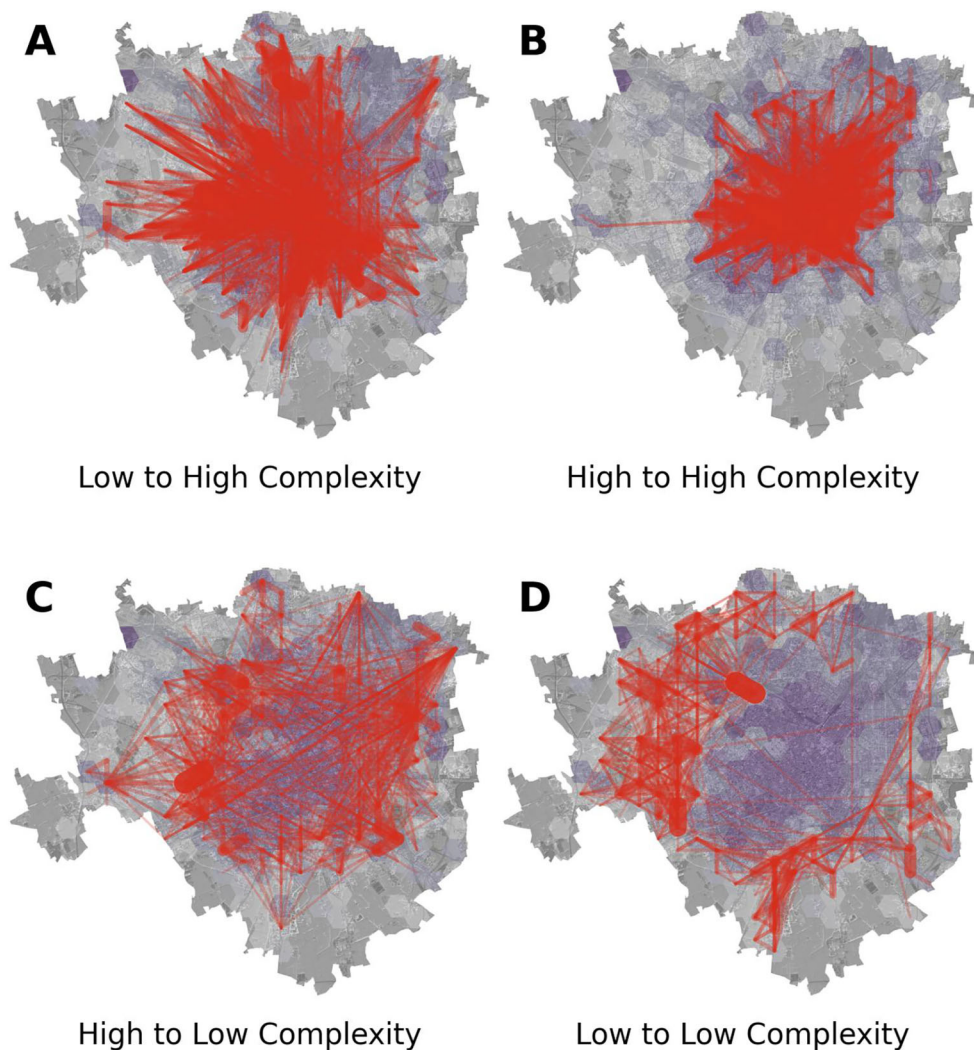


Figure 3 Origin-destination flows by neighbourhood complexity class. Panel A: flows from low- to high-complexity neighbourhoods; Panel B: flows within high-complexity neighbourhoods (high-to-high); Panel C: flows from high- to low-complexity neighbourhoods; Panel D: flows within low-complexity neighbourhoods (low-to-low). For visual clarity, only trips exceeding the 90th percentile of flow volume are displayed.

tions of thermal exposure and thermal protection coexist within the same urban environment (Table A3).

To assess the robustness of model estimates to the choice of aggregation unit, SAR models are re-estimated at two alternative hexagonal grid resolutions, 400 m and 600 m side length, for all three thermal hazard indicators. Across all specifications and both scales, regression coefficients remains stable in sign, magnitude, and significance, indicating that the main findings are not an artefact of the chosen spatial scale (Figure A2). Moving from 400 m to 600 m, model fit generally improves and residual spatial autocorrelation weakens. For $P95(T_{mt})$ and shadow fraction, Moran's I on SAR residuals indicates well-specified mod-

els at both scales. The mode gap indicator shows residual spatial autocorrelation in a subset of hours at 400 m, which disappears at 600 m, suggesting that the finer partition captures local heterogeneity not fully absorbed by the SAR lag specification, while coarser aggregation smooths part of this residual spatial structure. This result is also consistent with the way the Neighbourhood Complexity Index is constructed. NCI is derived from the diversity and ubiquity of amenity categories within each neighbourhood and therefore requires a sufficient number of distinct activity types to produce a stable and interpretable measure. By contrast, coarser grids aggregate a broader set of activities, yielding a more stable NCI and generally better model

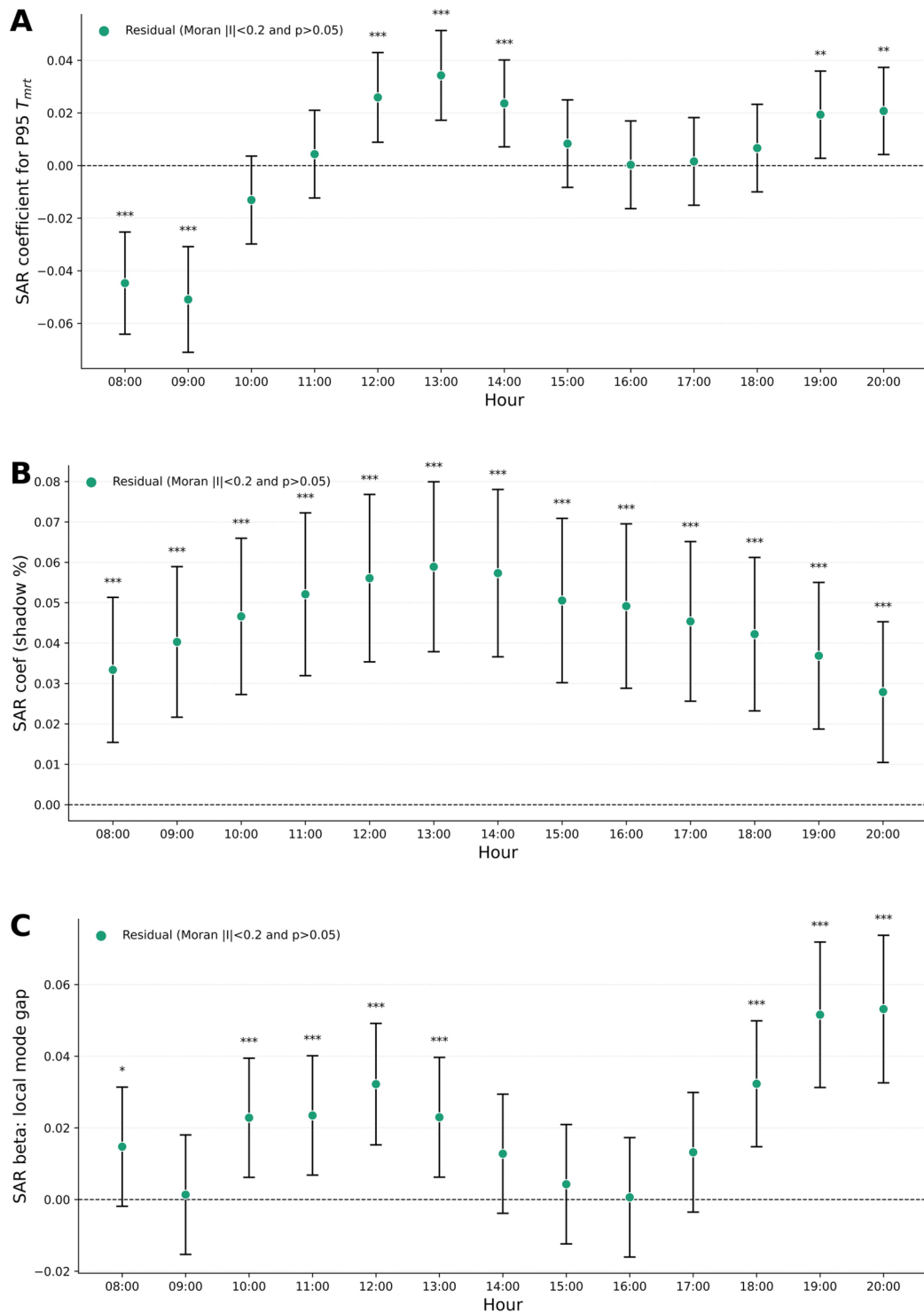


Figure 4 Temporal variation in the spatial association between NCI and the 95th percentile of mean radiant temperature, $P_{95}(T_{mrt})$ (A), shadow share (B), and thermal modal gap (C), estimated using hourly SAR-lag models. Each point represents β with its 95% confidence interval; green markers indicate adequate residual diagnostics (Moran's $I < 0.2$, $P > 0.05$). Note: * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$.

fit. For this reason, although the 600 m specification shows slightly better model fit, the 500 m baseline is retained as a conservative compromise between spatial granularity and interpretability.

Discussion

The objective of this study is to broaden the concept of heat hazard beyond a strictly residential perspective by also accounting for the everyday consumption of urban space. Hazard is treated as a destination-based phenomenon, shaped not only by where people live, but also by where their daily destinations are located across the city. To operationalise this perspective, we construct a complexity index based on the composition of local amenities within neighbourhoods, assuming that their diversity and specialisation capture latent forms of urban attractiveness that shape individual mobility behaviours and, consequently, the spatial organisation of daily destinations. We then validate the index using an origin-destination matrix derived from census data. The results show that destination flows are primarily concentrated between highly complex neighbourhoods and from low-complexity neighbourhoods toward more complex ones. By contrast, flows from highly complex neighbourhoods to less complex areas, as well as flows between low-complexity neighbourhoods, remain comparatively limited. Next, we investigate how neighbourhood attractiveness relates to the environmental implications of urban form, focusing on the thermal hazard pedestrians encounter across urban destinations, by simulating mean radiant temperature at 1-metre resolution across the entire city and integrating both climatic forcings and urban morphological characteristics. The empirical analysis reveals that complexity is associated with higher levels of extreme thermal burden during midday and evening hours, while greater levels of shade are consistently found in more economically complex urban fabrics across all hours of the day. At the same time, thermal contrasts within neighbourhoods tend to be more pronounced in such environments, particularly during central hours and from late afternoon onwards. We interpret this pattern as evidence that hazard in complex neighbourhoods is not simply higher or lower in average terms, but structurally more uneven across space and time. We term this coupling the *Urban Heat-Vitality Tension*: the tendency for high-complexity neighbourhoods to simultaneously concentrate the conditions of urban vitality and a more stratified, heterogeneous thermal hazard regime.

Theoretically, this tension emerges from the hierarchical socio-spatial organisation of cities (Scott & Storper, 2015; Swyngedouw & Heynen, 2003). It can be understood as the spatial manifestation of co-existing agglomeration externalities: the same urban configurations that sustain vitality also generate uneven thermal conditions. Complex neighbourhoods therefore emerge as spaces where ag-

glomeration economies and heat-related diseconomies are simultaneously concentrated. Urban form properties characteristic of complex neighbourhoods intensify heat accumulation and generate pronounced localised extremes in heat hazard, while simultaneously co-locating passive and semi-passive cooling resources within short walking distances of high-exposure spaces. Passive resources include building and tree shade, while semi-passive resources may include air-conditioned commercial premises and work- and study-related indoor environments, reflecting the concentration of commercial and work practices that characterises high-complexity neighbourhoods. Consequently, thermal exposure and adaptive capacity are not independent features of these neighbourhoods but are shaped by the same agglomeration processes that underpin urban vitality, consistent with vulnerability perspectives that view exposure and coping capacity as emerging from shared socio-spatial configurations (Adger, 2006). Paradoxically, complex neighbourhoods may sustain destination-oriented mobility under high thermal stress precisely because the same functional fabric that generates the hazard also embeds a richer repertoire of cooling resources within it. As a result, thermal environments in high-complexity neighbourhoods differ qualitatively from those in lower-order neighbourhoods, which attract fewer arrivals and where access to nearby cooling options may be more limited. A final aspect worth considering is that these dynamics exhibit seasonal contingency. The present analysis focuses on a representative summer period, when radiant load and solar exposure are dominant drivers of outdoor thermal stress. In cooler seasons, however, the same morphologies that provide summer protection may reduce beneficial solar access. Seasonal changes in vegetation phenology, sun angle and activity rhythms may further redistribute microclimatic benefits and burdens. The Urban Heat-Vitality Tension should therefore be understood as a climate-contingent urban condition emerging from the interaction of urban form, atmospheric forcing and destination patterns.

Conclusion

This study conceptualises the co-occurrence of destination mobility and heterogeneous thermal hazard as the Urban Heat-Vitality Tension, a relational condition in which the neighbourhoods that function as the primary destination of daily urban life are also those that concentrate the most heterogeneous thermal environments. Rather than a simple burden, this tension reflects the structural coupling between functional complexity and microclimatic diversity that characterises dense, mixed-use urban cores. This tension can be interpreted as the spatial expression of agglomeration externalities, whereby the benefits of centrality are co-produced with microclimatic burdens arising from urban form. In this reading, the elevated and heterogeneous

thermal hazard of complex neighbourhoods is entailed by the same morphological and functional conditions that make them attractive destinations.

Several directions for future research emerge from this work. First, daily exposure could be reconstructed at the person level, enabling the assessment of vulnerability arising from socio-economic characteristics. Second, comparative application across cities with contrasting agglomeration intensities, planning traditions, and climatic contexts would allow systematic identification of the conditions under which the tension emerges, intensifies, or is mediated, moving beyond the compact European urban form examined here. Third, future work could assess how this tension evolves under climate change, evaluating whether the adaptive resources embedded in complex neighbourhoods expand or erode as extreme heat events intensify. From a policy perspective, recognising neighbourhood complexity as a meaningful dimension of urban structure would enable heat adaptation strategies tailored to the functional character of specific places. Interventions aligned with the mix of destinations and morphological features that define each neighbourhood are likely to be more effective than generic approaches, as thermal environments in complex urban areas form heterogeneous landscapes where exposure and adaptive capacity coexist.

Endnotes

- 1 Source: Osservatorio sui consumi culturali della Città di Milano.

Supplementary material

Supplementary material is available at *Cambridge Journal of Regions, Economy and Society* online.

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