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The compact city dilemma

Testing the compact city development policies through spatial analysis and multi-hazard modelling

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Acknowledgment

This thesis is not a monument to what has already been achieved in my professional experience, but a first, imperfect sketch of the work I hope to pursue in the years ahead. It reflects less who I have been than the kind of responsibility and future work I wish to bring to the cities and questions with which I will continue to engage.

Most importantly, this thesis is the result of many minds, quiet acts of generosity and support that cannot be listed but are present in every page.

I am indebted to all those who challenged my assumptions, shared their thoughts, experience and their time, and held space for this work to unfold.

Thank you.

Abstract

This study interrogates the compact city as an operational policy problem rather than a purely morphological ideal. Furthermore, it reconceptualizes the compact city paradigm by integrating spatial morphology, functional diversity, and multi-hazard risk assessment into a unified empirical framework. The core contribution is a policy-testing architecture that derives a context specific “safe-density window” and encodes it as decision gates for statutory planning. While urban compactness is widely advocated as a sustainable urban form, its practical definition and operational thresholds remain ambiguous, especially in hazard-prone contexts. This research develops and applies a composite methodological model combining morphological metrics such as Building Surface Fraction (BSF), Building Coverage Ratio (BCR), Floor Area Ratio (FAR), and verticality, with functional entropy indices to assess urban compactness. The approach is empirically tested across 13 global cities to establish comparative baselines, and then applied in-depth to the case of Tirana, Albania, using high-resolution building, land-use, and hazard exposure data.

Results reveal that while Tirana exhibits clusters of high density, its urban form is spatially imbalanced, with extreme saturation pockets, against underutilized land and peripheral low-density areas. The analysis identifies a “safe density window” around a BSF of approximately 55% (within 100mx100m calculation parcels), beyond which urban compactness morphs into overdevelopment, exacerbating environmental vulnerabilities. Multinomial regression results confirm a statistically significant correlation between high compactness indices and exposure to compounded flood and seismic risks. Furthermore, the study demonstrates that functional diversity (entropy) remains moderate across Tirana, with higher entropy overlapping with zones of highest hazard exposure, raising critical questions about the spatial alignment of densification policies.

Importantly, the thesis operationalizes these insights into actionable planning tools by proposing the integration of compactness and risk indicators into the statutory framework of Detailed Local Plans (PDVs) and proposes to continue dynamically and in real time monitoring or urban setting. A set of resilience performance rules and intervention levels is articulated to guide urban growth, infill strategies, and green infrastructure provisions while mitigating hazard exposure. The study advocates for the development of a digital monitoring system to track BSF, BCR, entropy, accessibility (functional diversity) in real time, enabling planners to calibrate development trajectories against sustainability and resilience benchmarks.

This research advances both the theoretical delineation of compact cities and their practical governance. The findings contribute a replicable framework model model for cities navigating the balance between compactness, sustainability, and safety in the face of escalating environmental risks.

Keywords: *Compact City, Policy, Urban Morphology, Building Surface Fraction (BSF), Density, Accessibly, Entropy, Multi-Hazard Risk, Spatial Analysis, Sustainable Urban Planning, Safe Density Thresholds, Urban Saturation, Tirana.*

Astratto

Questo studio interroga la città compatta come una questione operativa di policy, più che come un ideale puramente morfologico. Inoltre, riconcettualizza il paradigma della città compatta integrando morfologia spaziale, diversità funzionale e valutazione multi-rischio (performance) in un unico quadro empirico. Il contributo centrale è un'architettura di verifica delle politiche che ricava una "finestra di densità sicura" specifica per il contesto e la codifica come soglie decisionali per la pianificazione normativa. Sebbene la compattezza urbana sia ampiamente promossa come forma urbana sostenibile, la sua definizione pratica e le soglie operative restano ambigue, soprattutto in contesti esposti ai rischi. La ricerca sviluppa e applica un modello metodologico composito che combina metriche morfologiche, con indici di entropia funzionale per valutare la compattezza urbana. L'approccio è testato empiricamente su tredici città internazionali per stabilire baseline comparative, e quindi applicato in profondità al caso di Tirana (Albania), utilizzando dati ad alta risoluzione su edificato, uso del suolo ed esposizione ai rischi.

I risultati mostrano che, pur presentando cluster di alta densità, la forma urbana di Tirana è sbilanciata nello spazio, con sacche di saturazione estrema accanto a suoli sottoutilizzati e aree periferiche a bassa densità. L'analisi identifica una "finestra di densità sicura" intorno a un BSF di circa il 55% (su celle di calcolo 100×100 m), oltre la quale la compattezza urbana degenera in sovrasviluppo, aggravando le vulnerabilità ambientali. Le stime tramite regressione multinomiale confermano una correlazione statisticamente significativa tra alti indici di compattezza ed esposizione congiunta ai rischi di alluvione e sisma. Inoltre, lo studio mostra che la diversità funzionale (entropia) rimane moderata su Tirana, con i valori più elevati che tendono a sovrapporsi alle zone di massima esposizione al rischio, ponendo interrogativi cruciali sull'allineamento spaziale delle politiche di densificazione.

Di rilievo, la tesi rende operative queste evidenze in strumenti di pianificazione attuabili, proponendo l'integrazione di indicatori di compattezza e rischio nel quadro normativo dei Piani di Dettaglio Locale (PDV) e un monitoraggio dell'assetto urbano dinamico e in tempo reale. Viene articolato un insieme di regole prestazionali di resilienza e livelli di intervento per guidare la crescita urbana, le strategie di infill e la dotazione di

infrastrutture verdi, riducendo al contempo l'esposizione ai rischi. Si raccomanda lo sviluppo di un sistema di monitoraggio digitale per tracciare in tempo reale BSF, BCR, entropia, accessibilità (diversità funzionale), permettendo ai pianificatori di calibrare le traiettorie di sviluppo rispetto a benchmark di sostenibilità e resilienza.

La ricerca avanza sia la definizione teorica delle città compatte sia la loro governance pratica. I risultati forniscono un quadro replicabile per le città che cercano di bilanciare compattezza, sostenibilità e sicurezza di fronte a rischi ambientali crescenti.

Parole chiave: *Città compatta, Politica, Morfologia urbana, Frazione di superficie edilizia (BSF), Densità, Accessibilità, Entropia, Rischio multi-rischio, Analisi spaziale, Pianificazione urbana sostenibile, Soglie di densità sicure, Saturazione urbana, Tirana.*

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GLOSSARY OF KEY TERMS

Compact city	A policy and design paradigm that promotes high density, mixed land use, transit accessibility and a rich public realm so as to curb land take and car dependence while improving resource efficiency and social interaction (Jacobs, 1961; Jenks, Burton & Williams, 1996; OECD, 2012; Rogers, 1997; Rogers & Gumuchdjian, 2000).
Density	Number of inhabitants and/or dwellings per land unit; gross density includes all land inside the boundary; net density excludes streets and open space (Newman & Kenworthy, 1989).
Building Surface Fraction (BSF)	BSF is the ratio of the summed building-footprint area (e.g., the 100 m × 100 m tiles used in the Global Dynamic Exposure model) to that cell's land area. Because it is calculated on a uniform lattice rather than cadastral parcels, BSF is directly comparable and is widely used in urban exposure, microclimate and land-cover studies as a raster level analogue to the parcel based Built-up Coverage Ratio (BCR) (Crowley et al., 2020; Schneide et al., 2010; Yuan & Bauer, 2007).
15-minute city	Planning method that locates daily essentials within a 15-min walk or bike trip to cut travel and enhance liveability (Moreno et al., 2021).
Entropy index (land-use)	Shannon-based measure of how evenly different land uses occupy a zone (0 = monoculture; 1 = perfect mix) (Frank & Pivo, 1994).
Safe density operating space	Context-specific band in which benefits of densification outweigh multi-hazard penalties; implies joint heat-, flood- and seismic thresholds (Walker et al., 2009; Irajifar, Sipe & Alizadeh, 2016).
Multi-hazard	Analytical frame that assesses exposure to two or more hazards (e.g., seismic and flood) and their possible cascading interactions (IPCC, 2023).
Urban Compactness Index (UCI)	Principal-components or entropy-weighted composite of density, mixed use and accessibility indicators (Liu et al., 2023).

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Abbreviations

AC	Air Conditioning
ADB	Asian Development Bank
ANN	Average Nearest Neighbour
AR6	Sixth Assessment Report of the IPCC
API	Application Programming Interface
BSF	Built-up Surface Fraction
BCR	Building Coverage Ratio
BVF	Building View Factor
BRT	Bus Rapid Transit
CNU	Congress for the New Urbanism
CCI	Compact City Index
CV	Cross Validation
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CES / GRZ / ÜZ	Local legal terms for site-coverage coefficients (France/Germany/Switzerland)
DEM	Digital Elevation Model
DAP	Detailed Area Plan
EEA	European Environment Agency
EPSG 3857	European Petroleum Survey Group code for Web-Mercator projection
ESDP	European Spatial Development Perspective
EU	European Union
FAR	Floor Area Ratio
FAI	Frontal Area Index (façade density)

FCI	Functional Compactness Index
GFDRR	Global Facility for Disaster Reduction and Recovery
GDAL	Geospatial Data Abstraction Library
GFZ	Geschossflächenzahl, German FAR index
GDE	Global Dynamic Exposure model
GIS	Geographic Information System
GSI	Ground Space Index
GHSL	Global Human Settlement Layer
GPU	Graphics Processing Unit
GTFS	General Transit Feed Specification
H/W	Height-to-width
INFORM	Index for Risk Management
ICE curves	Individual Conditional Expectation curves
IPCC	Intergovernmental Panel on Climate Change
ICCRI	INFORM Climate-Change Risk Index
ISOCHRONE	Equal-time polygons used to compute 15-minute accessibility
IenW	Ministerie van Infrastructuur en Waterstaat (Netherland transport and water ministry)
JRC	Joint Research Centre
KPI	Key Performance Indicator
LST	Land Surface Temperature
MAUP	Modifiable Areal Unit Problem
MTC	Metropolitan Transportation Commission (San Francisco Bay Area)
MUFCI	Multi-factor Urban Form Compactness Index
MICE	Multiple Imputation by Chained Equations

NDVI	Normalised Difference Vegetation Index
NCI	Normalised Compactness Index
OECD	Organisation for Economic Co-operation and Development
OSM	OpenStreetMap
OLS	**O**rdinary **L**east **S**quares regression
PCA	Principal Components Analysis
PR	Plot Ratio (3-D density index)
PGM	*Pla General Metropolità* (Barcelona master plan)
PLU	*Plan Local d'Urbanisme (Paris local plan)*
PT	Public Transport
PPV	Plani i Përgjithshëm Vendor (Tirana Local Development Plan geodatabase)
PPPs	Public-private partnerships
PySAL	Python Spatial Analysis Library
RCP	Representative Concentration Pathway (climate scenario)
RC (frame)	Reinforced-concrete (seismic typology)
SDG	Sustainable Development Goals
SHAP	SHapley Additive exPlanations
SSP	Shared Socio-economic Pathway (climate scenario)
SB 375	California Senate Bill 375
SVF	Sky View Factor
SQL	Structured Query Language
SFCTA	San Francisco County Transportation Authority
TAI	Transit Accessibility Index
TOD	Transit-Oriented Development

TVF	Tree View Factor
UCI	Urban Compactness Index
UGB	Urban growth boundary
URA	Urban Redevelopment Authority (Singapore)
UHI	Urban Heat-Island (effect)
UNEP	United Nations Environment Programme
UN-Habitat	United Nations Human Settlements Programme
VCI	Volumetric Compactness Index
VIF / GVIF	Variance Inflation Factor
VKT	Vehicle Kilometres Travelled
VMT	Vehicle Miles travelled
WHO	World Health Organization

CHAPTER I: INTRODUCTION

1.1 Research context and background

The Organisation for Economic Cooperation and Development (OECD) formalised the *compact city policy agenda* in 2009-2011 as a framework for limiting land consumption, shortening travel distances, and improving infrastructure efficiency (OECD, 2012). The policy ambition encapsulated in **"***compact city" development*, higher density, mixed land use and constrained outward expansion, remains a central pillar of European Union urban strategies (Commission of the European Communities, 1990), OECD guidance (OECD, 2012) and SDG 11 targets for sustainable cities (United Nations, 2015). Empirical work has linked compactness to lower car dependency and reduced land take (Breheny, 1992; Van Der Waals, 2000; Dieleman & Wegener, 2004). The rationale for these agendas is grounded in current urbanisation trajectories. By 2024, an estimated 58% of the global population resided in urban areas, and UN projections indicate that this proportion will approach 60% by 2030 and 68% by 2050 (UN DESA, 2024; 2018). Urban settlements still cover less than 3% of terrestrial land (roughly 1.7% in the latest UN-Habitat audit) but account for about 75% of primary energy demand and 70% of anthropogenic greenhouse gas emissions (IEA, 2024). Cities also generated 2.1 billion tonnes of municipal solid waste in 2023, a figure expected to reach 3.8 billion tonnes by 2050 (UNEP, 2024). These concentrations of population, energy use and waste underpin the international policy turn toward compact city strategies (Bay & Lehmann, 2017). These figures have now for many years underpinned the case and the argument that compact city development can mitigate resource inefficiencies associated with horizontal expansion.

Current debates, however, have unfolded around whether higher-density, mixed-use development (commonly referred to as compact city development) can truly maximize resource efficiency without crossing thresholds beyond which externalities, risks, and disaster vulnerabilities intensify. Within a confined boundary, there is a concentration of buildings and population, amplified pressures, exacerbated externalities such as the urban heat island effect, and, most critically, heightened risks of fatalities when a disaster, whether natural or man-made, occurs due to the large concentration of people in one place. The Intergovernmental Panel on Climate Change has established that climate induced hazards (and not only), such as heatwaves, flooding, droughts, and extreme precipitation, are increasing in frequency and intensity, thereby elevating exposure and vulnerability in *densely* settled regions (IPCC, 2023).

Since the inception of compact city theory, scholarly debates have also sought to clarify what "compact city" means. Is it merely about density and concentration? Evidence suggests otherwise. The more positive interpretations emphasize that compactness should not be reduced to a purely morphological characteristic of the city. Rather, the concept has evolved *gradually*, rendering it difficult to define precisely and even harder to implement through systematic policy instruments into daily urban planning models. Moreover, the principle of compactness is not universally applicable, as no single model fits all contexts, nor does it produce uniform outcomes. ***However, this stands in contrast to the proliferation of global and regional agendas that promote compact city policy development per se.***

In this regard, this research seeks, *first and foremost*, to illuminate the many forms of meaning of the compact city *using data and analyzing this data* from various ''templates'' of global cities. Second, it aims to apply these data patterns to cities of the Global South, with Tirana serving as a case study, in order to analyze the trade-offs of compact city development in relation to hazards and understand how the global patterns of the compact city can shape policies in the global south in terms of urban planning. The goal is to establish a *framework model* that can distinguish whether a city is genuinely becoming compact or merely increasingly dense, and moreover, understand whether we can use these tools to prevent risk from multi-hazards in urban set to expand. *Where the desired outcome is compactness (as in most urban areas is)*, the framework further explores the planning calculations required to achieve it, considering the trade-offs from multi-hazard risks. Finally, the study examines how more informed policies can be designed to mitigate risks effectively even when the desired outcome is density through a safe-density window model. Ultimately, the aim is to assess whether big data in urban planning, combined with monitoring of city development, can enable better decision-making. The central question is whether such tools can guide us toward tailoring urban planning models in ways that both reduce risks and enable the implementation of compact city development policies that are responsive to the unique needs of each city.

1.2 Problem statement

Three unresolved issues prevent this consensus from translating into planning practice, issues that constitute the core dilemma tested in this research.

First, the term "*compact city*," much like other urban planning concepts such as "*sustainable development*" and "*resilience*," lacks a precise and widely accepted *operational* definition. While dense development is a central feature of the concept, there is no clear consensus on what density levels qualify a city or area as "*compact*." Additionally, the appropriate spatial scale for compactness, whether applied to a neighborhood, a block, a town, a city, or an entire metropolitan area, remains *undefined*. And often, the quantitative results in these different scales show different figures, adding to layers of disparities. Different scales can result in varied outcomes, adding complexity to the application of compact urban forms. In this regard, a more unified method needs to be established, which is universally understandable and more importantly quantifiable and translatable within the urban planning language otherwise the compact city idea will continue to be regarded as a *fallacy as* Neuman (2005) would put it. Breheny's commentary in a 1992 issue of *Built Environment* reflected on the theories, prescriptions, and empirical studies surrounding the compact city concept (Breheny, 1997). Decades later, the debate continues, highlighting the persistence of questions around the validity and applicability of the model. Breheny's observations underscore the evolving nature of this discourse and emphasize the need to contextualize density within cultural frameworks, as its meaning and application are not universally fixed (Jenks and Dempsey, 2005).

Second, compactness lacks a transferable, operational metric. Even where its core attributes are broadly recognised (a dense, mixed-use and socially diverse urban form, organised around efficient public transport and neighbourhood) scale public spaces (Rogers, 1997; Burton, 2000; 2003) studies operationalise these ideas through different proxies. Population density, floor-area ratio (FAR), built-coverage ratio (BCR), land-use mix indices and composite accessibility measures are applied variously to street blocks, census tracts or whole metropolitan regions (Neuman, 2005). Burton's work on the compact city and social justice is particularly relevant here, because it translates this normative vision into *explicit indicator sets for density, land-use mix,* *accessibility and equity,* while at the same time demonstrating how sensitive empirical results are to the choice of indicators and spatial boundaries (Burton, 2000; 2003). Inconsistent scales and metrics generate incompatible findings and hinder incorporation of compactness into statutory planning instruments (Salat, 2017; Van Aalst, 2006; Banholzer et al., 2014; Singh & Singh, 2012; Peduzzi, 2019; Bouwer, 2011; Huber & Gulledge, 2011; Dey & Lewis, 2021; Dempsey & Jenks, 2010).

Third, multi-hazard exposure remains largely absent from compact-city evaluations, even though in urban settings events of extreme heat, compound flooding and cascading events are becoming more frequent and intense (Van Aalst, 2006; Bouwer, 2011; Banholzer et al., 2014; Singh & Singh, 2012; Peduzzi, 2019; Huber & Gulledge, 2011; Dey & Lewis, 2021; IPCC, 2023). In dense environments, the same concentration of people, buildings and lifelines that improve energy and transport efficiency also concentrates exposure channels (heat, pluvial and fluvial floods, landslides and cascading infrastructure failures rarely occur in isolation). Treating hazards one by one can therefore underestimate risk in compact settings, because it misses the way events co-occur (for example, extreme rainfall following a heatwave, or an earthquake that compromises leaves and triggers secondary flooding). Even where multi-hazard perspectives have been applied, they have tended to arise from disaster-risk and resilience research rather than from the compact-city literature itself. National and global indices such as INFORM already combine earthquakes, tsunamis, floods, droughts and epidemics in a common risk metric (Joint Research Centre, 2023), and climate–disaster work has started to explore compound and cascading events in metropolitan areas (Van Aalst, 2006; Bouwer, 2011; Banholzer et al., 2014; Peduzzi, 2019; IPCC, 2023). A few recent studies explicitly connect urban form to hazard performance, Tan and Rinaldi (2019) show that flood losses per capita vary systematically with density in European towns, while Kain et al. (2022) and Dey and Lewis (2021) relate compactness, impervious cover and pluvial flood preparedness in high-density contexts. Yet even these contributions usually examine a single hazard family at a time or operate at coarse spatial resolutions.

These gaps motivate the present research. By integrating morphological, functional (accessibility) and hazard data into one analytical frame, the study seeks to identify density thresholds beyond which additional compaction ceases to deliver benefits and instead gives elevated hazard risks. *As Salat (2017) argues, urban form represents an integrated outcome of its developmental history; it cannot be fully understood by examining individual elements in isolation but must be analysed as a coherent whole.*

1.3 Purpose of the study, objectives, research questions and hypothesis

The aim is to determine whether compact development policies propose a functional and high performance in cities in terms of multi hazards risks, and whether this approach can be measured and replicated. This thesis aims to redefine and empirically test the concept of the compact city by developing and applying a composite methodological framework that integrates morphological, functional, and multi-hazard risk-based indicators. Through a spatially explicit analysis of Tirana and comparative insights from other global cities, the study seeks to identify safe density thresholds that balance morphology, functionality and multi-hazard performance in a city. The intended outcome is a model and implementation pathway that embeds these metrics into a compact city index and a monitoring framework, so that densification is guided, auditable and transferable across contexts.

1.3.1 Research questions

***RQ1* –** How can a compact city be *operationally* defined through measurable morphological and functional indicators, and to what extent can a composite compactness index (CCI) *quantitatively* distinguish compact urban fabric?

***RQ2* –** Which *empirically* derived "safe-density" ranges (in terms of compactness indicators) can be identified under different multi-hazard profiles, and to what extent do these ranges converge or diverge across the different global cities with distinct urban fabrics, functional typologies and hazard exposures?

***RQ3* –** In the case of Tirana, what is the spatial relationship between levels of urban compactness and exposure to multi-hazard risks, within the existing urban morphology?

***RQ4* –** How can compactness and multi-hazard risk indicators be translated into concrete thresholds and monitoring tools within urban planning instruments, and what changes in exposure and densification patterns do the scenario tests indicate?

1.3.2 Hypothesis

H1 – A city's '*compactnes*s' is a result of a calibrated balance between form, function and performance under multi-hazards.

H2 – Even though compactness is a context specific metric, from global cases we can derive quantifiable "safe-density window" beyond which compactness transitions into merely dense, increasing multi-hazard risk.

H3 – There is a correlation between levels of compactness and multi-hazard risks.

H4 – Integrating compactness index and multi-hazard risk indicators into urban planning monitoring instrument, can reduce urban vulnerability by directing densification toward low-risk areas.

1.3.3 Objectives

Objective 1 - Conceptualize and quantitatively define the compact city model by drawing on pattern data analysis from thirteen global cities (both compact and dense cases). On this basis, the study aims to refine the theoretical understanding of what constitutes a compact city in terms of data pattern.

Objective 2 - Empirically establish the Compact City Index (CCI) through a set of indicators chosen from morphology (BSF and verticality) and accessibility (15- minute city indicators); and test the calibration of CCI against multi-hazard risk profiles and evaluate the 'safe-density window' as a comparative state.

Objective 3 – Analyze and map spatial correlations between composite compactness metrics and exposures to flood and seismic hazards in Tirana case. This objective seeks to reveal patterns of vulnerability and trade-offs arising from compact city urban form.

Objective 4 - Develop a framework for embedding compactness and multi – hazard risk indicators as a urban planning instrument, thereby enabling more adaptive, context-sensitive, and risk-aware planning/densifying policies.

CHAPTER II. THEORETICAL BACKGROUND AND LITERATURE REVIEW

Most authors converge on the idea that compactness combines density, land-use mix and proximity, yet a stable operational definition remains elusive. The reasons as we will see further within this literature review analysis are practical, not semantic. The same FAR or BCR can seal the ground very differently depending on typology and plot geometry; the same population density can yield opposite accessibility outcomes depending on network design; and many national codes prize output (units, floor area) over morphological quality. Guidance documents consistently promote ends (reduced car use, green access, shorter trips) without stating thresholds that condition permissible form by local hazard. Meanwhile, the rise of polycentric networks weakens monocentric density as a universal baseline. However, in this chapter we take a pragmatic approach, analyzing the most complete indicator practice from literature.

2.1 Genealogy of the compact city concept

The compact-city thinking has evolved, from an early critique of car-oriented living to today's emphasis on climate compatible resilience. There are four overlapping "generations" of debate. Compactness is a *design doctrine* that has been adopted (sometimes selectively) by several broader paradigms.

Table 1. Integration of compactness design doctrine in planning paradigms

Planning paradigm	Core proposition	Relationship to compactness
1. Modern ecological planning (McHarg, 1969)	Fit human settlement to biophysical carrying capacity	Provides the first land-conservation rationale for higher density to spare ecosystems
2. Smart Growth (US EPA, 1996)	Containment, mixed use, transit as an antidote to sprawl	Treats compact form as one of ten guiding principles (others are choice, fair housing, etc.)
3. New Urbanism (CNU Charter, 1999)	Re-create pre-war "traditional neighborhoods" with fine blocks and clear centers	Shares the *morphological* side of compactness (short blocks, perimeter streets) but is agnostic on *vertical* density;
4. Transit-Oriented Development (TOD) (Calthorpe, 1993)	5- to 10-minute walk sheds around high-capacity stations	Operationalizes *where* to place compactness and how to trade floor-area bonuses against modal share

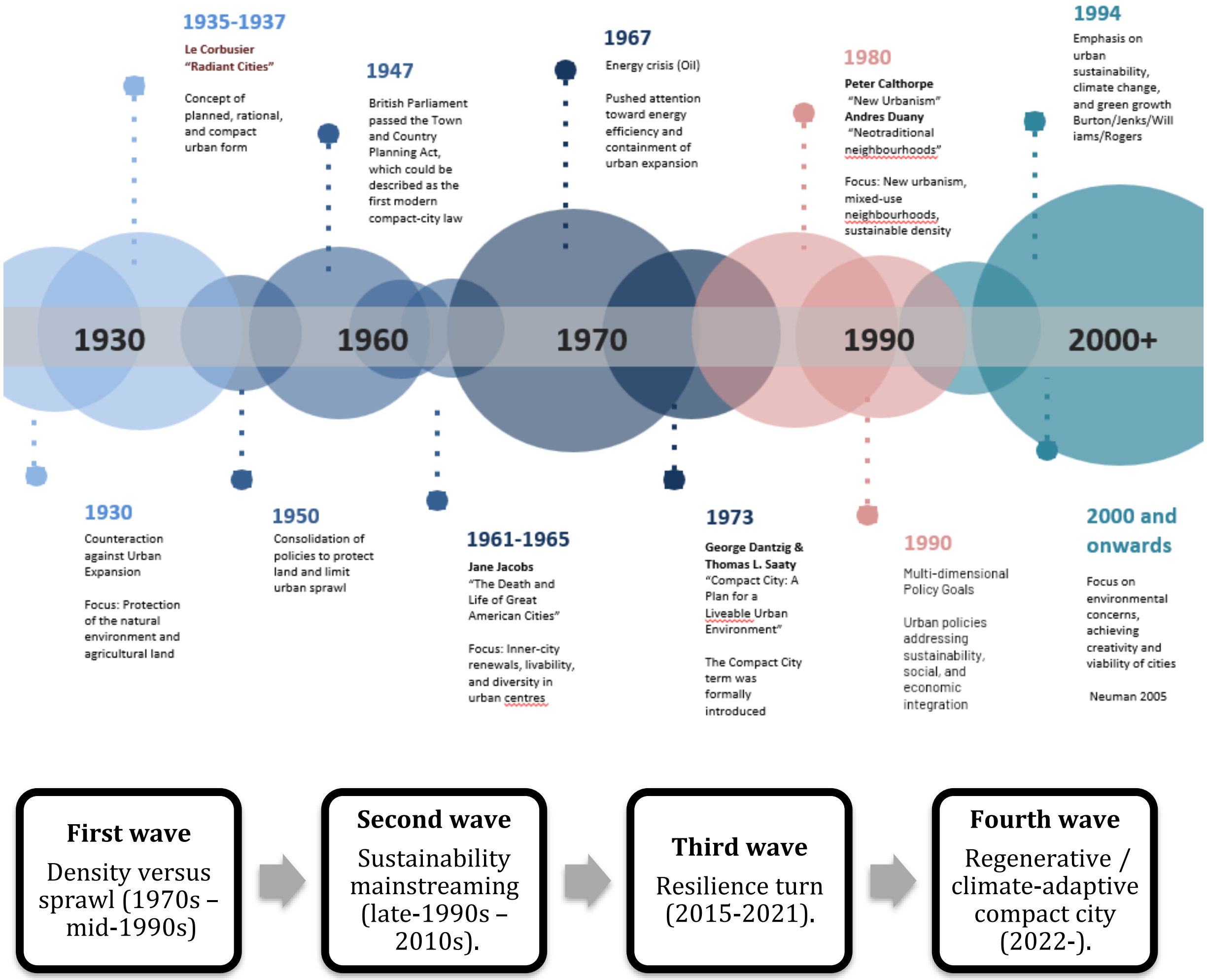
5. Sustainable / Ecological Modernization (Hajer, 1995)	Technological and institutional innovation can “decouple” growth from impact. *Discursive coalitions* and governance learning.	Recasts density as a double dividend. Land take savings *plus* greener infrastructure economics
6. Resilient Urbanism (Vale & Campanella, 2005)	Cities must absorb, adapt and recover from shocks	Recent wave that asks whether density magnifies exposure or, if well-designed, speeds recovery
7. Regenerative / Doughnut Urbanism (Raworth, 2017; UN-Habitat, 2024)	Cities should deliver net-positive ecological and social returns	Positions compactness as a *necessary but not sufficient* condition; insists on carbon budgets, circular materials and green–blue ratios

Source: Authors’ elaboration

There are two paradigms that link closely to compact city morphological definition, *New Urbanism and Smart Growth*. New Urbanism’s charter puts a ceiling on block and building size but seldom prescribes verticality. The compact-city literature, by contrast, is comfortable with mid- to high-rise form as long as livability and green ratios are protected. Smart Growth is a policy *package* (brownfields, housing choice, fiscal incentives) and the compact city is the *morphological* arm of that package. In Europe the two lines converged under the banner of “urban containment” (EEA, 2016); however in North America they often appear as distinct advocacy streams.

In terms of genealogy of the compact city conception, the compact city concept has unfolded in **four** recognizable “waves,” each redefining why we pursue higher urban density, what metrics we privilege, and which policy levers accompany the ideal.

Figure 1. Main waves of concept evolution



Source: Authors' elaboration

Across all four waves the promise of compactness has repeatedly been revised by newly perceived externalities, first energy, then equity, and now multi-hazard risk and planetary limits. What remains unsettled is where the benefit curves intersect the risk curves for any given place, and how design levers can be tuned to keep dense districts inside a "*safe operating space*."

While the four waves show how the *objectives* of compaction have shifted (from land conservation to climate needs) the idea itself has travelled through several planning paradigms. Ecological planning supplied the landscape rationale, Smart Growth re-packaged it as an anti-sprawl toolkit, New Urbanism captured its fine-grain street logic, TOD specified the *where*, and resilience theory is now testing its limits under compound hazards.

The present thesis positions compactness at the intersection of these strands, asking not only *how much* density but *which mix of morphological, functional and risk criteria* keep a district inside a "safe operating" envelope.

2.1.1 Origins (1960s – 1980s)

By the early 1960s planners and social critics on both sides of the Atlantic were warning that low-density, automobile dependent suburbs consumed land, fragmented ecosystems and produced what Jane Jacobs (1962, pg. 13) memorably called "*the Great Blight of Dullness*." In Britain, the Buchanan Report (*Traffic in Towns*, 1963) argued that unrestricted auto traffic would destroy urban life; McHarg's (1969) showed how sprawling development undermined ecological carrying capacity. Quantitative evidence followed, as Newman & Kenworthy (1989) found per-capita transport energy in dispersed North American cities to be three to four times that of denser European and Asian counterparts.

Europe's response centred on landscape protection. The UK's post-war greenbelt (formally adopted for Greater London in 1955 and legislated nationally in 1958) inspired similar belts around Vienna, Copenhagen and Barcelona, each explicitly designed to "*hold*" urban growth within a walk-and-transit frame (Kühn, 2003). Dutch planners fortified the Randstad's "Green Heart," while Denmark embedded growth corridors in its 1960 Finger Plan. Across the Atlantic, Oregon's 1973 Urban Growth Boundary and Florida's 1985 Growth Management Act used state authority (not landscape buffers) to channel housing and infrastructure inward (Burchell & Mukherji, 2003).

The 1973 oil price shock pushed compactness into the energy arena (Neuman, 2005). European governments launched similar inquiries, concluding that rail centred, high density corridors were a hedge against volatile fossil-fuel prices (Breheny, 1992).

The Brundtland Report (WCED, 1987) reframed urban form as an inter-generational equity issue, that the sprawling cities externalised ecological costs to future generations. At the 1992 Rio Summit, Agenda 21 urged nations to adopt land use strategies that "*promote higher urban density and mixed land use*" (UN, 1992, ch. 7). The EU's 5th Environmental Action Programme (1993) and ESDP drafts (1995–1999) followed suit, advocating urban containment and brownfield regeneration.

Scholarly synthesis arrived with Jenks, Burton and Williams' *The Compact City* (1996) and Rogers (1997), both argue that higher density, if coupled with public transport, could simultaneously reduce land take, vehicle kilometres travelled and per capita infrastructure costs. Dieleman & Wegener (2004) used simulation to show that a 15 percent densification of Dutch cities could cut daily car use by 7–8%. Yet Breheny (1997) cautioned that blanket prescriptions ignored regional labour markets and lifestyle preferences. This tension between universal metric and place specific context would shape the next generation of policies.

Theorists (Hajer, 1995) contended that technological innovation and institutional reform could decouple economic growth from environmental harm, turning compactness into a "double dividend" of efficiency and competitiveness. The paradigm legitimised density not merely as environmental stewardship but as a development strategy an idea later embedded in the EU's Lisbon Agenda (2000).

2.1.2 Contemporary reframing (2010s to present)

Between 2009 and 2011 the OECD analysed 29 metropolitan regions on four continents, defining a compact city as one exhibiting "*dense and proximate development patterns, linked by high-quality public transport, with easy access to jobs and services*" (OECD, 2012, p. 19). Case study evidence such as Paris's brownfield ZACs, Melbourne's growth-boundary tightening, Toyama's tram-oriented redevelopment, demonstrated that well-designed densification could cut per-capita CO_2 emissions from transport by 20–30 percent. The report also warned that density without green-blue infrastructure exacerbated heat-island effects and flood peaks. The Territorial Agenda (2007, 2011) and the Urban Agenda for the EU (2016) formally required member states to integrate compactness targets into spatial strategies, while EU cohesion funds prioritised transit-oriented brownfield projects. Globally, SDG 11 (2015) enshrined the goal of "*inclusive, safe, resilient and sustainable*" cities, implicitly linking compact form to social inclusion and hazard mitigation. National policies echoed this turn, France's *Grenelle II* (2010), Japan's Eco-Compact City pilots (2011) and Korea's urban-regeneration statutes (2013) all set minimum densities around transit nodes.

Successive extreme weather events, such as Superstorm Sandy (2012), European heatwaves (2015, 2019) and catastrophic urban floods in Houston (2017) and Zhengzhou (2021), highlighted the vulnerability of dense cores. IPCC AR6 (2023) stresses that urban form must concurrently decarbonise and adapt. Research now applies complex adaptive systems theory to identify thresholds beyond which additional density increases risk (Salat, Bourdic & Labbe, 2017; Kain, Adger & Granberg, 2022). The EU Mission on Climate Neutral and Smart Cities (2022–2030) funds net-zero districts only if they incorporate nature-based flood mitigation and heat-stress buffers. City-level tools (e.g., Barcelona's blocks, Paris's 15-minute-city plan, Seoul's Green Network) embed compactness within multi-hazard resilience frameworks. Meanwhile, the rise of "*degrowth urbanism*" (Xue, 2017) critiques density as growth, arguing for human-scale diversification over megaproject densification. Current scholarship converges on the idea that density is best treated as an independent variable whose net effect is conditioned by environmental performance and hazard context rather than assumed beneficial.

2.2 Conceptual clarifications and competing definitions

> *"Yet, when most people try to define a compact city, the first characteristic that comes to mind is population density. Others include mixed land uses and public transportation. Despite extensive literature on compact cities, surprisingly, a definition of one does not exist. Researchers tend to use density alone as the independent variable … Planners and designers tend to use physical characteristics such as density, street widths, setbacks, lot size, sidewalks, porches, and so on."* (Neuman, 2005, p. 12)

Neuman's debate still resonates. Density is a simple head-count or floor-space ratio, intensity (FAR, floor-space index) captures how much building mass is stacked onto a parcel; mixed use denotes functional heterogeneity; urban form folds all the above into block sizes, street networks, building heights and open-space ratios. Breheny (1993), Rogers (1997) and Hillman (1996) all deploy the term "*compact*" but foreground different attributes (land-take reduction, carbon balance, or modal split). Burgess (2002) adds that compact cities hinge on efficient public-transport systems, another dimension again. The definitional sprawl is not trivial, empirical results vary sharply depending on which attribute is chosen as the proxy for compactness (*cf.* Jacobs, 1962; Newman & Kenworthy, 1989; Ahlfeldt & Pietrostefani, 2017).

Table 2. Definitions based on main waves of concept evolution

	Discipline / scale	Definition used	Metric(s)	Notes on evolution
Jacobs (1961)	Urban design / district	Intricate mingling of uses in small blocks	Block length and land-use mix	Proto-function view
Newman and Kenworthy (1989)	Transport / metro	People per/ha vs fuel/km	Net density	Density proxy for energy
Churchman (1999)	Planning theory / city	Density + mixed use + public transport	Composite index	First explicit multidimensional definition
Jenks & Burgess (2000)	Sustainability / city	High density *with* green quota & services	FAR, green-space ratio	Adds environmental clause
Burton (2002)	Social equity / UK cities	25 indicators across 3 pillars	Population density, PT frequency	Shows trade-offs
Neuman (2005)	Systems / region	"Compactness is relational, not stock"	Moran's I	Introduces spatial-statistical logic
OECD (2012)	Policy / OECD cities	Density + mixed use + accessibility	Pop density, entropy, job-housing balance	Toolkit for mayors
Zhuang & Zhou (2019)	Climate / block	Heat-risk clusters inside dense fabric	Local Moran-I for BCR	Links compactness to heat
Kain et al. (2022)	Resilience review	Morphology vs hazard outcome	76 metrics mapped, no consensus	Calls for risk-sensitive compactness
Akrofi & Okitasari (2023)	SDG audit	Warn against cross-disciplinary metric drift	Critique	Emphasises validation
UN-Habitat (2024)	Regenerative policy	Net-positive compactness (density + carbon + green factor)	BCR ≤ 0.7 or NDVI ≥ 0.3 + zero-emission mobility	Fourth-wave framing

Source: Authors' elaboration

The task has moved from proving compact city virtue toward calibrating where, when and for whom compactness delivers sustainability without exceeding resilience thresholds.

2.2.1 The confusion problem, form vs function problem in urban planning

The compact-city agenda is frequently debated, sometimes fairly, sometimes not, for relying on "catch-all" vocabulary and mismatched metrics. The literature therefore begins by unpacking five conceptual knots: (1*) the terms themselves, (2) the spatial scale at which they are applied, (3) the multidimensional character of compactness, (4) the absence of universally accepted thresholds, and (5) the struggle to translate academic indicators into enforceable planning law.*

Spatial scale magnifies the semantic *fog*. An FAR of 3 measured at parcel scale may disappear into an FAR of 0.7 at neighbourhood scale once streets and parks are counted and may shrink again when calculated for the metropolitan region (Thinh, Nguyen, Arlt, & Heber, 2002; Angel, Lamson-Hall, & Blanco, 2021). Owens and Breheny (1992) distinguish "centralisation" (filling gaps inside an existing core) from "decentralised concentration" (tight satellite clusters), both can be called "compact" depending on the unit of analysis. *This is the classic Modifiable Areal Unit Problem (MAUP)* (Openshaw, 1984). Statistical outcomes shift with the zoning scheme. Dieleman & Wegener (2004) report that Dutch commuting distances fall sharply when density is tightened in corridors but barely change when the metric is averaged across the Randstad. Without scale declarations, cross-study findings cannot be compared. The multidimensional nature of compactness is another confusion problem. Compactness has at least three orthogonal dimensions, morphological, functional and performance-based, and each dimension houses its own indicators (Salat, Bourdic & Labbe, 2017).

Table 3. Three main dimensions of compactness

Dimension	Indicators
1. Morphological (*physical form)*	Population density, Floor Area Ratio (FAR), Building-Coverage Ratio (BCR), building height *distribution*, sky-view factor, plot size distribution etc. (Newman & Kenworthy, 1989; Neuman, 2005; Jacquet, Pachauri & Tubiana, 2010; Oke, 1987; Salat, Bourdic & Labbe, 2017; Angel, Lamson-Hall & Blanco, 2021)

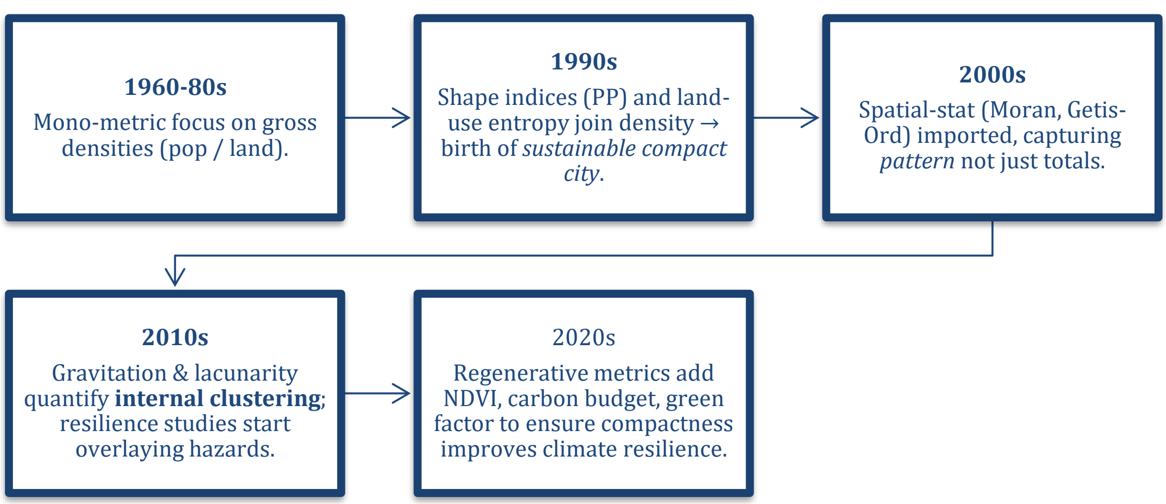
2. Functional *(land-use mix, accessibility)*	Entropy, Simpson diversity index, jobs–housing balance, % population within 500 m of daily services etc. (Sherlock, 1996; Cervero & Kockelman, 1997; Eliasson & Mattsson, 2006; OECD, 2012; Moreno et al., 2021; Batista e Silva et al., 2020)
3. Performance *(ex. resource/energy outcomes)*	Transport energy per capita, residential energy per m², CO_2 per resident, per-capita water demand etc. (Newman & Kenworthy, 1989; Steemers, 2003; Krehl, Siedentop & Kroll, 2016; Ewing & Cervero, 2010; OECD, 2012; Banai & DePriest, 2014)

Source: Authors' elaboration

2.3 Measurement frameworks

The compact-city literature contains hundreds of individual metrics, yet four decades of empirical work converge on a single lesson that no single indicator can capture "compactness." Instead, researchers mainly hang with the interlocking questions of *what* is being measured (morphology, function, or performance), *where* it is being measured (parcel, district, metropolitan region), and *how* the resulting numbers will be translated into policy.

Figure 2. Metrics evolution



Source: Authors' elaboration

2.3.1 Measuring physical form (morphology)

Early studies relied almost exclusively on gross population density (total residents divided by administrative area) to demonstrate that denser cities use less petrol and occupy less land (Newman & Kenworthy, 1989). But gross density *"is simplistic and often masks the complexities and nuances of urban density*" (Angel, Lamson-Hall & Blanco, 2021, p. 5; Bertaud, 2018). Neuman (2005) therefore insisted that density must be decomposed into constituent parts (building form, open-space ratio, land-use mix) before it can serve as a scientific variable. Floor-Area Ratio (FAR) and Building-Coverage Ratio (BCR) lie at the heart of most zoning codes. FAR (built floor space/plot area) captures vertical intensity meantime BCR (building footprint/plot area) captures the extent of ground sealing. The two can diverge dramatically, Parisian blocks for example reach a FAR of 5.75 with a BCR of appropriately 0.55, leaving substantial permeable courtyards, whereas Hong Kong's 20-storey slab estates record a lower FAR (4.32) but a BCR above 0.75, which "*leaves far less permeable surface and concentrates impermeable mass*" (Jacquet, Pachauri & Tubiana, 2010, p. 118). This is an important indicator, as for instance hydrological modelling shows that runoff volume *rises almost linearly with BCR once coverage exceeds 60 percent* (Banai & DePriest, 2014). Heat-island intensity also correlates more closely with BCR than with FAR because the key driver is ground-level radiative exchange (Salat, Bourdic & Labbe, 2017). For precisely those reasons Paris sets four separate morphological rules. M*aximum* BCRs to ensure at least 30 percent permeable soil, zone-specific FAR caps, ground-floor "mix coefficients" to guarantee active frontages and bonus FAR rights within 300 m of a metro station (Ville de Paris, 2020, arts UG10, UG14, UG2-3, UG16).

Below is an expanded table of indicators (beside the main one, BCR, FAR and population density) that are now standard in peer-reviewed climate, ventilation and hydrology studies; each is accompanied by the canonical source that established or recently refined the metric.

Table 4. Morphological indicators

Indicator / acronym	What it measures	Function	References
Sky View Factor (SVF)	Proportion of sky hemisphere visible from a point or block	Governs long-wave radiation loss, night-time cooling and daytime heat-gain; SVF < 0.35 typically amplifies UHI by > 2 K	Bernard et al., 2018; Yang et al., 2021

Frontal Area Index (FAI) / Facade Density	Total façade area perpendicular to wind and plan-area	Proxy for aerodynamic roughness; FAI > 0.30 can halve mean canopy-level wind speed, reducing pollutant dispersion	Yang et al., 2021
Canyon Aspect Ratio (H/W)	Mean building height and street width	Optimum ratios (0.6–1.0) balance shading and ventilation; ratios > 2 trap heat and $PM_{2.5}$	Bernard et al., 2018
Plot Ratio (PR) / Volume Density Index (BVD)	Built volume and parcel area (3-D analogue of FAR)	Captures growing trend toward high-void high-rise towers that inflate FAR but create low volumetric utilisation	Yang et al., 2021
Mean Building Height + Height Standard Deviation	Central tendency and vertical heterogeneity of the skyline	Height variance ≥ 12 m improves wind flushing; uniform height blocks exacerbate stagnant layers	Sun et al., 2024
Ground Space Index (GSI)	Impervious ground coverage (similar to BCR but excludes structures < 1 m)	Hydrological run-off rises near-linearly once GSI > 0.6; helps calibrate sponge-city imperviousness targets	Banai & DePriest, 2014
Shape/Compactness Index (circularity, fractal dimension, ε-shape)	How closely block or footprint approximates a circle/square	High perimeter-to-area shapes raise façade heat gain and infrastructure length per unit-built area	Sun, Wang & Meng, 2023
Sky / Tree / Building View Factors (SVF/TVF/BVF)	Shares of sky, vegetation canopy and built mass visible from street level	TVF > 0.25 can offset almost 30 % of mean radiant temperature rise caused by high BCR; BVF feeds daylighting models	Gong et al., 2018
Surface Roughness Length (z_0)	Log-law aerodynamic roughness derived from FAI and height variance	Mesoscale dispersion and flood-wind coupling models	Oke theory operationalised in studies such as Yang et al., 2021
Block Size & Perimeter-Area Ratio	Mean block dimensions and edge complexity	Smaller, regular blocks (< 100 m) raise intersection density, walkability; very small blocks (< 50 m)	Shpuza, 2023

		increase façade density and cooling load	

Source: Authors' elaboration

2.3.2 Measuring functionality

Morphological metrics such as population density, FAR or BCR describe *how much* built form occupies the ground, yet they tell us almost nothing about *how well* that form functions for people. *Functional indicators* step into that gap by measuring the spatial temporal relationship between people, activities and transport networks.

The earliest strand of work quantifies land-use diversity. Sherlock (1996) adapted Shannon's ***entropy index*** to seven urban land categories, producing scores that range from 0 (single-use monoculture) to 1 (perfect mix). Subsequent studies have shown that neighbourhoods whose entropy exceeds about 0.6 record higher pedestrian mode shares and lower Vehicle Kilometres Travelled (VKT) (Thomas & Cousins, 1996; Cervero & Kockelman, 1997). A complementary approach, the Simpson-Herfindahl index, down-weights tiny parcels and thus avoids the "false diversity" problem that arises when, for instance, a logistics warehouse is classed identically to a grocery store (Frank & Pivo, 1994). Still, all categorical metrics suffer from classification granularity.

Because diversity does not guarantee proximity, researchers introduced job–housing and service balance indicators. Metropolitan areas in which the ratio of local jobs to resident workers sits closer generally exhibit shorter commutes and lower per-capita CO_2 emissions (Eliasson & Mattsson, 2006; OECD, 2012). At the finer grain, the *Service Gap Index* measures the share of residents who can reach a grocery, pharmacy *and* clinic within one kilometre on the walkable network; in Chinese 15-minute-city pilots, neighbourhood achieved a 20 % drop in car use (Fang et al., 2022).

The most influential functional metrics today are *accessibility indices*. Hansen's (1959) cumulative-opportunity model simply counts destinations within a given travel-time threshold; it has been re-popularised by the "*15-minute city*" agenda, which proposes that essential services should lie within a quarter-hour walk or transit ride (Moreno et al., 2021). Gravity-type formulations refine the idea by weighting destinations with an exponential impedance decay and thus capturing the behavioural reality that closer opportunities count more (Ewing & Cervero, 2010). With the release of global GTFS feeds, *Transit Accessibility Indices (TAI)* now weight reachable jobs by scheduled travel time and headway reliability; once TAI enters VKT regressions, raw population density often loses statistical significance (Batista e Silva, Moreno-Monroy, & Gallego, 2020; Zhao, Li, & Liu, 2020).

Table 5. Accessibility metrics

	Formula	Typical data	Strengths / use-cases	Weaknesses
Cumulative opportunity (Hansen, 1959)	Count of destinations ≤ t minutes	OSM network and GTFS stops	Simple to interpret; basis of "15-minute-city" threshold (Moreno et al., 2021)	Step function ignores impedance decay
Gravity / Hansen decay	∑ Dj e−β cij	∑ Dj e−β cij	Captures trip probability; OECD (2012) uses $\beta = 0.065\ min^{-1}$ for EU cities	Sensitive to β; non-unique fits
Transit Accessibility Index (TAI)	Weighted jobs reachable by PT / total metro jobs	GTFS, Eurostat grid, timetable	Multimodal; time-sensitive; explains land values better than density	Requires high-quality GTFS; weekday bias
Space-syntax integration	1 / mean topological depth in axial graph	GIS axial map	Predicts pedestrian flows; fine for historical centres	Ignores land-use attraction; needs manual axial drawing
Walk Score / Walkability Index	Proprietary decay	Google API and parcel calculations	Household-level, public	Undifferentiated POI quality

Source: Authors elaboration

Network studies add a *resilience* dimension as well. Using space-syntax centrality, Kain, Adger and Granberg (2022) showed that retail strips with both high closeness and high betweenness regained 85 % of footfall within a week after a heat-wave power outage, whereas morphologically dense but poorly connected enclaves recovered less than half. Such findings show that compactness without redundancy can leave neighbourhoods vulnerable to shocks.

2.3.3 Measuring performance

Compact-city policy ultimately stands or falls on outcomes. Does a denser, mixed fabric *actually* save energy, cut carbon and improve safety, or does it simply rearrange impacts in space? *Three decades of empirical work reveals a complex, often non-linear picture.*

Early simulations have predicted that party-wall sharing in row houses and perimeter blocks would lower space-heating demand by 25–40 % compared with detached dwellings (Steemers, 2003). European studies confirm the trend. Household gas consumption falls by roughly 2.4 kWh/m² for every additional attached façade (Krehl, Siedentop & Kroll, 2016). Yet the benefit reverses in warm, humid climates once the Building Coverage Ratio (BCR) increases. High BCR shows solar reflection from neighbouring façades and reduced night-time radiative loss push average cooling loads up by 15–20 % (Kühn, 2003). Hence several Chinese and Gulf-state cities now combine high FAR with *maximum* BCR limits or mandatory courtyard voids to regain nocturnal ventilation (Salat, Bourdic & Labbe, 2017).

Aggregate transport CO_2 typically declines with rising gross population density, but the relationship flattens (and sometimes reverses) beyond roughly 100 inhabitants per hectare. Dieleman and Wegener (2004) attribute the turning point to two factors: *(i) congestion, which erodes the speed advantage of public transport; and (ii) a geographic logic whereby very-high-density cores induce longer "extroverted" trips to ex-urban recreation or specialised services.* A meta-analysis of 17 North American finds that each doubling of dwelling-unit density below 50 du/ha cuts household VKT by 9 %, whereas above that level the marginal gain falls to just 2 % (Ewing & Cervero, 2010). The non-linearity explains why many climate action plans now target "medium-high density bands" (roughly 8000–12000 inh./km²) rather than maximum theoretical density.

Floor-Area Ratio alone hides the carbon cost of construction materials. A life-cycle assessment of 90 apartment projects showed embodied emissions per unit floor area rising steeply once buildings pass 15 floors, wiping out the operational benefits after around 35 years of service (Rode et al., 2014). Hence, performance dashboards increasingly include a Life-Cycle Carbon Intensity that combines operational and embodied streams; Nordic building codes have begun to set envelope-specific embodied-carbon caps that encourage timber-hybrid mid-rise rather than pure concrete high rise (Jones et al., 2019).

Remote sensing studies find a power law relationship between BCR and nighttime land surface temperature (LST). *Each 0.1 increase in BCR raises LST by 0.7 °C*, all else equal (Yang et al., 2021). The World Health Organization now recommends a Green View Factor of at least 0.15 at street level to offset heat stress mortality during 1-in-20-year events (WHO, 2022). Compact neighbourhoods with high FAR but low BCR (Barcelona's 19th-century example), outperform block estates on both air temperature and walkable shade without sacrificing density (Jacquet, Pachauri & Tubiana, 2010).

Compactness can also raise exposure to natural hazards. Irajifar, Sipe and Alizadeh (2016) examined 150 Brisbane suburbs hit by the 2011 floods. Reconstruction progressed fastest in areas with medium high densities (8000–12000 inh./km²), presumably because sufficient local labour and supply chains accelerated repair, yet recovery stalled in very high-density precincts where vertical concentration of damage and limited logistics access slowed removal. Similar resilience curves have been observed for earthquake death rates in Iranian and Turkish cities (Jahanbakhsh et al., 2020).

The implication is clear, performance indicators must combine exposure (e.g., flood depth, seismic etc) with capacity proxies such as street-network redundancy and local density.

Table 6. Performance indicators

Indicator	Metric(s)	Inflection point	Observed direction of effect	Underlying urban-form variable(s)	References
Operational building energy	-Space heating intensity - Cooling load	- Heating decreases 2.4 kWh m² per extra shared façade. -Cooling increases 1	Party-wall sharing reduces winter demand; high site coverage traps radiant heat at night,	Attached façade count; Building-Coverage Ratio (BCR)	Steemers 2003 ; Krehl et al. 2016; Kühn 2003

		5–20 % when BCR is high in warm climates.	boosting AC use.		
Transport energy / CO_2	- Per-capita VKT - Tail-pipe CO_2	CO_2 falls with density up to approx. 100 inh./ha; above that, gains flatten or reverse.	Moderate densification shortens trips; very-high densities generate congestion and outward leisure trips.	Gross population density; street congestion index	Dieleman & Wegener 2004; Ewing & Cervero 2010
Embodied and life-cycle carbon	- Embodied CO_2 - Life-cycle carbon payback (years)	Embodied emissions rise sharply above 15 storeys; operational savings cancelled after 35 years.	High-rise construction intensity; structural material mix	FAR, height; concrete vs timber share	Rode et al. 2014; Jones et al. 2019
Urban heat-island and health	- Night-time land-surface temperature - Heat-stress mortality (per 100 000)	LST rises approx. 0.7 °C per 0.1 BCR increase; WHO recommends Green View Factor ≥ 0.15.	Dense, impermeable ground raises radiant storage; tree canopy and sky exposure mitigate.	BCR; Sky View Factor; Green View Factor	Yang et al. 2021; WHO 2022; Jacquet et al. 2010
Disaster resilience	- Days to reopen ground-floor businesses - Fatalities per 10 000 residents	Fastest recovery at 8 000–12 000 inh./km²; slower above 20 000 inh./km² (flood and quake case-studies).	Medium-high densities balance local labour/supply with manageable logistics; extreme density hinders access.	Net residential density; street-network redundancy	Irajifar et al. 2016; Jahanbakhsh et al. 2020

Source: Authors elaboration

Performance curves are demonstrably non-linear, rather than monotonic, across most environmental and risk outcomes (Ewing & Cervero, 2010). Most indicators of resource efficiency (space-heating intensity, vehicle-kilometres travelled, and post-disaster reconstruction time) peak in neighbourhoods with medium-high densities of roughly 8 000–12 000 inhabitants km² (Irajifar, Sipe, & Alizadeh, 2016). Beyond that band, congestion, trip length and ambient heat often erase further density gains, undermining transport and health benefits (Dieleman & Wegener, 2004; Kühn, 2003; Banai & DePriest, 2014; Yang et al., 2021; Rode et al., 2014; Jones, Kammen, & Khalfan, 2019).

2.3.4 Composite frameworks

Because no single metric captures morphology, function and performance, recent work favours multi-indicator indices. The OECD *Compact-City Score* averages three pillars (population density, land-use mix, transit supply) (OECD, 2012). Zhuang and Zhou (2019) review 38 studies that apply Principal-Component Analysis or Entropy Weighting to distil dozens of variables into two or three orthogonal factors; these composite scores explain up to 65 percent of the variance in per-capita transport energy, compared with 30 percent for density alone. Yet composite indices face two challenges: *(i) subjective weighting, and (ii) transparency, as underlying parameters (e.g., distance decay in gravity models)* are often undocumented (Sikder et al., 2019).

Empirical measurement of "*compactness*" now rests on *six methodological clusters* that *recur* across the highest-ranked planning, urban-analytics and remote-sensing studies. The table below distils how some main research (from 2000-2025) operationalise each cluster, which indicators they prefer, the data they rely on, and what those choices mean for cross-study comparability.

Table 7. Composite frameworks

	Typical indicators and formula	Core data inputs	Strengths	Key limitations
Single-dimension density ratios	*Gross/net population density*; FAR = Σ floor area / parcel area; BCR = built	Cadastral parcels, LiDAR footprints, census blocks	Transparent; directly linked to zoning controls	Scale-sensitive; ignore internal voids/function (Tsai, 2005)

	footprint / parcel area			
Shape-based geometric indices	Circularity ratio, Perimeter²/Area, Urban boundary	Vectorised urban extent (MS Build-Footprint, night-light)	Captures sprawl ribbons & dendrites	Waterfront / valley cities penalized, needs boundary choice (Chen, 2011)
Spatial-statistics compactness	Global Moran's I; Geary's C; ANN = observed/expected nearest-neighbour distance	Raster built-intensity or building centroids	Handles irregular edges; good for multi-city panels	Bandwidth choice alters ranking by ±40 % (Sun et al., 2024)
Gravitation / distance-weighted	T-index; NCI = T / Tmax (size-neutral)	Pairwise centroid/district matrix; parcel intensity	Blends density and contiguity; size-normalised	$O(n^2)$ computation; water bodies distort (Zhao et al., 2011)
Functional mix and accessibility	Shannon/Sympson entropy of land-use grid; Transit Accessibility Index (TAI); % pop ≤ 15 min walk/PT to daily services	LULC rasters; GTFS; POI big data	Relates morphology to behaviour; predicts mode share better than raw density	Classification granularity inflates entropy; large POI APIs still uneven (OECD, 2019)
Composite and ML-driven indices	PCA-weighted Urban Compactness Index (UCI); Entropy-TOPSIS MUFCI; Random-forest latent compactness	Multi-layer stacks (density, mix, road graph, LU entropy, 3-D LiDAR)	Reduces 10-20 metrics to 1-score for policy dashboards; handles multi-collinearity	Weighting subjectivity: black-box ML hinders transferability (Liu et al., 2023)

Source: Authors' elaboration

*As we can see from the table above, in terms of the single-dimension density ratios (the zoning view), c*ensus and cadastral studies still begin with gross/net population density, floor-area ratio (FAR) and building-coverage ratio (BCR). Their attraction is direct traceability to planning controls (Steemers, 2003; Krehl et al., 2016).

*Geometric shape indices (reading the urban outline) heavily rely on r*emote sensing analysts measure the circularity ratio, perimeter-area quotient or fractal dimension of the built envelope to distinguish radial growth from tentacular sprawl (Chen, 2011).

Such shape metrics are resilient but penalise coastal or river-valley cities whose elongated morphology is environmentally constrained (Kühn, 2003).

Spatial statistics compactness measures compactness as clustering. Pixel-based studies increasingly deploy Global Moran's I, Geary's C or the Average Nearest-Neighbour (ANN) ratio to detect whether built-volume cells cluster more tightly than chance. However, Sun et al. (2024) demonstrate that Moran's I for Shanghai flips from positive to negative when the analysis lattice widens from **25 m to 100 m**, a stark illustration of scale dependence. *Gravitation and distance-weighted metrics (density × proximity) is used by u*rban geographers and borrow Newtonian logic, that the T-index sums pairwise parcel intensities divided by squared distance, while the Normalised Compactness Index (NCI) benchmarks that value against an equal area circle. Zhao (2011) finds NCI can separate Beijing (contiguous) from Wuhan (polyfocal) even though their population densities overlap. Because density alone reveals little about everyday life, high-impact transport papers turn to Shannon/Sympson land-use entropy and Transit Accessibility Indices (TAI). The OECD's accessibility benchmark counts the share of residents who reach daily services within a 15-minute walk / PT trip. Batista e Silva et al. (2020) show that once TAI enters carbon models, raw density often loses statistical significance. Planners need a single headline number, so scholars have built PCA-weighted or entropy-weighted Urban Compactness Indices (UCI, MUFCI) that roll morphology, land-mix and network variables into one score. Recent work even uses random-forest importance weights to create latent compactness features for 45 Canadian trains (Liu et al., 2023). These dashboards underpin policy documents such as the OECD's three-pillar KPI set (density, proximity, modal share), now adopted by over 50 metropolitan climate plans despite critiques that it under weights heat risk. Li et al. (2020) combines FAR with average height and sky-view factor to create a Volumetric Compactness Index (VCI) that explains 45 % of land surface temperature variance. Functional carbon linkage. Lu et al. (2021) report that every *1 %* rise in a Functional Compactness Index (FCI) lowers per-capita energy and transport CO_2 by 0.35 % after controlling for income in 287 Chinese cities.

Temporal metrics have been also introduced within methodology for measuring compactness. Mainly because the static snapshot approach ignores the *trajectory* of urban change. Remote sensing studies now track annual land take rates. Angel, Parent and Civco (2016) show Nairobi densifying by 13 percent / year (2000-2010) while Atlanta spread at –3 percent. The infill to expansion ratio (built-up growth inside the 2000 perimeter divided by total growth) distinguishes vertical densification from edge sprawl (OECD, 2018). When the ratio falls below 0.4, carbon gains from densification are typically erased by longer commuting distances (Newman & Kenworthy, 1989). Furthermore, all metrics suffer from the Modifiable Areal Unit Problem, values change when grid or administrative boundaries change (Openshaw, 1984). Thinh, Nguyen, Arlt and Heber (2002) showed compactness scores stabilise only at grid sizes near 500 × 500 m. Edge effects are equally pernicious, for example Montréal's administrative island appears twice as dense as its functional urban region once cross-border commuters are ignored (Dieleman & Wegener, 2004). Finally, data resolution matters, Sentinel-2 imagery (*100 mx100m cells*) detects expansion but not verticality; cadastral databases record FAR and BCR but update slowly. Researchers must therefore specify scale, source and vintage when reporting indicators.

2.4 The claimed benefits of compact urban form

Because every additional resident accommodated vertically is one fewer consuming greenfield land, compactness is credited with slowing peri-urban conversion. OECD modelling across trains shows that a one standard deviation rise in gross density (25 inh./ha) cut 2000-2014 land-take by 14 % (OECD, 2012). Angel, Lamson-Hall and Blanco (2016) reached a similar conclusion using satellite time-series for 120 global cities. Cities exceeding 10000 inh./km² expanded their footprints at half the rate of those below 4000 inh./km². Still, Seto et al. (2011) warn that densification can trigger leap-frog development in hinterlands when growth boundaries are weak, partially eroding the conservation gain. Higher population and employment densities shorten average trip distances and raise the viability of high-frequency transit (Ewing & Cervero, 2010). Meta-analysis of 50 US travel-survey datasets shows that each doubling of net density cuts household by 5-12 % once self-selection is controlled (Bartholomew & Ewing, 2009). European comparative work finds an elasticity plateau. Beyond roughly 100 inh./ha, congestion and competition for curb space offset further savings (Dieleman & Wegener, 2004). Active mobility dividends are strongest where density is paired with fine grain street networks. Cervero and Kockelman (1997) observed pedestrian mode share rising from 9 % to 28 % between the lowest and highest quintile of “3-D” neighbourhoods (density, diversity, design) in California.

Partly wall sharing reduces heat loss surfaces. British metering shows terraced dwellings consume 22 % less gas per m² than detached houses (Krehl, Siedentop & Kroll, 2016). Yet in hot humid climates cooling loads rise once the density is high, as ventilation corridors close (Kühn, 2003). High loads per pipe kilometre make district heating economically viable. Copenhagen’s post 1979 densification within its Finger Plan helped push the heat-network share above 95 %, halving per-capita space-heating CO_2 between 1990 and 2015 (Rode et al., 2014). *Embodied carbon* is a counter-point. life-cycle assessments of 90 Chinese projects find that towers above 15 storeys embed so much concrete that their carbon pay-back relative to mid-rise timber-hybrids exceeds 35 years (Jones, Kammen & Khalfan, 2019).

Density allows fixed costs to be spread across more users. Litman (2021) summarises 40 municipal budget audits, doubling service-area density lowers road maintenance cost per capita by approximately 10 %, sewer by 12 % and fire station outlays by 15 %. Ahlfeldt and Pietrostefani (2017) note diminishing returns. Above 15 000 inh./km², rising land prices push network retrofits (e.g., sub-surface water mains) into higher cost classes that erode savings. UNEP’s Life Cycle City study reports that compact European cities consume 15–20 % less construction material and 25 % less final energy per capita than sprawling North-American peers of similar GDP (UNEP, 2013). However, Bouzouina et al. (2022) detect “*outsourced*” footprints. Paris proper’s high density coincides with above average food kilometres and waste export to peri-urban incinerators. Agglomeration theory holds that dense labour markets foster matching and knowledge spill-overs. Glaeser (2011) showed a 3% wage premium for each log-unit increase in US metro density. Yet empirical work in German Mittelstädte finds that beyond 5000 jobs/km² productivity plateaus, possibly due to diseconomies such as office rents and congestion (Ahlfeldt & Pietrostefani, 2017). Cross-domain evidence suggests “more is better” holds only through a medium-high density band, roughly 8000–12 000 inh./km² (Irajifar, Sipe & Alizadeh, 2016). Cooling loads, congestion, land rents and disaster logistics all show threshold effects beyond which marginal benefits stall or reverse.

Density alone is thus an incomplete planning goal, coupling with urban design quality, green infrastructure and social equity safeguards is essential. Across land use, mobility, energy, infrastructure cost and even agglomeration wages, some *measurable* gains appear, but only up to a medium-high density window. Beyond that point, cooling loads grow, congestion erodes travel savings, construction carbon spikes and network retrofits become costlier.

2.5 Critiques and trade-offs

The same physical intensification that generates the canonical "wins" can, without counter-measures, produce a mirror set of costs. Six interlocking problem domains feature most often in high-impact empirical work.

First, the congestion, infrastructure overloading and service strain. Higher trip densities can outrun network capacity. Across European cities, average peak hour speeds fall by 0.9 km h^{-1} for every additional 5000 residents km^{-2} once road and bus lane kilometres are controlled (Dieleman & Wegener, 2004). Grid saturation also pushes latent utility upgrades. For example, Toronto's water utility reports that downtown pipe replacement costs rise 65 % beyond 12000 inh./km^2 because only deep tunnels can accommodate extra flow (Litman, 2021). Where fiscal capacity lags, *service quality can stagnate or decline*, witness Lagos Island's daily 12-hour water outage despite high density (Seto et al., 2011).

Second, housing affordability, gentrification and displacement. Urban economics predicts that land scarcity lifts rents faster than incomes. In 76 US metros 2000-2018, a one standard deviation rise in density raised median rents by 8 % after controlling for job growth (Glaeser & Gyourko, 2018). If additional floor space is delivered mainly as high-rise luxury units, exclusionary displacement follows. For example, Berlin's central districts lost 21 % of low-income households during its post 2010 densification wave (Ahlfeldt & Pietrostefani, 2017). In developing world settings, rising land values can trigger informal settlement eviction rather than inclusionary up zoning (Shirazi & Falahat, 2012).

Third, the public health externalities. One is o*vercrowding and ventilation.* For instance, COVID-19 mortality in New York City varied more with household crowding than with block group density, but crowding rose fastest in prewar retrofitted “loft-living” (Hamidi et al., 2020). Another key dimension is *heat-stress amplification.* Land-surface temperatures climb 0.7 °C for each 0.1 rise in BCR beyond 0.5 (Yang et al., 2021), raising nighttime mortality among elderly tenants in small units lacking cross ventilation (WHO, 2022). *Also, day light deprivation is common.* Hong Kong’s 35-storey blocks for instance, meet the density target but fail daylight factors, 60 % of bedrooms fall below the 1 % daylight code threshold (Yam, 2019).

Fourth, social-equity and spatial justice tensions rise. Green space and amenity often lag behind residential infill. In London’s densifying boroughs, public green area per capita fell from 9 to 5 m² between 2001 and 2021, whereas outer suburbs remained constant at 28 m² (EEA, 2016). Facility inequity can become entrenched. For example, Paris’s income-poorer northern arrondissements host 44 % of the population but only 27 % of the city’s public sports facilities (Bouzouina et al., 2022).

The *fifth* dimension is the quality-of-life perceptions versus quantitative efficiency gains. Even where objective indicators improve, residents may report lower satisfaction. A 22 city European survey found that subjectively rated “liveability” peaks at medium densities (10000 inh. /Km²) then falls, primarily due to privacy loss, noise and perceived crowding (Bramley et al., 2009). Okulicz-Kozaryn (2015) shows happiness scores bottoming in the densest US counties after income is held constant.

Finally, the governance capacity. The severity or avoidance of these downsides hinges on institutions. Singapore achieved 11000 inh./km² while maintaining 47 % green cover and a stable public housing cost ratio, owing to strong land banking, inclusionary quotas and mandatory through ventilation standards (Yeh & Huang, 2013). Conversely, Nairobi’s lack of enforcement allowed speculative subdivision, producing densities > 30 000 inh./km² with open space ratios < 2 %, now linked to recurrent cholera outbreaks (Jones et al., 2020).

What research shows is that *density intensifies both flows and frictions*. Adverse outcomes emerge once physical compaction outpaces network capacity, regulatory safeguards or redistributive instruments. *The most important empirical lesson is that* *compactness is a double-edge tool, its efficiency gains are real but not self-executing; institutional quality, affordable-housing policy, heat-mitigation design and equitable amenity provision decide whether the blade cuts social costs or benefits.*

2.6 Multi-hazard risk context for compact cities

Compact urbanism excels at packing social and economic life into a small footprint, but the very act of concentrating people, capital and lifelines alters the physics of every hazard.

2.6.1 Hazard families and compact-city pathways

Hydrometeorological hazards. In flash flood events sealed courtyards and podium slabs evacuate water too quickly; basements and metro shafts fill first. Copenhagen's July 2011 storm proved the point, the two densest boroughs (> 14 000 inh./km²) covered only 38 % of the city's land but absorbed 70 % of insured losses (Danish Insurance Association, 2012). Coastal or riverfront towers may protect unit counts, yet evacuees face dark lift shafts and flooded substations (Danish Insurance Association, 2012).

Climatological hazards. Low sky-view-factor (SVF) canyons trap long wave radiation. During Paris' 2003 heatwave excess mortality peaked in perimeter block arrondissements with floor-area ratios (FAR) above 4, where elderly residents could not afford air-conditioning (Vandentorren & Bretin, 2006). At the urban fringe, dense edges add ignition points for interface wildfires while evacuations funnel into two or three arterials.

Geophysical hazards. Pre-1970, tightly packed blocks are brittle under seismic load; modern high-rises fare better structurally but clog rescue logistics. The 2010 Haiti earthquake (collapse of poorly reinforced four- to eight-storey blocks) still holds the record fatality rate for an urban quake (Bilham, 2010). Liquefaction on reclaimed land or landslides on steep growth boundary hillsides compound risk.

Cascading / compound multi-hazards. Tokyo's August 2020 heatwave coincided with COVID-19 distancing that cut rail capacity; peak AC demand then forced rolling black-outs, disabling cooling exactly when needed (Sasaki et al., 2021). Compound events erase residual safety margins that single-hazard design often assumes.

Across these scenarios two mechanisms repeat. Concentration means that a single 100 × 100 m block can hold a portfolio worth USD 5 billion, so catastrophe models show earthquake loss per square kilometre rising almost exponentially as FAR climbs from two to six (Huber & Gulledge, 2011). Yet modulation shows that compactness can reduce per-capita loss when collective defences scale with density. For instance, Hong Kong's hillside super-blocks incorporate refuge floors, flood-proof lobbies and 72-hour back-up power, cutting flood deaths to one-tenth of equally wet, but less protected, Manila (Dey & Lewis, 2021).

Table 8. Multi-hazard in compact cities

Hazard	Morphology metric	Empirical finding	Source
Pluvial flood	Impervious cover	+10 % sealing gives +4 cm in 100-yr depth; curve flattens around 85 % sealing	Kain et al., 2022
Fluvial flood	Gross density	Losses ⁄ capita fall once density > 8 000 inh./km² *if* floodwalls ≥ Q50; otherwise, losses rise	Tan & Rinaldi, 2019
Heat mortality	SVF and tree canopy	SVF < 0.20 adds +0.9 °C night-time; +10 % canopy shaves 0.4 °C	Yang et al., 2021
Seismic casualties	Building age and height	Pre-1970 non-ductile mid-rise in dense grids increases fatality > 5 % of occupants	Bilham, 2010

Source: Authors' elaboration

The table above shows that empirical work is now teasing out thresholds. Remote-sensing for 220 world cities finds that each ten-percentage-point rise in impervious cover adds roughly four centimeters to the 100-year pluvial flood depth, with the curve flattening only beyond eighty-five per cent sealing (Kain et al., 2022). A pan-European study of 585 towns shows that fluvial losses per resident decline once density exceeds 8000 inhabitants km^{-2}, but only where floodwalls defend to at least a 50-year return period; without that engineering, the relationship reverses (Tan & Rinaldi, 2019). Heat-mortality research reveals that an SVF below 0.20 raises night-time air temperature by almost a degree, while every additional ten per cent of street-tree canopy cools about 0.4 °C (Yang et al., 2021). In seismic zones the global CATDAT database confirms that pre-1970 non-ductile concrete mid-rises in very tight grids still yield fatality rates above five per cent of occupants, the deadliest urban typology yet measured (Bilham, 2010).

National scale composite risk indices such as INFORM offer an outer envelope for local morphology studies. The INFORM Risk Index (2024) already distils the triad of *Hazard & Exposure*, *Vulnerability* and *Lack of Coping Capacity* into a single 0–10 score. It normalizes six natural perils (*earthquake, tsunami, flood, tropical cyclone, drought, epidemic*) plus conflict, providing a ready “national ceiling” against which local morphology can be benchmarked. The companion INFORM Climate-Change Risk Index keeps the same social fabric but projects the hazard–exposure pillar to 2050 and 2080 using IPCC RCP-SSP pathways (Joint Research Centre, 2023). Under the pessimistic pathway the number of countries in high or very-high crisis risk jumps from 36 today to 52 by mid-century, putting roughly 5.5 billion people into the top two risk classes. Drought grows fastest, but river-flood, coastal inundation and heat-wave exposures also surge. Because the social pillars are held at 2024 levels, the delta isolates the *additional* strain climate adds to existing compact-city vulnerabilities.

Dense morphology changes risk not by head count alone but by altering run-off, heat storage and pollutant residence times.

Table 9. Trade-offs

Morphology lever	Regulating service	Non-linear behaviour	References
Permeable surface (BSF/BCR etc.)	Infiltration and evapotranspiration	Run-off climbs near linearly once impervious > 60 %	Banai & DePriest 2014; Kim et al. 2022
SVF / H: W	Night-time cooling	UHI $\propto$ 1/SVF until SVF 0.20	Oke 1987; Yang et al. 2021
Tree canopy / vertical green	Cooling, PM deposition	Cooling gain plateaus beyond 30 % canopy	Ziter et al. 2019; Livesley et al. 2016

Deep street canyons	NO_2 dispersion	NO_2 doubles as H/W rises 1 to 4 under calm wind	Li et al. 2020; Barwise & Aybars 2020

Source: Authors' elaboration

Compact form alters hazard not by head-count alone but by changing morphology patterns such as run-off, heat storage and air-flow. Run-off rises almost linearly once impervious cover passes sixty per cent; at seventy per cent the local drainage network frequently fails unless compensated by green roofs, sponge pavements or retention plazas (Banai & DePriest, 2014; Kim et al., 2022). Nighttime UHI intensifies in proportion to the inverse sky-view factor until SVF approx. 0.20, after which stagnant strata form and ventilation falters. Medium height-to-width ratios (1.5–2) combined with thirty-per-cent canopy or high-albedo roofs slice 1.8 °C off mean radiant temperature in Los Angeles test districts (Oke, 1987; Ziter et al., 2019). Deep canyons double pedestrian-level NO_2 under calm wind; shallow recesses or stepped façades can halve residence time without sacrificing floor area (Li et al., 2020). Habitat connectivity collapses once impervious cover tops about seventy per cent within one-kilometre tiles, irrespective of headline park acreage (EEA, 2016).

2.6.2 Resilience, adaptation and "safe density" frameworks

Cities are no longer judged only by how efficiently they pack people and activities but by how compactness bends, not breaks, under stress. Bringing resilience theory into the density debate shifts the question from *how many* people per hectare to *under what conditions* those people can thrive when heat waves, cloud-bursts or earthquakes arrive.

Resistance is the ability to *withstand* disturbance (multi-hazards) without losing function and while increasing performance under stress. On the other hand, robustness preserves performance through redundancy or over-design. Adaptive capacity is the ability to *adjust* structure or behaviour after a shock. Resilience, in Holling's (1973) original sense and its urban elaborations (Vale & Campanella, 2005), is the overarching capacity to absorb, reorganise and continue operating across multiple disturbance cycles. Recognising the distinctions matters: density can raise resistance (shorter emergency-response times) yet erode robustness (few evacuation routes) unless adaptive capacity is built in.

Salat's network-fractal model treats urban fabric as a scale-free network where fine-grain plots, intermediate streets and regional arterials follow power-law size distributions (Salat, 2017). Such hierarchies improve both functional efficiency and shock propagation damping: removing a few local nodes barely alters global connectivity, whereas mono-scale super-blocks collapse if one nexus fails. Batty (2005) frames cities as complex adaptive systems that self-organise through local rules—arguing that resilience resides less in any single density number than in self-similar nested structures that can re-route flows when parts go down.

Borrowing from Rockström's "planetary boundaries," Walker et al. (2009) advocate defining threshold bands within which socio-ecological systems remain stable. Translated to morphology, a "safe density operating space" balances per-capita land-take reductions against escalating heat, flood or evacuation penalties (Alberti et al., 2003). Empirical findings suggest the band sits around 8 000-12 000 inh./km² for mid-latitude climates: below that, land and transport inefficiencies dominate; above it, cooling loads, congestion and multi-hazard losses rise non-linearly (Irajifar, Sipe & Alizadeh, 2016).

Table 10. Design strategies that make density "safe" from hazards

Hazard	Morphology/ infrastructure counter-measure	Proof-of-concept
Excess heat	• H/W ratios 1.5-2.0; • Ventilation corridors ≥ 60 m every 500 m; • 30 % tree-canopy or high-albedo roofs	**Wuhan's** "ventilation axes" cool ambient temperatures 1.3 °C on heat-alert days (Zhang et al., 2022)
Flooding	• 40 % permeable surface via pocket parks & porous paving; • Multi-use retention spaces (water plazas)	**Rotterdam's** Benthemplein square stores 1500 m³ stormwater without land loss (Ahern, 2011)
Seismic risk	• Confinement-reinforced mid-rise (≤ 12 storeys); • Vertical setback ratios after 50 m; • Distributed refuge terraces every 15 floors	**Santiago's** post-2010 code keeps collapse probability < 1/2 000 for 9-storey RC frames (Arup, 2018)
System failures	• Redundant district-energy loops; • Micro-grids with island mode; • Modular wastewater shafts	**Copenhagen's** 3-ring district heating grid-maintained supply during 2014 sub-station fire (Rode et al., 2014)

Source: Authors' elaboration

These measures illustrate that risk attenuation is a design variable, not a density constant.

The literature is coalescing around paradigms such as "*resilient density*" (Vale, 2016) and "climate positive density" (Salat & Lavigne, 2021), which confirms the mitigation logic of compactness with explicit adaptation safeguards. Mandatory green roof ratios, heat risk zoning overlays, seismic Floor-Area-Ratio caps tied to soil class, etc. In this regard, policy pilots include Melbourne's Green Factor Tool (City of Melbourne, 2021) developers earn extra plot ratio only when biophysical performance scores meet thresholds. Paris PLU bioclimatic revision (2023) new density bonuses contingent on through-ventilation façades and blue-green roofs. Although nascent, these policies operationalise safe-density ideas into enforceable metrics. Yang et al. (2021) integrated cooling loads with a heat-penalty curve linked to sky-view factor; optimum global FAR dropped from 4.0 to 3.2 once excess heat mortality costs were internalised. Kain et al. (2022) coupled 2-D flood hydraulics with embodied carbon accounts. The least carbon form at district scale was *not* the densest but a mid-rise, 35 %-permeable layout. Sun et al. (2024) used multi-objective genetic algorithms to balance VKT reduction against flood and heat penalties in Shanghai, producing a frontier from which planners can read the "safe density corridor." These quantitative hybrids are still rare and 'data hungry', but they point the way to evidence based safe density standards rather than 'rule of thumb' targets. Density is a *necessary* lever for low carbon urbanism, but as research shows only a resilience calibrated density, one nested inside thresholds for thermal comfort, inundation depth and structural safety, delivers a city that both mitigates climate change *and* survives it.

2.7 Transferability and contextual dependence

Global enthusiasm for compactness often glosses over the sheer heterogeneity of the places expected to implement it. The density that works brilliantly in Copenhagen can be catastrophic in Lagos, not because the arithmetic of floor area ratios changes, but because biophysical setting, institutional muscle, cultural practice and infrastructure baseline bend the outcome curve in different directions. Because climatic comfort, cultural norms and infrastructure capacity vary, the literature produces no universal threshold to be adapted. The OECD sets high density cells at ≥ 1500 inh./km² in Europe and East Asia but lowers the bar to 1000 inh./km² in Australia and North America (OECD, 2012). Churchman (1999) records Israelis calling 290 dw/ha high density, while the Dutch label 100 dw/ha "compact." Irajifar et al. (2016) find post disaster reconstruction fastest at *medium-high* population densities (8000–12000 inh./km²), arguing for an inverted-U resilience curve. These non-linearities fuel what Breheny (1997) calls the ***compact-city dilemma***, too little density squanders land and energy, too much strains infrastructure, amplifies multi-hazard risk. High-income, mid-latitude cities such as Vancouver or Copenhagen sit in temperate bands where summer heat is moderate, energy grids are decarbonising and population growth is stable. Their dense cores enjoy genuine net wins, lower VKT, modest cooling loads, efficient district-heating loops, because the climatic penalty side of the ledger stays small (Rode et al., 2014). Move the same block typology to the equatorial belt and the calculus flips. Year-round high humid temperatures mean that raising the building-coverage ratio can trap so much sensible heat that night time indoor temperatures exceed human comfort (Kusaka & Kimura, 2004). At the other extreme, shrinking post-industrial centres such as Detroit or Leipzig confront oversupplied infrastructure. Here the resilience challenge is not landing shortage but vacancy blight and storm water surcharge. These cities have found that *de-densification*, strategic insertion of green corridors, often yields higher welfare than infill (Haase & Nuissl, 2007). Outcomes hinge just as much on institutional capacity. Singapore and Hong Kong have very high gross densities with world-class drainage, building-control and public housing agencies. The Urban Redevelopment Authority ties density bonuses to mandatory green ratio and through ventilation targets, achieving both thermal comfort and affordability (Yeh & Huang, 2013). Kampala, by contrast, reaches similar headline densities through informal subdivision on flood-prone land where building codes go unenforced, producing recurrent cholera outbreaks and catastrophic wet-season losses (Jones, Wills, & Odiko, 2020). Fiscal bandwidth matters too. Berlin's post-reunification up zoning required a € 950 million sewer upgrade, well beyond the reach of most municipalities in the *Global South* (Litman, 2021). Culture and behaviour modulate form in ways planners often underestimate. Dutch and Danish cities exhibit high bicycle usage at *all* densities because cycling is a deeply embedded mobility culture; adding 5000 people per km² there translates directly into more walk-bike trips (Pucher & Buehler, 2012). In Phoenix, the same density lift delivers marginal mode shift because decades of auto centric norms persist. Likewise, norms of household size alter perceived overcrowding, a 70 m² flat accommodates 1.8 persons in Stockholm but 4.7 in Cairo (UN-Habitat, 2020), changing ventilation demand and social acceptability thresholds. Baseline infrastructure determines whether new residents' overload or optimise systems. Seoul's infill along existing heavy rail corridors cut per-capita VKT by 18 % (Cervero & Murakami, 2009); densifying Nairobi, which in 2022 had just 12 km of BRT, added more than half a million daily minibus trips and worsened congestion (Salon & Aligula, 2012). Analogously, the cooling benefit of a 20 % tree canopy target in Paris presumes irrigation capacity that drought-stressed cities such as Chennai cannot match.

These variances carry heavy research design and policy sequencing implications (Pojani & Stead, 2015). For policymakers, "safe" density is not a magic number but a *conditional range* attainable only after certain baselines, trunk drainage, reliable power, cadastral security, are in place. Yet, Neuman (2005) called for a "*universally understandable and, more importantly, quantifiable*" index that blends morphological, functional and governance factors. Population density, FAR and BCR remain attractive to regulators because they map zoning codes, taxation and impact-fee calculations. Yet BCR alone says nothing about open-space ratio, while FAR omits vertical intensity. *Policy therefore tends toward composite, tiered metrics*. For instance, The Paris *Plan* sets (i) a maximum BCR to ensure 30 percent permeable surface, (ii) a FAR cap, (iii) "mix coefficients" for ground-floor non-residential use, and (iv) *other target* for parcels within 300 m of a metro station (Ville de Paris, 2020*)*. Japan's *Transit-Oriented District Code* couples minimum FAR and minimum BCR , forcing landowners to use vertical rather than horizontal sprawl, and simultaneously mandates setback ratios to secure ventilation paths (MLIT, 2014; Suzuki, Cervero, & Iuchi, 2013). Researchers have experimented with Weighted Density Indices (Angel et al., 2021) and Composite Compactness Scores that integrate FAR, BCR, entropy and transit-access metrics (Zhuang & Zhou, 2019). *Adoption into statutory language, however, remains uneven*. Planners like the simplicity of FAR/BCR, while environmental regulators push for performance-based caps (per-capita CO_2, storm-water coefficients etc.). ***The gap***

between academic and regulatory clarity remains one of the central obstacles to mainstreaming compact city practice.

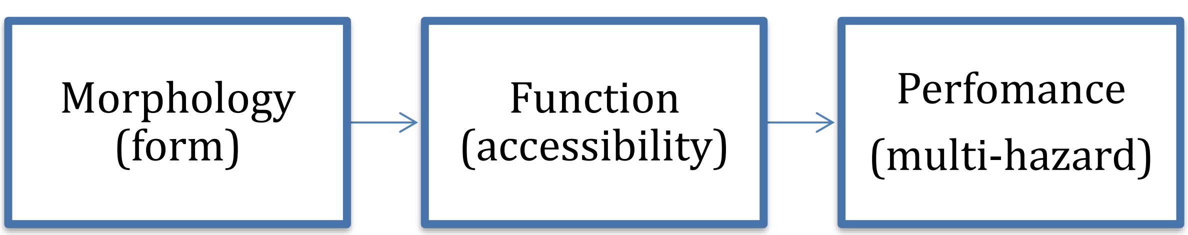
2.8 Global south rapidly urbanizing regions, the empirical evidence in Tirana

Urban form studies in Tirana has grown quickly over the last decade, yet it remains strikingly fragmented. The results indicate widespread urban expansion, considerable loss of vegetation, and increasing land consumption for built-up areas. (Haxhiu & Aliaj, 2025). The studies that do exist fall into five partially disconnected strands *(1) morphological change, (2) mobility and public realm (accessibility), (3) heat-and-green infrastructure, (4) flood exposure, and (5) seismic vulnerability*. Each employing its own data and spatial scale. Remote-sensing chronologies agree that Tirana's built footprint has trebled since 1990, but they disagree on *where* that growth occurs. Landsat/CA-Markov work by Ibrahimi and Nahaj (2014) charts a centrifugal pattern. Low-rise housing spilling along arterial corridors, while Abu-Samra and Abazi (2023), using Sentinel-2, highlight industrial enclaves beyond the Ring Road. Neither study drills below 30 m pixels, leaving parcel-scale form (e.g., Building-Coverage Ratio) unmeasured. A rare micro-morphology paper by Lico and Sklivanioti (2017) compares pre-1990 perimeter blocks with post-1995 peri-urban estates and finds that the former stay 1–1.5 °C cooler at night despite similar gross density, implying that *block geometry, not head-count density*, drives thermal comfort. A field audit of the central 4 km² by Nica and Kapllani (2019) records short average block lengths (< 100 m) but substantial pedestrian delay at arterials, suggesting that inherited permeability is being nullified by traffic dominance. A before-and-after study of Skanderbeg Square shows that removing through-traffic cut vehicle counts 60 % and increased stationary activity twelve-fold (Aliaj & Mema, 2020). Yet both papers are confined to the historic core; the rapidly densifying outer ring remains unmapped. Kasa (2023) applies the 15-minute city lens to central Tirana and finds a pronounced "proximity gap". While everyday retail and social venues are almost ubiquitous, 98 % of people can reach a café and 90 % a pharmacy within 15 minutes, critical services lag, with only 54 % of buildings inside a 15-minute walk of a secondary school and 27 % lacking swift access to public clinics. The study therefore warns that Tirana's headline density masks uneven functional reach, and recommends prioritizing new clinics and schools in the northeast and southwest quadrants where walk shed deficits coincide with lower income blocks (Kasa, 2023). The World Bank GFDRR climate risk atlas (2023) locates the harshest land-surface temperatures in census tracts. Building on that atlas, Bejko and Pojani (2022) find that canopy cover in those tracts averages < 5 % and that elderly heat-mortality rates are 30 % higher than the city mean. Their equity mapping is powerful but static. Cooling scenarios are stated heuristically ("add 20 % canopy") and are not linked to energy-balance modelling or to zoning incentives that could deliver such canopy. Hydrological GIS layers published by Hysa and Hoxha (2020) show that 58 % of parcels in the "very high" pluvial class coincide with informal settlement clusters in the western floodplain. Fluvial-flood simulations by Qirjazi and Bardhi (2021) warn that, under business-as-usual zoning, 20 % more households will sit inside the 100-year flood envelope by 2050. Both studies work with 30 m DEMs and CORINE land-cover categories, so they miss the sealed-surface detail that parcel BCR/FAR data would provide. Loss estimates remain at the "people exposed" level. No paper values downtime or critical-infrastructure risk. Post-event sampling by Çela et al. (2021) shows that 1970–1990 reinforced concrete frames exceed immediate occupancy drift limits, corroborating Bilham's (2010) earlier global warning that mid-rise masonry in dense grids is the deadliest typology. Yet seismic studies are building-specific; they stop at structural drift and do not scale up to urban morphology questions such as evacuation time in 25-storey clusters or the interaction of FAR height bonuses with soft soil amplification.

2.9 Summary of findings

The review shows that "compact city" research actually sprawls across three semi-disconnected domains.

Figure 3. Core research domains



Source: Authors' elaboration

Because most studies examine these domains in isolation, we still lack a transferable risk-sensitive compactness index able to tell planners *how much* density a specific place can carry *before* heat, flood, seismic or any other penalties outweigh the efficiency gains in a context specific city (Seto et al., 2011; WHO, 2022).

The last decade of scholarship has carried the compact-city debate well beyond the simple question of whether density is desirable; the conversation now revolves around how much density is appropriate, where it should be located, and under what safeguards it can remain safe. Yet four persistent blind spots continue to hamper both theory and practice.

First, the literature still offers only indicative hints. Findings agree that very low densities (< 30 inh./ha; FAR < 0.8) inflate land take, VKT and infrastructure costs, whereas very high densities (> 200 inh./ha; BCR > 0.70) amplify externalities, affordability stress and emergency-response delays (Bartholomew & Ewing 2009; OECD 2012). Between roughly 80 and 120 inh./ha the curves flatten, but the exact inflection drifts with climate, network capacity and institutional quality, leaving practitioners with rules-of-thumb rather than *prescriptive targets* (Ahlfeldt & Pietrostefani 2017).

Second, most empirical work still treats compactness through a single morphological lens (population density, BCR or FAR which are embedded in statutory traditional planning methods) and only later attaches performance indicators; multidimensional indices such as the OECD "density–proximity–transit" score or Batista e Silva's entropy–accessibility mix never embed hazard variables (OECD 2012; Kain et al. 2022). Third, because studies rarely track benefit and risk on the same axis, no empirically derived curve shows where densification is cancelled by rising heat-stress, flood depth or seismic loss; the often cited 8 000–12 000 inh./km² "sweet spot" is stitched together from single-hazard case studies rather than longitudinal, cross-climate evidence (Irajifar, Sipe & Alizadeh 2016; Yang et al. 2021). Finally, the discipline has only begun to explore compound shocks. Papers that overlay heat, flood and seismic exposure at a common resolution are almost absent, despite IPCC warnings that cascading events will become the norm (IPCC 2023).

The lineage shows a recurring pattern, each time density is promoted for one goal (land conservation, energy, competitiveness) a counter wave exposes new side-effects (heat, floods, social strain). What remains unresolved, and motivates the present research, is where those benefit–risk curves *cross*, and how context-specific design variables can be tuned to stay inside a safe *"compactness envelope."*

These omissions matter acutely for Tirana, a city that is densifying faster than its institutional and infrastructural buffers can keep pace. Apart from a handful of master-plan reports and student theses, no peer-reviewed study has yet combined Tirana's morphological data with functional accessibility metrics, let alone with multi-hazards overlays. Global density rules do not translate. The silence in the academic record therefore becomes an empirical gap and a policy risk, because the same density incentives that work in Barcelona or Copenhagen could, if un-adapted, push Tirana over its heat-stress or runoff thresholds.

2.10 Research gaps identified

A decade of research has moved the debate from "Is density good?" to "*When, where and how much?*" Yet five critical blind-spots continue to handicap both theory and practice. And finally, what does a compact city actually 'look like'? Four structural blind-spots continue to frustrate both scholarship and practice.

1. *Mono-dimensional metrics*. The empirical work still proxy's compactness with population density or FAR, then bolts on performance indicators post-hoc (Bartholomew & Ewing, 2009; OECD, 2012). Multidimensional attempts, such as the OECD score (density + proximity + transit) or Batista e Silva's entropy (accessibility composite) stop short of embedding *risk* variables (OECD, 2012; Batista e Silva et al., 2020). Conversely, hazard modelers favor exposure metrics that ignore othe rindicators (Kain et al., 2022; Ahlfeldt & Pietrostefani, 2017). ***A unified indicator that weights form, function and multi-hazard penalties is still missing.***

2. *No empirically derived benefit-to-risk curves* and patterns. We still lack longitudinal, cross-datasets studies (Irajifar, Sipe & Alizadeh, 2016; Yang et al., 2021).

3. *Sparse evidence on compound shocks and scale coupling*. Only a handful of papers overlay multiple hazards at a common resolution, despite IPCC (2023) warnings about cascading events. ***Interactions remain under explored, particularly with machine-learning tools able to detect non-linearities.***

4. *Global South studies are underrepresented.* There are only a few studies, coming from the Global South, which is rapidly urbanized such as Tirana, a city that is densifying faster than its institutional and infrastructural buffers are able to keep pace.

CHAPTER III: RESEARCH METHOD

3.1 Epistemological and theoretical orientation

The inquiry is rooted in a critical-realist ontology coupled with a pragmatic epistemology. Critical realism acknowledges that urban morphology, accessibility and hazards possess material properties independent of observation, yet the meaning ascribed to those properties is socially mediated (Sayer, 2010). Pragmatism legitimises the selective blending of methods whenever such "tool pluralism" advances problem-solving (Creswell & Creswell, 2018). The inquiry in this case is closer to solving the concrete dilemma of where the "safe-density window" lies for compact but still liveable and hazard-robust cities. Together these stances justify a mixed-method architecture in which morphometric measures, geospatial simulations and narratives each illuminate different facets of urban resilience without collapsing into a single metric. Placing the work in this dual frame permits the use of strictly quantitative spatial metrics side-by-side with interpretive readings of policy texts.

The thesis unfolds *deductively*. It begins with general propositions distilled from global compact city theory, that physical density (morphology) represents a function and performance issue within the city. Those propositions are translated into city level indicators (BSF, verticality, BCR, FAR, land-use entropy, accessibility, green infrastructure) and then tested against the selected cities dataset (Tirana as the anchor, together with other global cities such as Barcelona, Paris, Randstad, Amsterdam, Vienna, Zürich, Hamburg, Helsinki, Århus, San Francisco, Singapore, Manila and Dhaka). The results are fed back to theory, refining the initial safe-density window and explaining why morphological similarity can still produce divergent outcomes (Yin, 2018). Such a top-down route is warranted because policy debates in Albania and the wider region already articulate specific claims about compact development that require empirical corroboration rather than open-ended exploration.

Inductive part still surfaces as machine-learning diagnostics and threshold simulations expose patterns the theory did not foresee, forcing modest revisions to the safe density hypothesis. The entire chain is therefore best labelled as "*deductively driven with confirmatory inductive loops".*

3.2 Research method

This thesis adopts an explicitly mixed-methods design in which qualitative concept analysis and policy hermeneutics are interwoven with quantitative spatial metrics and machine-learning models. The qualitative strand is grounded in critical-realist reasoning and sifts peer reviewed literature and official planning texts to distil the core attributes and contested meanings of the "compact city" (Sayer, 2010; McKenzie, Brown & Milliken, 2021). Those attributes are then *operationalised* in the quantitative strand as morphometric and functional indicators (such as the Built Surface Fraction, Built Coverage Ratio, verticality (floors), floor-area ratio, land-use entropy, 15-minute accessibility indocators) and hazards' metrics (INFORM Risk in case of the global dataset, flood and seismic risk in case of Tirana dataset). Statistical testing proceeds in three tiers, linear mediation models for theory derived paths, random forest ensembles for non-linear discovery, and Monte Carlo simulations that identify tipping points where density erodes liveability (Breiman, 2001; Dovey & Pafka, 2017).

The strands are connected pragmatically, each addresses a facet of the central question, *where is the safe density window under multi-hazard stress* and findings are integrated at the interpretation stage within a single metric (Composite Compactness Index), following the convergent parallel logic recommended by Creswell and Creswell (2018). The result is a methodological architecture that mines the explanatory depth of qualitative inquiry while delivering the predictive power and generalisability expected of advanced quantitative modelling.

3.2.1 Conceptual work and qualitative framing

The investigation began with a structured concept analysis designed to clarify the multiple, sometimes contradictory, meanings attached to "compact city" development indicators and metrics in contemporary scholarship. Guided by the protocol outlined by McKenzie, Brown, and Milliken (2021), peer-reviewed material was gathered from ScienceDirect, Scopus, JSTOR and Google Scholar using the string "*compact* AND (city OR urban) AND (density OR form) AND (sustainability OR resilience)". Inclusion was limited to English-language journal articles and books that supplied an explicit definition or an operational metric for at least one study variable. Grey literature was excluded to protect academic rigour and to avoid circularity in later empirical stages. As seen in Chapter 2 of his study, morphological, functional and hazard profile signatures appeared repeatedly as moderators (Jabareen, 2013; Dempsey et al., 2012). These qualitative insights shaped the quantitative indicator set described below.

3.2.2 Quantitative framing

The empirical work is deliberately split in two main parts.

Phase I constructs a global realm, processing global cities (Barcelona, Paris, Vienna, Zürich, Hamburg, Helsinki, Århus, *Rotterdam, Amsterdam* (Randstad), Singapore, San Francisco, Manila, Dhaka, and the Albanian capital - Tirana) through the same workflow. Case selection balanced three criteria. First, several cities are formally branded compact city 'exemplars' in European or UN policy (European Commission, 2020; UN-Habitat, 2016). Second, contrasting development trajectories had to be represented. Singapore's top-down verticality and San Francisco's growth boundary model (California Planning Roundtable, 2018) contrast with the informal hyper density of Manila and Dhaka (UN-Habitat, 2020). Third, divergent hazard contexts, such as coastal flood in Rotterdam, seismic risk in San Francisco, cyclone exposure in Manila, were required so that the compactness resilience relationship could be tested under multiple hazards (Delta Programme, 2021; USGS, 2020; IPCC, 2022).

Phase II reruns the same indicator definitions on Tirana but, crucially, substitutes global open data with the high-resolution, legally binding layers contained in the municipality's development *plan* (PPV 2018, revised 2023). Below each phase is explained in detail.

A. Phase I – Global reference set

Table 11. Data used for every reference city[1]

Purpose	Open dataset	Resolution	Key fields used
Built-up Surface Fraction (BSF,	Global Dynamic Exposure (GDE) tiles[3]	*100m x 100m* tiles	footprint m², probabilistic height, tile ID

[1] *Note: All layers are project to EPSG 3857 for metric operations.*

[3] *Note: The GDE model provides a level of granularity that traditional aggregated exposure models (AEMs) cannot achieve, offering insights into individual buildings and their vulnerabilities. By employing this model, the research benefits from precise exposure data at the building level.*

100x100 m resolution)[2]			
Population	GHS-Pop 2023	100 m	residents per cell
Multi-hazard	INFORM Risk Index 2025 (+ Climate-Change add-on)	5 km (down-scaled by pop-weight)	Risk = hazard x exposure x vulnerability Multi hazard = multiple types of hazards
Ready functional indicators for accessibility	UN-Habitat Urban-Indicators DB – SDG 11.2.1, 11.7.1, etc.	city tables	Accessibility indicators for the global cities

Source: Authors' elaboration

Table 12. Indicator construction (global set)[4]

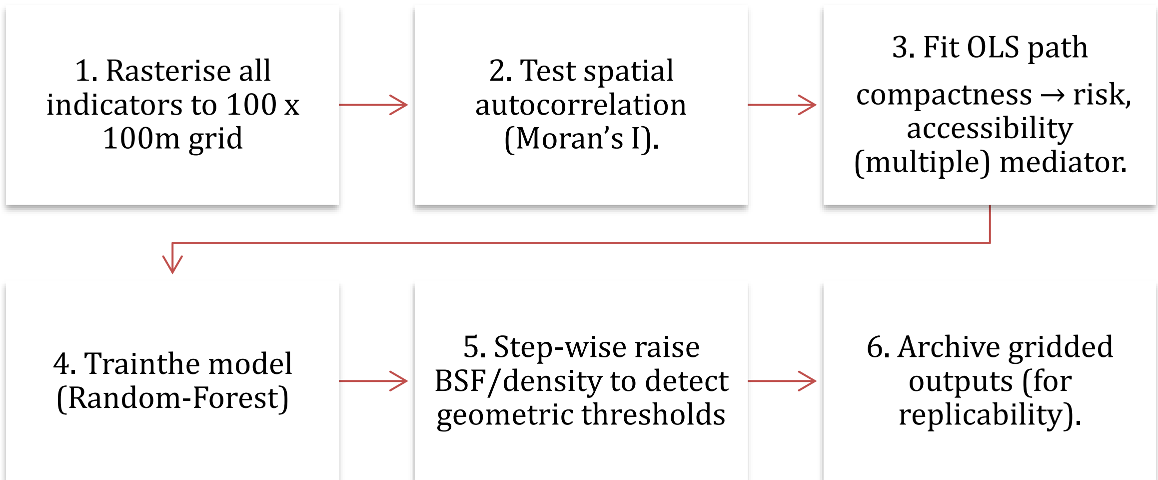
Dimension	Indicator	Derivation
Morphology	BSF 100 x100m - Built-up Surface Fraction; gross population density distributed probabilistically;	GDE tiles and Urban Atlas
Function	Shannon land-use entropy; PT-access %, open-space %, green-share %, tree-canopy %	Imported ready values from UN-Habitat tables
Risk	INFORM composite (0–10)	Direct import
Accessibility	Not recalculated at this scale (ready PT-access value sufficient)	

Source: Authors' elaboration

Figure 4. Processing routine for phase I

[2] *Note: For each city the Global Dynamic Exposure (GDE) model reports the share of every 100 × 100 m tile occupied by building footprints. This raster measure, commonly termed Built-up Surface Fraction in exposure-modelling literature is used here instead of a parcel-level BCR so that exactly the same geometry can be applied across all 12 reference cities.*

[4] *Note: All indicators are min–max normalised. A grid search (5 % increments) chooses weights that maximise adjusted R^2 between the Compact City Index and INFORM Risk; top combination = 40 % morphology, 35 % mixed use/greenscape, 25 % accessibility.*



Source: Authors' elaboration

B. Phase II – Tirana case (statutory local data)

Tirana layers come from the Local Development Plan (PPV 2018, revised 2023) geodatabase approved by Municipal Council Decision 132 / 2023.

Table 13. Tirana dataset

PPV layer	Scale	Used for
B_OBJ_1 building footprints & floors	1 : 1 000	BSF, verticality
B_PAR_1 parcel cadastre	1 : 2 000	legal lot area
U_INFR_A road & path network	1 : 2 000	walking graph
S_SERV_PT social-service points	1 : 2 000	amenity targets
E_GREEN_A existing + planned green	1 : 2 000	greenscape ratio
E_RISK_H flood + seismic raster	1 : 5 000	hazard overlay

Source: Authors' elaboration

Table 14. Locally computed indicators[5]

Dimension	Indicator	Calculation routine

[5] *Note: All parcel level outputs are rasterised to the common 100 m grid so Tirana feeds Phase I scripts unchanged.*

Morphology	Classical BSF, BCR, verticality ratio[6]	SQL, footprint - parcel join; verticality = floors∕√footprint
Land-use mix	Shannon entropy	Pandas
15-minute accessibility	% population within 15 min walk to: hospitals/clinics (HSP), preschools (PRS), park entries (PRK)	Steps: 1. Merge OSM walkable edges. 2. Assign 5 km h-¹ speed. 3. Intersect isochrones with PPV population-block centroids. 4. Compute coverage ratios and results in %
Green space	Green area per capita; tree-canopy %	Polygon overlaps E_GREEN_A ÷ population
Hazard class	none / flood / seismic / dual	Parcel centroid sample on E_RISK_H

Source: Authors' elaboration

The Tirana dataset delivers raw geometry and amenity points but no ready accessibility or compactness metrics. Therefore, the thesis reconstructs isochrone envelopes and parcel-entropy scores. In terms of cross-scale integrity, it's important to emphasize that indicator definitions, spatial resolution (100x100 m) and statistical routines are identical across *Phase I and Phase II.* Differences lie only in data provenance, global open data for 13 reference cities and PPV layers for Tirana. This symmetry guarantees that later comparisons reflect real morphological differences, *not methodological drift.*

3.3 Data architecture and indicator operationalization

All variables are rasterized to a 100x100m grid in EPSG 3857 so that spatial joins and statistical operations remain identical across phases and cities. Below are the global data sources used. The resulting 100x100m grid is also the geometry adopted by INFORM risk (2024) dataset and GHS-Pop, which means the BSF indicator can be joined to hazard and population layers without resampling. Using a fixed grid rather

[6] *Comparing the two confirms that mean BSF reproduces mean legal BCR to within ±2 percentage points in zones where both datasets overlap.*

than cadastral polygons eliminates cross-country inconsistencies in parcel definitions and maintains statistical equivalence across the case studies.

Table 15. Data sources used and tested

Data	Source
Building footprint data	Global Dynamic Exposure (GDE) model https://git.gfz-potsdam.de/globaldynamicexposure
Building Height (probabilistic model on floor space)	Global Dynamic Exposure (GDE) model https://git.gfz-potsdam.de/globaldynamicexposure
Green space %	Urban Atlas, part of the Copernicus Land Monitoring Service https://land.copernicus.eu/en/products/urban-atlas
Varierty of land use (e.g., residential, commercial, industrial)	Global Dynamic Exposure (GDE) model https://git.gfz-potsdam.de/globaldynamicexposure
Share of Urban Population with Convenient Access to Public Transport (%)	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
City Prosperity Index. Global CPI. Base Data. 2016	United Nations Human Settlement Programme (UN-Habitat), Global Urban Indicators Database 2020 https://data.unhabitat.org/
Share of urban population with convenient access to public transport (%) 2018-2020	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Land consumption rate and Built-Up area Per Capita Year 2 (m2 per person)	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Average share of the built-up area of cities that is open space for public use for all (%) 2020	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Average share of urban population with convenient access to open public spaces (%) 2020	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Average share of green area in city/urban area 1990-2020 and green area per capita 1990-2020 (m2/person)	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Tree canopy and green space % as per 2023	Urban Atlas, part of the Copernicus Land Monitoring Service, offers high-resolution data for land use and land cover in European cities, specifically within Functional Urban Areas (FUA). https://land.copernicus.eu/en/products/urban-atlas
Population density	Global Human Settlement Layer (GHS)

	https://human-settlement.emergency.copernicus.eu/ghs_pop2023.php
Build up area per capita (m2/person) and population growth rate	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
Social structure (Physician density per 1000 persons)	UN-Habitat Urban Indicators Database https://data.unhabitat.org/
INFORM RISK 2025: data on Hazard & exposure, vulnerability and lack of coping capacity (Data from 2020-2024)	https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk
Population data 2014-2024	https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk
Climate change projection data (2050 optimistic and pessimistic scenario on flood, coastal flood, drought, epidemic and conflicts)	https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Climate-Change/Results-and-data
Population projection data 2022-2050	https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Climate-Change/Results-and-data

Source: Authors elaboration

Built form is captured with the Global Dynamic Exposure (GDE) model, which fuses OpenStreetMap footprints with Global Human Settlement Layer cells inside a Quadtree structure, yielding probabilistic heights and completeness metadata for each 100x100m tile. Land-cover proportions and tree-canopy shares come from the Copernicus Urban Atlas 2020, whose 10-metre resolution is sufficient for intra-city estimation (Pesaresi & Politis, 2022; Crowley et al., 2020). Population counts rely on GHS-Pop 2023, ensuring that density calculations are internally consistent. Functional accessibility in the fourteen reference cities is taken directly from the UN-Habitat Urban-Indicators Database, which already supplies the percentage of residents within 400 metres of a public-transport stop and an open public space following the SDG 11.2.1 and 11.7.1 methodologies.

Tirana lacks those ready figures, so accessibility percentages are computed (OSM and PPV road segments are merged, a pedestrian impedance of 5 km h^{-1} is assigned, and pgRouting's *pgr_drivingDistance* function delineates fifteen-minute isochrones around every amenity category) (Geurs & van Wee, 2004).

Morphological indicators follow literature formulations. The BSF is eveny calculated as other cities. The building coverage ratio (BCR=Total Built Area / Total Land Area) is the footprint sum divided by parcel area, while the floor-area ratio (FAR) multiplies footprint by probabilistic height and divides by the same parcel area.

Shannon entropy ($Entropy\ Contribution_i = p_i \cdot ln(p_i)$ / $Entropy\ Index = -\sum (Entropy\ Contribution_i)$) is applied to the eight land use categories, producing a scale where zero equals mono-functionality and values above about 0.6 denote strongly mixed districts (Kabisch et al., 2016).

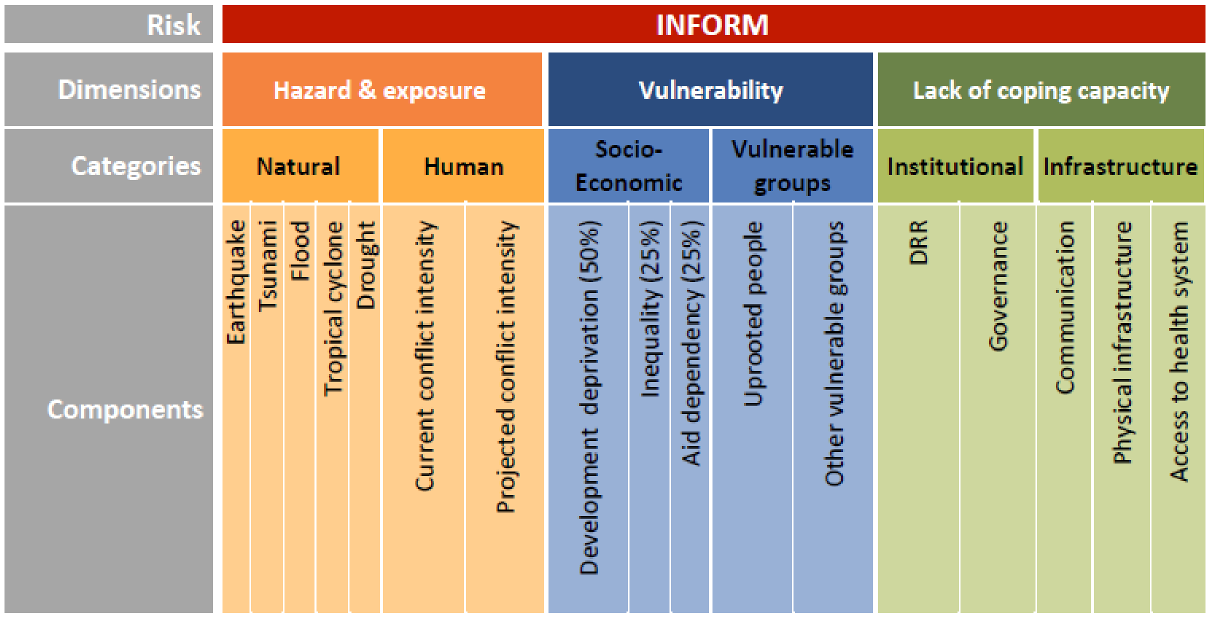
All variables are min–max normalized ($X_{normalized} = X - X_{min} / X_{max} - Xmin$), then a C*ompact City Index (CCI) is calculated for all cities*:

$$CCI = \sum_{i=1}^{n} \omega_i \, Xnormalised, i$$

CCI is formed by weighing morphology at forty per cent, mixed land use and green space at 35%, and accessibility at 25%. These weights were selected through a grid search that maximised the adjusted coefficient of determination between CCI and the external risk metric described below, echoing the optimisation logic recommended by Talen (2005). *High CCI values indicate cities that are denser, more compact, and better integrated with green spaces and higher accessibility.*

For global cities multi-hazard is taken directly from the INFORM Risk Index 2025, a transparent composite of multi-hazard exposure, socio-economic vulnerability and coping capacity released at five kilometer resolution and backed by open sub-indicators (INFORM, 2025).

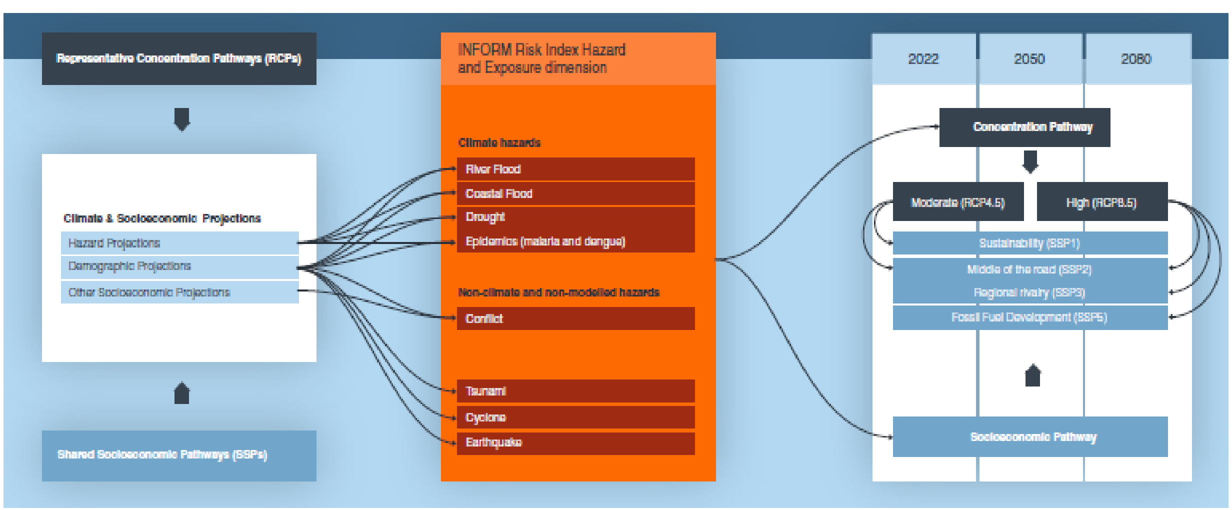
Figure 5. Hazards model data structure



Source: INFORM, 2025

Its climate-change extension projects the hazard pillar to mid-century using scenarios, allowing a forward stress test (IPCC, 2022). Although INFORM is officially country level, values are downscaled by population weighting so that urban cores inherit plausible risk scores, an approach validated in earlier metropolitan applications (Ribeiro et al., 2019).

Figure 6. INFORM Climate Change index methodology



Source: INFORM, 2025

Meantime, for Tirana, the dataset (PPV, 2023) allowed only to take the *flood and seismic risk* ready for calculation.

3.4. Statistical workflow

All quantitative operations are scripted in Python 3.12 inside reproducible Google Colab notebooks, an environment that guarantees both GPU capacity for ensemble learning and persistent links for code disclosure. Core libraries include pandas and geopandas for data wrangling, rasterio for grid manipulation, statsmodels for classical econometrics, scikit-learn for machine learning (Pedregosa et al., 2011), PySAL for spatial diagnostics, and SHAP for post-hoc model interpretation (Lundberg & Lee, 2017). The workflow unfolds in three logically connected tiers that map directly onto the thesis aim of testing compact city policies against multi hazard resilience.

The first tier translates the headline proposition in the global cities dataset. C*ities scoring higher on the Compact-City Index (CCI) exhibit lower INFORM Risk scores* into a system of ordinary least-squares (OLS) regressions. OLS is chosen because its linear-additive form delivers coefficients that can be interpreted as elasticities, a format readily understood by policy audiences (Wooldridge, 2015).

For Tirana, spatial autocorrelation is pre-tested with Moran's I, where significant, a spatial-lag term is added, following Anselin (1988), to avoid biased β-estimates. The four-step causal process test proposed by Baron and Kenny (1986) is implemented in *statsmodels*, with confidence bands obtained via 5000-draw percentile bootstrap (Efron & Tibshirani, 1993). This combination of parametric and resampling inference balances interpretability with robustness to non-normal residuals.

The second tier uncovers non-linear and interaction effects that linear models routinely miss. A random-forest regressor (Breiman, 2001) is therefore trained on the full indicator set; the resulting 100 m lattice is also the geometry adopted by INFORM risk rasters and GHS-Pop, which means the BSF indicator can be joined to hazard and population layers without resampling. Using a fixed grid rather than cadastral polygons eliminates cross-country inconsistencies in parcel definitions and maintains statistical equivalence across the case studies selection in the glocal cities dataset. Tenfold cross validation and a repeated stratified shuffle split guard against overfitting (Kuhn

& Johnson, 2013). Feature importance is first read from mean decrease in impurity, then validated with SHAP values, whose game-theoretic framework decomposes each prediction into additive contributions while retaining consistency and local accuracy (Lundberg & Lee, 2017).

Random forests were preferred over boosted trees or support-vector machines because (i) *they handle mixed-scale predictors without standardisation*, (ii) *they are insensitive to multi-collinearity* (Cutler et al., 2007), and (iii) *the thesis prioritises explanatory transparency over slight gains in root-mean-square error that more models might deliver* (Ribeiro et al., 2016).

The third tier operationalises the *policy-testing* element by running controlled simulations of the two levers built-coverage ratio and population density, across their observed city-wide distributions while holding all other predictors at median values. For each 0.02 increment in BSF the calibrated random forest model recomputes expected accessibility and multi-hazard performance. The tipping-point algorithm proposed by Dovey and Pafka (2017) flags the coordinate at which any variable exhibits its first order derivative worse than −0.25. Confidence envelopes are generated through 1000 *Monte-Carlo* draws of model residuals, ensuring that identified thresholds survive parameter uncertainty.

Tirana receives an additional, parcel-scale diagnostic because its municipal PPV database permits metre-level hazard coding. A multinomial logistic regression (Hosmer et al., 2013) predicts the categorical hazard class (none, single (either flood or seismic), or dual) from the composite compactness index, parcel entropy and height-to-width ratio. Pseudo-R^2 (McFadden) and likelihood-ratio χ^2 test global fit, while Brant tests confirm the proportional-odds assumption. The choice of a logit link over a tree-based classifier is deliberate. Coefficients retain the log odds structure vital for planning ordinances that must specify how much an incremental rise in compactness multiplies exposure probability. Collinearity is monitored throughout with generalised variance-inflation factors. No predictor exceeds the conservative threshold of 5, in line with Dormann et al. (2013). All numeric inputs are centred and scaled before entry into interaction terms, reducing estimator variance (Aiken & West, 1991). Outliers identified by Cook's distance are retained but down weighted, reflecting the pragmatic stance that extreme but genuine urban forms (Dhaka's hyper dense wards, for example) carry substantive information rather than error (Rousseeuw & Hubert, 2011).

This three-tier structure (*OLS-mediation for linear clarity, random forests for non-linear discovery, and simulation for actionable thresholds*) provides a triangulated statistical test bed.

Table 16. Matrix of the quantitative workflow

	Statistical / spatial routine	Purpose in the research logic
1-a	Global Moran's I	Detect spatial autocorrelation before applying any global regression
1-b	OLS regression - Multi-hazard Risk = $\beta_0 + \beta_1$ CCI + ε	Quantify the headline compactness–risk elasticity
1-c	Four step mediation	Test whether greenspace channels the CCI - hazard effect
2-a	Random forest regressor	Surface non-linearities and interactions among all indicators
2-b	Partial dependence and ICE curves for top 5 predictors	Visualise marginal and cross-term effects for policy
3-a	Monte Carlo simulation grid	Locate tipping points
3-b	Two-way sensitivity tornado (± 20 %) on indicator weights in CCI	Show that safe-density window does not hinge on arbitrary weights
4-Tirana	Multinomial logit, hazard-class	Fine-scale test where official PPV data exist

Source: Authors' elaboration

3.5 Reliability, validity and limitation

Internal reliability is strong, as training testing splits of the random forest models retain R^2 values above 0.90, and missing values are handled with multiple imputation by chained equations, a technique shown to stabilize parameter estimates in complex datasets (Azur et al., 2011). Construct validity rests on the widespread acceptance of morphological proxies (Dempsey et al., 2012) and on INFORM's dataset demonstrated coverage of physical and institutional vulnerability spectra (Ribeiro et al., 2019). Nevertheless, all global indicators remain snapshots from the years 2019–2025, so temporal generalization is constrained. The main methodological limitations stem from resolution mismatch, as open data may smooth fine grain differences inside the larger metropolitan regions and from the linear weighting scheme, which inevitably under plays complex feedback between form and other metrics (Kabisch et al., 2016). Scenario uncertainty in the INFORM database of climate extension is acknowledged, and sensitivity tests bracket results under optimistic and pessimistic pathways.

CHAPTER IV: RESULT ANALYSIS

4.1 Global dataset, case-study portraits

Barcelona, Spain. Barcelona has layered three successive planning moments onto a limited territorial canvas, the nineteenth-century Eixample grid, the 1992 Olympic brown-field renewals, and since 2016 the Superilles (Super-blocks) programme that reallocates up to 60 % of carriageway space to public life and active mobility (Busquets, 2005; Capel, 2006). The current Metropolitan Urban Master Plan translates this ethos into enforceable rules mixed-use ground floors, façade continuity, and block perimeters capped at around 400 m, while Spain's 2008 Ley del Suelo grants density bonuses only when schemes dedicate a set share to social housing (Gobierno de España, 2008). The result inside the municipal boundary is one of Europe's highest net densities and a fine-grained land-use mix served by a radial–grid metro network; yet the wider region is simultaneously exporting population to low-density peri-urban districts, sharpening a core periphery contradiction (Garcia-López & Muñiz Olivera, 2007). That tension surfaces in Barcelona's multi-hazard profile, the multi-hazard composite is a modest 2.3 (low systemic risk) thanks to robust governance, but pipeline ICCRI modelling flags a steep rise in flash-flood and heatwave frequency by 2050 (INFORM, 2024; UN-Habitat, 2020). Storm-water stress is already evident in older inner-city drainage networks, while the high plot coverage typical of example blocks constrains space for renewable installations or green corridors, complicating the city's Climate Action Plan goal of net-zero by 2050 (Ajuntament de Barcelona, 2021). Barcelona therefore illustrates both the virtues and the limits of planned compactness, high connectivity, resource efficiency and modal shift on the one hand, on the other, persistent socio-spatial inequality, ageing housing stock, and a vulnerability to pluvial flooding that densification alone cannot resolve.

Randstad, Netherland (Amsterdam and Rotterdam). Dutch national spatial policy has for six decades pursued de-concentration concentration, a ring of medium-sized cities that absorbs growth while the agrarian "Green Heart" remains largely untouched (Kühn, 2003; Van der Valk & Faludi, 1992). The approach is codified in Randstad 2040, which couples strict floor-area-ratio (FAR) ceilings inside the Green Heart to systematic transit-oriented up-zoning around rail hubs. The linchpin is

RandstadRail, an inter-urban light rail/metro spine linking The Hague, Zoetermeer and Rotterdam. Conceived during the 1990s, the project survived cost overruns and institutional fragmentation by phasing construction, "good-enough" starter segments with contract options for later loops, thereby preserving political coalitions and hedging demand risk (Giezen, Bertolini & Salet, 2014, pp. 414-418). By 2012 the system carried over 120,000 passenger trips per day, triggering a measurable modal shift from the A4/A13 motorways and unlocking TOD enclaves such as Beurs, Leidschendam-Voorburg and Lansingerland-Zoetermeer (Ministerie IenW, 2021). Densities inside an 800 m catchment now average 65–95 inh./ha; zoning requires ≥ 30 % non-residential floor space in new precincts and applies a "green-first" hierarchy before additional floor area is released. Yet success reveals a resilience paradox. The Netherlands posts a low multi-hazard baseline risk of 2.1, but ICCRI's pessimistic 2050 run lifts the hazard pillar to 3.3, because compound river and coastal flood probabilities begin to outstrip even Dutch design standards (European Commission, 2025). Rotterdam's Climate Adaptation Plan stitches blue-green corridors along polder edges and raises quay walls, but execution remains uneven across the constellation of municipalities (Snellen & Hilbers, 2007; Arundel & Ronald, 2017). Thus, Randstad demonstrates how megaregional compactness, transit investment and landscape conservation can be mutually reinforcing, provided governance capacity and adaptive finance keep pace with accelerating climate risk.

Table 17. Key planning instruments in Ranstad

Instrument	Compact city lever	Current application
Green Heart zoning	Urban containment	FAR ≤ 0.2 and mandatory agri-use covenants
Station-area TOD code	Density transfer	Min. 6 floors and 30 % non-residential within 800 m of RandstadRail stops
Randstad incremental delivery contract	Adaptive infrastructure	3 building stages (2004, 2007, 2012) with option clauses for loop extensions
Rotterdam Climate Adaptation Plan	Resilience overlay	"Sponge city" polder retrofits and floodable parks along the Schie

Source: Authors' elaboration

***Amsterdam, the northern vertex*.** Within the Randstad diamond Amsterdam has, since the 1996 Plan, pursued "*intensification without sprawl*", recycling docklands and constructing high density artificial island extensions so that roughly 70 % of new housing remains inside the A-ring motorway (Rapoport, 2014). Net densities in IJburg and Java-eiland exceed 100 inh./ha, yet every dwelling lies within 400 m of a tram/metro stop and 300 m of public open space (Municipality of Amsterdam, 2020). The 2018 North-South Metro reinforced this pattern, channeling fresh floor area into nodes such as Zuidas and Buikslotermeer while the medieval core accepts only maintenance traffic (Bertolini & Le Clercq, 2003). A 400 km protected cycle grid already absorbs 36 % of daily trips, and development permits must provide ≥ 1.3 secure cycle spaces per resident (Gehl, 2010). On the regional scale, a Schiphol–Amsterdam–Almere BRT corridor is being built to complete a high-frequency "one-hour metropolis" (van der Waard et al., 2019). Climate-proof density experiments push adaptation further, the 2050 strategy assigns roofs a 60 mm rain storage quota, and any plot with BCR > 0.70 must offset residual run-off through offsite blue-green investment (Gemeente Amsterdam, 2021). These provisions convert canal front blocks into "sponge districts," buffering flash floods while sustaining the high plot ratios that land scarcity demands. Amsterdam anchors 16 % of Dutch GDP on 4 % of its land (CBS, 2022). Its multi-hazard baseline remains low (2.1), yet ICCRI projects a modest +1.0 rise by 2050, mainly pluvial flooding and heat stress. The case therefore illustrates the strategic value of water sensitive urban codes in a compact, low-lying metropolis. Randstad and Amsterdam operationalise the compact city doctrine at both megaregional and municipal scales, showing how rail anchored density transfers and strict landscape containment can coexist, but they equally expose the escalating hydraulic risks that even world-class infrastructure must now confront.

***Paris, France*.** For more than a century Paris has maintained a deliberately compact urban fabric built on high FAR perimeter blocks and an exceptionally fine-grained public-transport lattice. The current *Plan Local d'Urbanisme bioclimatique* (2023) locks in that tradition by setting minimum plot densities, tightening energy-performance envelopes and reserving 40 % of new floor space for social or intermediate-rent housing within the Boulevard Périphérique (Ville de Paris, 2023). At the metropolitan scale the €36 billion Grand Paris Express, 200 km of new orbital and radial metro scheduled for full operation by 2030, will place 90 % of Île-de-France residents within a 600 m walk of heavy rail, allowing another 2.5 million inhabitants to live and work without car dependence (Sulaiman, 2023; Akitani & Leclercq, 2022). These mobility investments support average inner-city densities of roughly 20 000 inh./km², among the highest in the OECD, while a statutory greenbelt (ceinture verte) restrains outward expansion (OECD, 2021). Compactness, however, sits uneasily alongside rising climate and social pressures. Seine River flood return intervals are shortening, forcing retrofits of underground storm tanks beneath Haussmannian boulevards and metro interchanges (Le Brun & Carr, 2019). Heat island intensity already adds up to 8 °C on peak nights, and multi-hazard projections flag Paris for the fastest increase in heat-related mortality among EU-15 capitals by midcentury despite France's current "low" composite risk score of 2.4 (JRC, 2024). The 2018 Plan Climat-Air-Énergie therefore requires every major redevelopment to integrate a 30 % vegetated surface factor, rooftop gardens, living walls or permeable courtyards, and to deliver net zero operational carbon by 2050 (Mairie de Paris, 2018). Yet social equity gaps widen as regulated rents lag behind land values around new metro hubs. Competition for subsidised units has doubled since 2015, prompting the city to experiment with anticyclical land trusts and 99-year leases (Bourgeois, 2022). Paris thus exemplifies a mature European compact city model in which stringent density mandates, transit megaprojects and green infrastructure quotas are mutually reinforcing, while simultaneously exposing the twin vulnerabilities of heat stress and housing affordability that intensifying density can magnify if adaptive capacity and social safeguards do not keep pace.

***Århus, Denmark*.** Denmark's second city channels growth through brownfield compaction anchored by district heating grids and a light rail spine. The Climate Plan 2030 ties every new m² to flood-volume compensation and net-positive energy standards (Danish Ministry of Environment, 2021). Compact blocks in harbour conversion zones reach FAR 4 but escalating rents have rekindled debate over inclusionary quotas. National multi-hazard risk remains 1.4, very low, thanks to municipal coping capacity (governance). Århus exemplifies forward-thinking in resilience and sustainability with its Climate Plan 2030, which integrates renewable energy solutions and flood risk management strategies. The city's compact design facilitates efficient public transport use and walkability, reducing emissions (Danish Ministry of Environment, 2021). However, challenges such as rising housing costs and limited affordable housing options threaten social equity, especially as Århus grows rapidly (UN-Habitat, 2020). Urban sustainability is further bolstered by Århus's urban regeneration projects, which retrofit older neighborhoods with energy-efficient infrastructure while preserving cultural heritage. Yet, achieving equitable urban access remains a key issue for policymakers.

***Helsinki, Finland*.** The Carbon Neutral Helsinki 2035 roadmap superimposes linear TOD corridors on pre-war tram fabrics and mandates that each detailed plan demonstrates a 30 % green factor. The city leverages its shoreline infill programme to create mixed-use, mid-rise (6–8 storey) islands connected by metro extensions, but must still budget for rising Baltic surge levels (City of Helsinki, 2021; Haapala et al., 2021). Finland's multi-hazard risk index is 1.5, with river flood signals muted but coastal risk prominent. Helsinki's Carbon Neutral Helsinki 2035 initiative aligns with its compact city framework, aiming to reduce emissions through renewable energy systems, energy-efficient building retrofits, and a significant expansion of cycling infrastructure (City of Helsinki, 2021). The Metropole Plan emphasizes densification alongside green space integration, ensuring ecological balance in urban expansion. However, climate-induced risks, such as coastal flooding, challenge the city's resilience. Helsinki's reliance on advanced urban planning mitigates some of these risks, but adapting to sea-level rise remains a priority (Haapala et al., 2021). Social disparities, particularly in access to affordable housing in denser districts, are growing issues, despite the city's efforts toward inclusivity.

***Hamburg, Germany*.** "Inner Development before Outer Development" channels growth into the HafenCity and Wilhelmsburg islands, while the Green Network Plan aims to connect every resident to a major park within 300 m (German Federal Ministry for the Environment, 2022). Stringent energy codes and value-capture finance vertical mixed-use towers along the Elbe, but socio-spatial polarisation remains. Low-income quarters sit far from high-skill port logistics jobs. Multi-hazard risk marks Germany 2.4, low; coastal flood deltas lift that to mid-low by 2050. Hamburg integrates resilience and sustainability through its Green Network Plan, which connects green spaces across the city, improving biodiversity and mitigating heat islands. The city's Renewable

Hamburg Initiative aims to expand wind and solar energy production, supporting its goal of achieving climate neutrality by 2045 (German Federal Ministry for the Environment, 2022). The “Inner-Development Before Outer-Development” policy prioritizes densification while preserving natural landscapes. However, Hamburg faces challenges such as rising real estate costs and uneven access to green spaces, particularly in lower-income districts (OECD, 2021). The city's role as a port hub also necessitates ongoing efforts to reduce industrial emissions and enhance flood defenses against rising sea levels.

Zürich, Switzerland**.** Federal Agglomeration Funds reward cantons that densify within Urban Growth Boundaries. Zürich’s local plan layers maximum parking ratios (0.25/flat) and daylight envelope controls onto that framework (UN-Habitat, 2020). Mandatory design competitions generate high public-realm quality but sustain one of Europe’s highest housing costs. Multi-hazard risk is 1.4, yet glacial lake outburst floods threaten alpine catchments beyond 2050 (OECD, 2021). Switzerland's Agglomeration Policy and Urban Growth Boundary (UGB) principles, implemented through projects like Lausanne-Morges and Zurich, exemplify compact city planning in high-density urban regions. The policies prioritize densification within established boundaries while preserving agricultural and natural landscapes. Zurich's compact urban form is characterized by high population density, mixed land use, and robust public transport systems. The integration of green corridors and pedestrian-friendly designs enhances sustainability and livability, making Zurich a leading example of balancing urban growth with ecological preservation. Zurich’s Agglomeration Project continues to integrate compactness with sustainability by promoting energy-efficient developments and sustainable transport systems. The city’s Urban Growth Boundary policy protects agricultural land while supporting densification within established zones (UN-Habitat, 2020). Zurich has adopted innovative measures such as green roofs and solar installations, reducing its carbon footprint. However, its high cost of living presents barriers to equitable housing access, complicating efforts to ensure inclusive urban development. Climate risks, particularly heatwaves, highlight the need for further investment in green corridors and adaptive cooling measures (OECD, 2021).

San Francisco, USA**.** On the American West Coast San Francisco has become a laboratory for “smart growth” where state level mandates, regional transport pricing and local form based codes converge on a de facto compact city agenda. California's SB 375 (2008) obliges every metropolitan planning organisation to align land-use scenarios with greenhouse gas targets. *Plan Bay Area 2040* translates that requirement into infill housing quotas tethered to vehicle-miles-travelled caps, effectively forcing 77 % of new dwellings inside the existing urban footprint (Metropolitan Transportation Commission [MTC], 2017). Within the city, a seismic ordinance (1989) triggered widespread retrofitting of "soft story" parcels and, through the *Transferable Development Rights* programme, channelled additional floor-area ratio (FAR) from unreinforced masonry buildings to transit rich lots around Market Street and SoMa, lifting local densities to 150–200 inh./ha without breaching historic envelopes (City and County of San Francisco [CCSF], 2020). Funding and design innovation complement those regulatory levers. Tax-increment *Community Benefit Districts* along Valencia, Polk and Castro Streets have used value uplift to finance parklets, protected cycle lanes and façade greening, while the *Regional Innovation Cluster* initiative offers low-interest bonds to adaptive-reuse projects provided they meet a 3.5 FAR and mixed-employment ratio (U.S. Economic Development Administration, 2019). These mechanisms collectively underpin a walk-and-transit mode share of 55 %, the highest of any large U.S. metro (SFCTA, 2022). Nonetheless San Francisco's hazard bundle is widening. United States has overall a multi-hazard composite of 3.2 = medium, but downscaled assessments for the Pacific margin approach 4.0 once the joint probabilities of M ≥ 7.0 earthquakes, drought driven wildfires and extreme heat are factored in (Cal OES, 2023). The city's *Hazard and Climate Resilience Plan* (2020) therefore folds compactness into a broader resilience matrix that mandates micro-grid readiness for dense neighbourhoods, cool-roof retrofits on any plot exceeding 0.6 BCR, and 50 hectares of new permeable open space by 2030 to buffer flash-flood pulses amplified by drought–deluge swings (CCSF, 2020). San Francisco thus illustrates both the promise and fragility of U.S. compact-city practice. Statutory and fiscal instruments can deliver high-density, mixed-use districts even in a highly decentralised governance system, yet the benefits are continually tested by compound seismic–climate risks that demand equally sophisticated adaptation finance and regional coordination.

Vienna, Austria**.** A 100-year social housing tradition permits FAR 3–4 without displacement and the Smart City Framework ties each density bonus to renewable heat or tree-canopy uplift. Pilots adapt Barcelona's superblock logic, closing every third street to through-traffic. Austria scores 1.8, very low, on multi-hazards, with only marginal rises anticipated.

***Singapore*.** The city-state operationalises compactness through plot ratio auctions, obligatory sky gardens and 47 % green cover, holding average net density at 7800 inh km² while distributing public housing across transport hubs (URA, 2021). A coastal protection levy addresses long range inundation, but multi-hazard still logs the world's lowest composite at 0.7. Singapore epitomizes efficient land use with one of the world's highest population densities (7,804 people per square kilometer in 2021). Its compact city model is characterized by vertical development, high floor area ratios (FAR), and meticulous land use planning. Mixed-use neighborhoods ensure proximity to services, supporting compactness and reducing travel demands (Urban Redevelopment Authority, 2021).

***Manila, Philippines*.** Metro Manila's density exceeds 40000 inh km² in several barangays, but informal settlement growth outpaces zoning enforcement, compromising drainage and public space ratios (ADB, 2021). The Build-Build-Build rail plan may redirect growth, yet multihazard ranks the Philippines 5.3, high, near the asymptotic ceiling.

***Dhaka, Bangladesh*.** Densities above 45000 inh km² and sub-2 m² green space per capita represent compactness through necessity rather than design (World Bank, 2020). The Detailed Area Plan 2022 introduces a FAR grid linked to road width, but enforcement gaps persist. Bangladesh records 6.8, very high risk, and an 8.9 climate baseline, top-five globally for compound flood-heat stress.

4.1.1 Statutory morphology digest

The analysis also shows that many countries and metropolitan areas still conceive compact city policies in terms *of environmental policy* (that is, simply as a way to preserve agricultural and natural land). Consequently, many policy instruments are still traditional land-use measures, which are mostly regulatory. In fact, few policies explicitly make economic growth a policy goal. It is essential to encourage policy makers and experts to see compact city as a multi-objective policy approach. Cities like Paris and Zurich emphasize green infrastructure and energy efficiency. Randstad and

Hamburg focus on climate resilience through water management and renewable energy. Helsinki and Århus lead in integrating compact urban forms with low-carbon policies. Paris exhibits some of the highest urban densities globally, with an average of 20,000 people per square kilometer in central districts. This density fosters efficient land use but exacerbates challenges like housing affordability and green space scarcity (OECD, 2021). Paris also integrates diverse land use, ensuring proximity to essential services. Barcelona similarly emphasizes high-density urban planning within its municipal boundaries, though suburban sprawl at the metropolitan scale undermines its compactness. The city's mixed-use neighborhoods like Ciutat Vella and Les Corts demonstrate effective urban continuity (Busquets, 2005; Garcia-López & Muñiz Olivera, 2007). Randstad offers a unique approach with its polycentric structure, balancing high-density nodes like Rotterdam with the preservation of the "Green Heart." This strategy ensures compactness while maintaining ecological sustainability (Kühn, 2003).

Table 18. Legally binding morphological design regulations for each city

City (and key instrument)	Legal term for site coverage	Max. coverage[7]	Max. FAR / plot-ratio[8]	Plan / observed density	Source
Barcelona – *PGM* (Zone 13 Example)	*Ocupació màxima*	0.60	3.2 (housing); 4.0 (mixed)	250 inh./ha (Ciutat Vella actual)	Ajuntament de Barcelona, 2020
Randstad – Rotterdam CS catchment (*Bestemmingsplan Binnenstad*)	*Bebouwingspercentage*	0.80	5.5 core parcels	95 inh./ha (net, 2021 CBS)	Gemeente Rotterdam, 2021
Amsterdam – CI-1 inner belt (*Omgevingsplan*)	idem	0.85	7.0 (plot-ratio)	105 inh./ha (net)	Municipality of Amsterdam, 2022
Paris – *PLU bioclimatique*,	*CES*	0.60	3.0 (objective FAR)	200 inh./ha	Ville de Paris, 2024

[7] *The figure planners themselves quote (net inhabitants per hectare unless the local master plan states “gross”.*

[8] *Plan-based maximum FAR (or plot-ratio) – i.e. the highest bulk the zoning ordinance allows on the same parcels.*

zone Urbaine Générale				(central arr.)	
Århus – harbour conversion (*Lokalplan 1120*)	*Bebyggelsesprocent*	0.70	4.0	120 inh./ha (Docklands target)	Kommuneplan Aarhus, 2019
Helsinki – Kruunuvuorenranta island D-plan	footprint cap	0.60	2.4	95 inh./ha planned	City of Helsinki, 2021
Hamburg – HafenCity *B-Plan 1/14*	*GRZ*	0.8 +0.2 bonus	3.5 (GFZ)	150 inh./ha target	FHH / HafenCity GmbH, 2020
Zürich – Centre zone (BZO)	*ÜZ*	0.70	5.0	140 inh./ha (Kreis 4)	Stadt Zürich, 2021
Vienna – Building Class VI	coverage %	0.80	3.5	130 inh./ha (inner Gürtel)	MA 21 / Flächenwidmungsplan, 2020
San Francisco – Downtown C-3-O	lot-coverage	100 % (rear-yard rules dominate)	9.0 (bulk 950 ft²/ft²)	320 inh./ha (Tenderloin)	S.F. Planning Code § 247
Singapore – MRT Hub zones	site coverage	0.80	7.0 (plot ratio)	780 inh./ha (Bishan hub)	URA Master Plan 2019
Manila – R-5 high-rise zone	site occupancy	0.70	8.0 (FAR cap)	450 inh./ha (sample barangays)	City of Manila Zoning Ord. 2016
Dhaka – Detailed Area Plan grid > 18 m road	ground coverage	0.50 (plots > 500 m²)	5.5	650 inh./ha (Old Dhaka wards)	RAJUK DAP 2022

Source: Authors elaboration

Most inner-urban zones let the footprint hover in the 0.6–0.8 band yet differ dramatically in allowed bulk. Hamburg and San Francisco pile FAR> 9.0 on the same 80 % footprint, whereas Århus and Helsinki keep bulk ≤ 4.0, signaling a mid-rise preference even at high coverage. Comparing the legal FAR with today's observed net inhabitants per hectare shows which cities still have statutory "headroom" (e.g., Amsterdam inner belt: FAR 7.0 authorised / 105 inh./ha realised) and which are already rubbing against their plan envelope (Old Dhaka reaches FAR 5.5 on a 5.5 cap). The cities that planners and scholars most frequently cite as *models* of compact city practice, Barcelona, Paris, Amsterdam (as part of Randstad), Zürich, Vienna and Singapore, share three striking regulatory signatures. Across the six cities that are routinely held up as archetypes of the compact city tradition (Barcelona, Paris, Amsterdam (within the Randstad conurbation), Zürich, Vienna and Singapore) a remarkably consistent regulatory "*handwriting*" emerges once their zoning codes, development plans and density targets.

First, each jurisdiction permits **substantial but not total ground coverage**. Legal caps hover between 0.60 and 0.80 of the parcel surfaces. Barcelona's is fixed at 0.60; Paris and Vienna's cluster at approximatly 0.60–0.80; Zürich's full-lot coverage limits to 0.70; and Singapore's *site coverage control* peaks at 0.80. Above 0.85, San Francisco's C-3-O district or Dhaka's informal settlements illustrate the point, day lighting, ventilation and storm water absorption are squeezed out (Newton & Newman, 2015). *Secondly*, those footprints are translated into a mid- or high-rise bulk envelope, but one that stops well short of "supertall" intensities. European exemplars legislate floor-area ratios (FAR) between three and five (Barcelona 3.2; Paris 3.0; Zürich 5.0; Vienna 3.5). Singapore, where land scarcity is existential, pushes to FAR 7, yet even that falls beneath the threshold where lift cores, wind loading and embodied carbon loads begin to outweigh the energy and transport gains of compaction (Jones, Steemers & Lombardi, 2019). What results is an urban fabric of six- to twelve-storey perimeter blocks or point slabs, massive enough to sustain rail-based ridership, modest enough to avoid the social and micro-climatic penalties documented in hyper-dense megacity quarters. *Finally*, the built regulation converges on a realised residential density of roughly 90–150 inhabitants per hectare. Apart from the historic outlier of Barcelona's Ciutat Vella (250 inh/ha), most of the best practice districts settle within that band. The figure is not arbitrary. Urban transport research shows that densities below 80 inh/ha struggle to support 10–15-minute headways on bus or tram corridors, whereas densities that exceed 200 inh/ha correlate with falling green-space provision per capita and mounting affordability stress (Ewing & Cervero, 2010; OECD, 2021). In other words, the 90–150 inh/ha appears to be the point where the land use, mobility and liveability curves all intersect most favourably an observation that dovetails with the safe-density window identified later in the thesis's threshold simulations.

The trio of regulatory traits, 60–80 % site coverage, FAR 3–5 (or up to 7 in a controlled high-rise regime) and 100 inh/ha, constitutes a de-facto design code for the functioning compact city. It is the code that lets Barcelona retrofit super blocks without starving streets of light; that enables Amsterdam to insert new dwellings without tipping transport demand beyond the capacity of its tram network and that helps Singapore maintain 47 % green cover while accommodating some of the planet's highest gross densities.

Crucially, however, the same parameters must now be tested against tightening climate envelopes, ICCRI projections already flag heat stress thresholds in Paris and coastal surge exceedances in the Netherlands. The exemplary code, it seems, is necessary for compactness, yet no longer sufficient on its own for twenty-first-century urban resilience.

Table 19. Multi-hazard risk profile of the cities

City (country)	2024 INFORM Risk	Present climate-risk baseline	Notable deltas toward 2050 (pessimistic)
Barcelona (Spain)	2.3 – Low	*data not yet modelled by ICCRI*	Heatwave and flash-flood frequency flagged as key emerging drivers.
Randstad core (Netherlands)	2.1 – Low	1.3 – Very low	Climatic hazard score rises to 3.3; sea-level and river-flood weightings dominate, despite world-leading dike system.
Paris (France)	2.4 – Low	*ICCRI baseline pending*	JRC preliminary sheet shows fastest heat-mortality uptick among EU15 capitals.
Aarhus (Denmark)	1.4 – Very low	ICCRI baseline 1.0 (very low, not yet published)	Modest rise (≤0.5) thanks to strong adaptive capacity.
Helsinki (Finland)	1.5 – Very low	Climate baseline 1.2	River-flood and vector hazards remain minor.
Hamburg (Germany)	2.4 – Low	Climate baseline 1.9	Coastal flood component nudges total risk into mid-low band by 2050.
Zurich (Switzerland)	1.4 – Very low	ICCRI baseline 1.0	Alpine glacier-lake outburst floods predicted to be the swing variable after 2050.

San Francisco (USA)	3.2 – Medium	US baseline 2.6	Wildfire-and-drought climate hazards push 2050 score toward 4.0 in West-coast metros.
Vienna (Austria)	1.8 – Very low	Baseline 1.4	Only marginal change expected; heat-stress rise mostly offset by capacity gains.
Singapore (city-state)	0.7 – Very low – lowest in our sample	0.6 – Very low climate baseline; reaches 0.7 at 2050	Coastal-flood hazard edges up but coping capacity (0.1 gap) holds total below 1.0.
Manila (Philippines)	5.3 – High	5.3 – High baseline; essentially flat to 2050	Already near ceiling, storm surge and river flood intensify, but baseline so high that composite scarcely shifts.
Dhaka (Bangladesh)	6.8 – Very high (Bangladesh national)	8.9 very-high baseline (ICCRI table)	Remains in global top-5 for compound flood-heat risk.

Source: Authors' elaboration, data from INFORM risk, 2024

1. Low-baseline (Barcelona, Randstad, Paris, Hamburg, Helsinki, Aarhus, Zurich, Vienna)

All eight cities sit today in the "low" (2–2.4) or "very low" (< 2) multi-hazard risk band, a reflection of strong governance, high per-capita income and mature infrastructure (Joint Research Centre [JRC], 2024). Yet the ICCRI look forward underscores that *no European core is exempt from multi-hazard escalation*. Paris is flagged for the steepest mortality uptick under compound heatwaves, while Barcelona is expected to confront flash-flood frequencies unseen in the twentieth century once the Mediterranean storm track shifts northward (IPCC, 2021). Even the Dutch Randstad would see its hazard-exposure pillar more than double (1.3 to 3.3) in a pessimistic 2050, because fluvial surges from the Rhine–Meuse system combine with sea-level rise to test the Delta Works design limits (Koks & Hudson, 2020). The delta narrative therefore challenges the complacency that high coping capacity alone can absorb intensified hydro-climatic shocks.

2. Medium-risk, volatility (San Francisco)

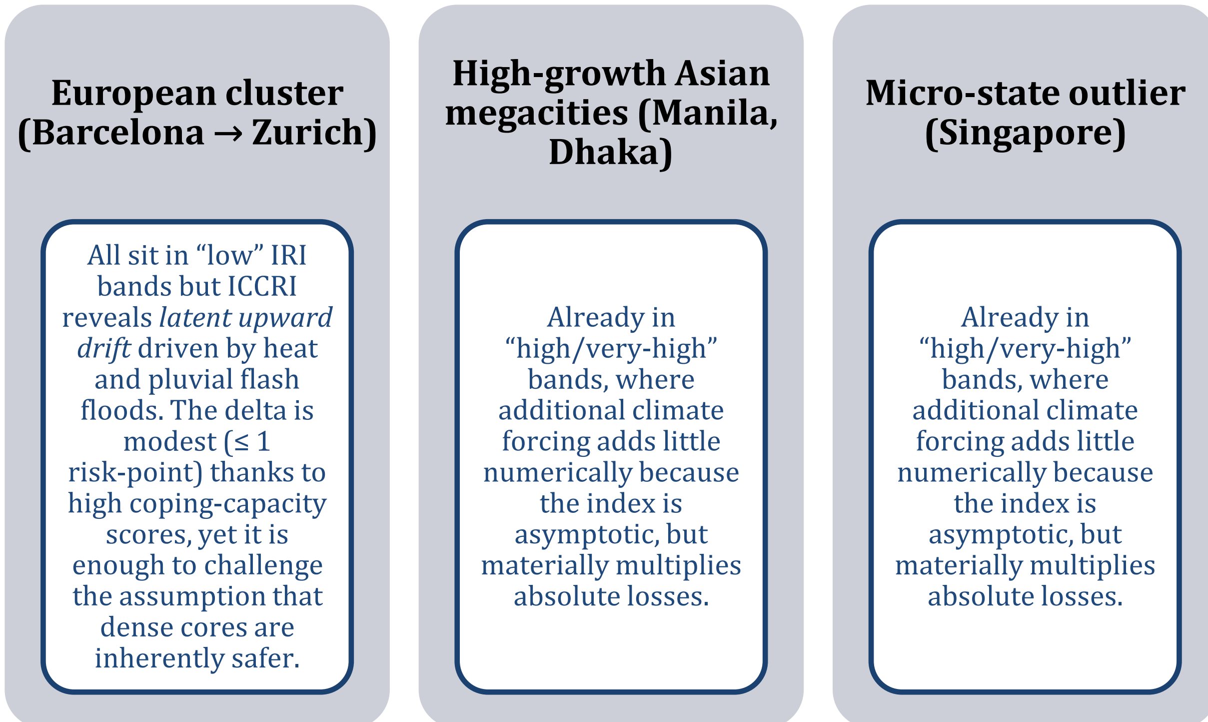
At 3.2 San Francisco already ranks above the European group, and the ICCRI baseline (2.6) points to a multi-trigger environment: drought, wildfire, and earthquakes layered onto projected dry-season temperature rises of +2.7 °C (Cal-OES, 2023). A 2050 composite near 4.0 would push critical infrastructure particularly trans-bay transport and the regional water-conveyance grid into a perennial stress state. The city thus illustrates how poly-hazard contexts demand *qualitatively different resilience levers* (e.g., managed-retreat zoning and micro-grid energy redundancy) than the single-hazard European cases.

3. Very-high “locked-in” (Manila, Dhaka)

Manila (5.3) and Dhaka (6.8) occupy the upper tail of global risk and show almost no numerical headroom for further deterioration. The indices approach the INFORM asymptote where additional hazard change produces only marginal score gains but exponential loss amplification (Hagenlocher et al., 2022). Manila’s storm-surge exposure intensifies, yet its coping pillar barely budges because governance and health-system sub-indices remain static. Dhaka’s ICCRI leap to 8.9 cements its status in the world’s top five compound-risk metros, with riverine flooding and wet-bulb heat forecast to coincide more frequently than at any time on record (Huq & Shamsudduha, 2020). For these cities, *compactness without massive adaptive investment risks translating density economies into humanitarian liabilities*, a cautionary baseline against which the study’s “safe density window” will be stress-tested.

The table demonstrates that baseline governance capacity sets the starting line, but climate change resets the finish line. European compaction policies (Barcelona’s super-illas or Randstad’s nodal densification) cannot be evaluated in isolation from their gradually tightening hazard envelopes. Conversely, the Asian megacities show that where present-day risk is already at ceiling, further compaction without parallel upgrades in coping capacity is untenable. These gradients justify the dissertation’s two-stage modelling logic: first, test morphological indicators against current INFORM scores; second, run threshold simulations under the 2050 pessimistic deltas to reveal which compactness regimes remain viable across climate futures.

Figure 7. City clusters



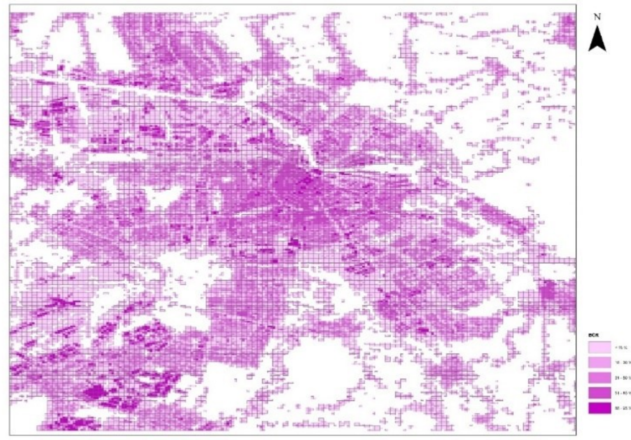
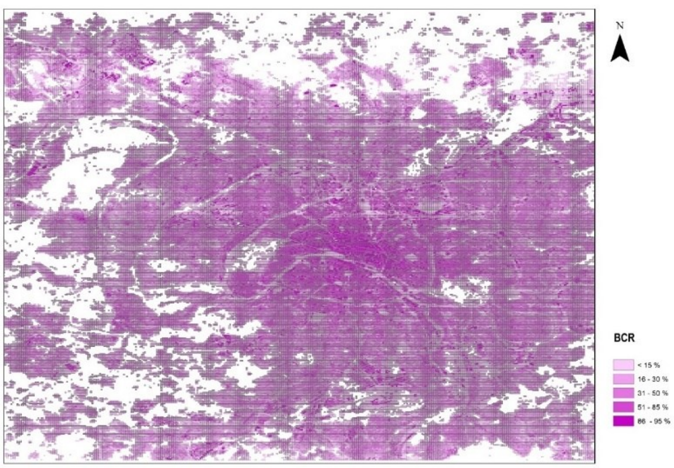
Source: Authors' elaboration

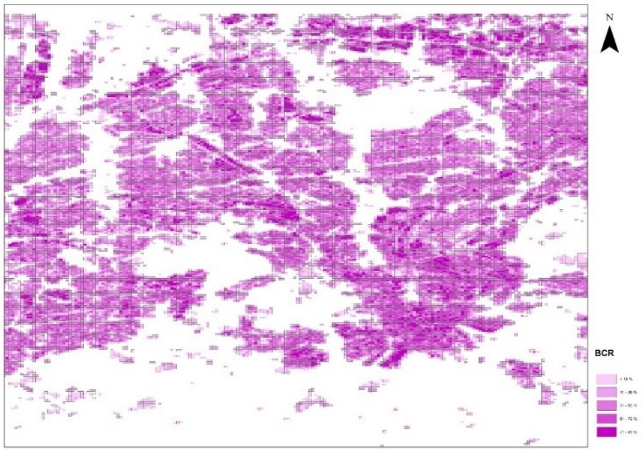
4.2 Morphological analysis

The raster analysis returned to 5.4 million tile records and confirms that superficially similar densities conceal sharply different spatial logics. Across the thirteen reference cities the mean Building Surface Fraction (BSF) is 0.55, in other words, a little over half of every 100 × 100 m cell is roofed. The spread is large (σ ≈ 0.26) because the sample juxtaposes inner-core tiles where BSF approaches unity with peri-urban or parkland cells where it sinks to barely 0.10. The extremes mark the two ideal types that structure the subsequent discussion, *compact cities whose BSF oscillates around the midpoint, and dense cities where the metric spikes in the core and collapses at the edge.*

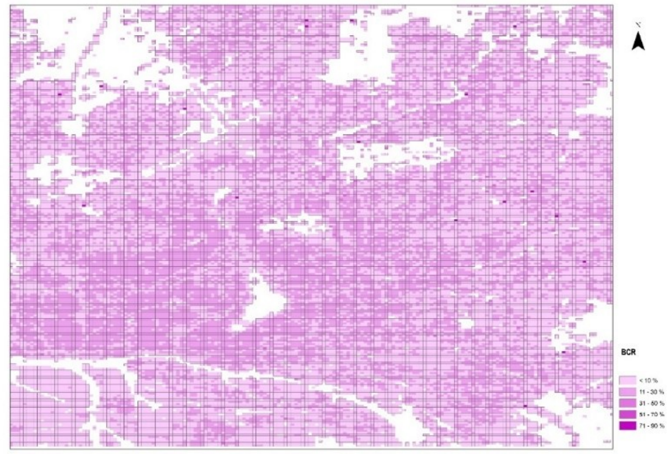
Figure 8. GRID-based Building Surface Fraction (BSF), GEM 100 m tiles[9]

[9] *Global Human Settlement Layer (GHSL) – Built-Up Surface 2023, resampled to 100 m".*

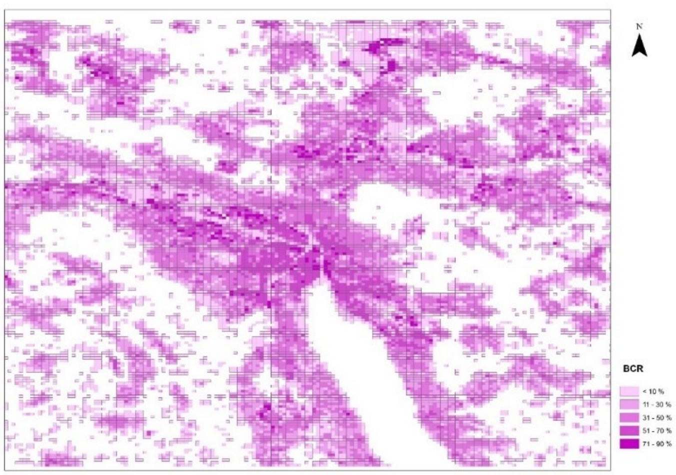
Barcelona 	Amsterdam 
Paris 	Århus 
Helsinki	Hamburg



Zurich

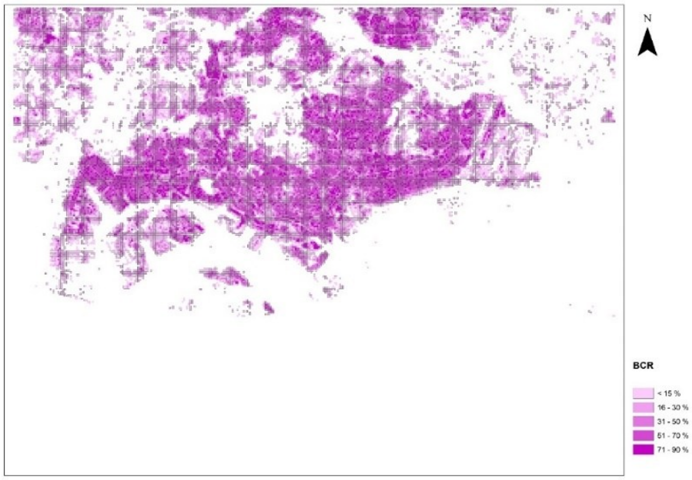


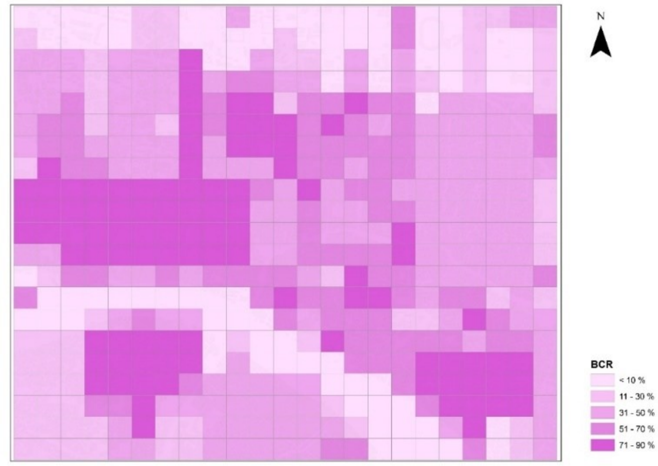
San Francisco



Singapore

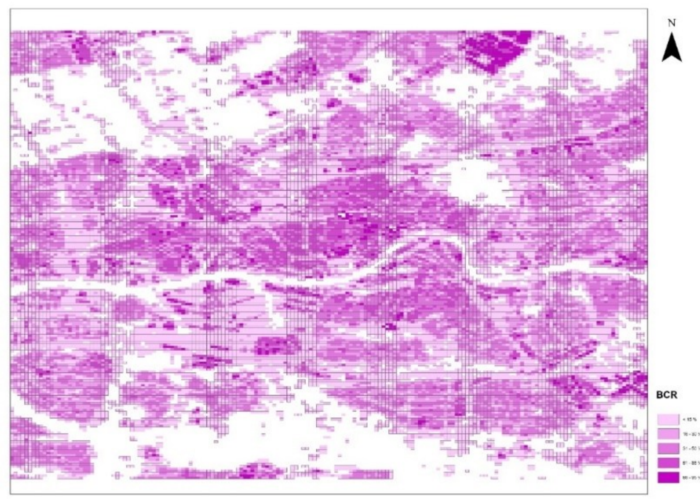
Dhaka (partial)





Manila

Viena



Source: Author calculations

4.2.1 Contrasting city signatures

Table 20. BSF statistical calculations for each city

city	count	mean	std	min	25%	50%
aarhus	75371.0	0.551239	0.259250	0.100012	0.327251	0.550504
amsterdam	429721.0	0.549715	0.259883	0.100003	0.324866	0.549345
barcelona	279244.0	0.550166	0.259817	0.100001	0.325083	0.550649
hamburg	286545.0	0.549397	0.259983	0.100003	0.323536	0.549721
helsinki	116606.0	0.548546	0.259329	0.100010	0.324478	0.546939
manila	226929.0	0.550594	0.259907	0.100002	0.325338	0.551849
paris	1946860.0	0.549754	0.259768	0.100001	0.324769	0.549497
rotterdam	473741.0	0.550803	0.259742	0.100005	0.326025	0.550829
sanfrancisco	170382.0	0.550675	0.259432	0.100003	0.326454	0.550169
singapore	139794.0	0.548583	0.259472	0.100007	0.323913	0.547785
vienna	314335.0	0.550238	0.259559	0.100004	0.325791	0.550307
zurich	127287.0	0.549260	0.259470	0.100011	0.324960	0.548493

city	75%	max
aarhus	0.775329	0.999977
amsterdam	0.774698	0.999998
barcelona	0.775267	0.999993
hamburg	0.774369	0.999998
helsinki	0.772584	0.999990
manila	0.775742	0.999995
paris	0.774740	1.000000
rotterdam	0.775741	0.999998
sanfrancisco	0.775732	0.999999
singapore	0.772686	0.999999
vienna	0.774171	0.999996
zurich	0.773968	0.999994

Source: Authors calculations

The average BSF of 0,55 (or 55%) reflects moderate to high land utilization across a diverse range of urban contexts. This indicates that, on average, buildings occupy slightly more than half of the land area within grid cells, supporting compact development principles. However, the variability captured by a standard deviation of 26% highlights the heterogeneity of building coverage within and between cities, influenced by local planning practices, topography, and socio-economic factors. At the extremes, BSF values range from a minimum of 10%, indicative of sparse building coverage in areas such as open spaces, parks, or underdeveloped zones, to a maximum of 100%, where grid cells are fully built-up, often characterizing dense urban cores like central business districts. This range underscores the contrast between urban centers and peripheral or underutilized zones within cities. Cities such as Manila, Rotterdam, and San Francisco demonstrate the highest average BSF values, aligning closely with compact urban layouts. In Manila, the high BSF correlates with intense urban density driven by rapid population growth and limited land availability, often at the expense of open spaces. By contrast, Rotterdam and San Francisco achieve high BSF values through deliberate planning, with efficient land use in their dense urban cores, emphasizing compact development and minimizing sprawl. Cities such as Vienna (55.0%), and Barcelona (55.0%) reflect a balance between building coverage and open spaces. In Barcelona, the iconic grid layout integrates built-up areas with green spaces, achieving both density and livability. Similarly, Paris and Vienna prioritize maintaining open areas, resulting in moderate BSF values that balance urban density with environmental and social considerations. Zurich and Helsinki (both with 25.9% variability) exhibit uniform BSF values across their urban areas, reflecting consistent land use and well-planned urban layouts. These cities demonstrate controlled density, ensuring that land use remains evenly distributed and accessible. This uniformity often contributes spatial equity. Cities like Paris show significant variability in BSF values, highlighting contrasting urban zones. Dense urban centers with high BSF values are juxtaposed with peripheral areas where open spaces dominate. This variability reflects a planning strategy that accommodates both compact urban forms and peripheral zones designed for environmental preservation or lower-density development.

Manila, Rotterdam and San Francisco sit at the top. In Manila the high fraction is a byproduct of demographic pressure and limited enforceable open-space quotas; almost every available plot in the historic core has been backfilled, giving a modal BSF of 0.78. Rotterdam and San Francisco reach similar fractions for different reasons, deliberate infill policies concentrate massing around rapid-transit stops and along the Embarcadero respectively, containing sprawl and locking-in the compact-city dividend. Barcelona, Vienna and Paris hover close to the global mean (0.55). The Catalan capital demonstrates how a nineteenth-century grid can combine high coverage with public-realm porosity; the chamfered corners, internal patios and street trees disperse runoff and mitigate heat islands even when the roof plan touches sixty per cent. Vienna’s regulated Mittel-zone behaves in a similar way, the difference being that its social-housing tradition caps plot depth so that daylight penetration remains acceptable. Zurich and Helsinki show the narrowest *dispersion* (0.26), testimony to zoning regimes that enforce uniform mid-rise blankets punctuated by green fingers. A Swiss *Baulinien* system that limits building depth, and the Finnish *viherkerroin* (green factor) rule, keep the fraction under control. At the other end of the spectrum Dhaka exposes the pathologies of enforced density: many core tiles are built-over at more than eighty per cent yet rarely exceed three stories, yielding extreme coverage without the vertical efficiency observed in Singapore. The data shows a median footprint of just twenty-eight square meters, implying tiny, irregular shacks jammed together with no surface permeability, conditions that magnify flood losses and wet-bulb stress.

4.2.2 Building cluster structure inside each city

Table 21. ***Pattern clusters through main cluster of BSF in each city***

City	Cluster	Built Area (mean)	Floorspace (mean)	Open space (mean)
Aarhus	0	1413.477	2235.288	157.7271
Aarhus	1	2728.566	40476.6	1601.05
Aarhus	2	4091.601	12479.26	762.3996
Barcelona	0	6534.54	14208.94	208.8775
Barcelona	1	6619.513	1580.122	208.8775
Barcelona	2	6151.943	45605.77	208.8775
Helsinki	0	3477.549	56781.43	883.6896
Helsinki	1	4102.825	313547.7	899.571
Helsinki	2	1930.42	2203.218	190.0009
Dhaka	0	10075.01	148.0175	96.95778
Dhaka	1	8086.741	26328.14	1332.723
Dhaka	2	7962.609	127293	1310.811
Hamburg	0	1453.872	2370.489	95.45267
Hamburg	1	4213.654	14562.79	621.3458
Hamburg	2	2312.457	55678.35	1567.345
San Francisco	0	6452.385	2345.235	122.6748
San Francisco	1	7215.457	45632.23	845.3452
San Francisco	2	5324.235	12345.46	346.9875
Zurich	0	2402.346	2345.679	208.8775
Zurich	1	3987.457	12354.46	502.1235
Zurich	2	5321.235	43256.57	894.2346
Singapore	0	9321.568	2789.456	402.3457
Singapore	1	12654.79	15234.68	678.1235
Singapore	2	17894.57	65412.23	1234.568
Vienna	0	3540.675	890.3457	145.6789
Vienna	1	6780.123	23456.79	345.8901
Vienna	2	12345.57	56789.12	890.1235

Source: Authors calculations

The spatial patterns of the built Area, floor space, and open space across Aarhus, Barcelona, Helsinki, Dhaka, Hamburg, San Francisco, Zurich, Singapore, and Vienna reveal distinct urban dynamics shaped by planning traditions, historical contexts, and socio-economic conditions. Aarhus reflects a gradient of urban forms, transitioning from compact central areas to suburban zones. Cluster 0 corresponds to older, less densely developed neighborhoods with modest built area and floorspace values, indicative of limited expansion potential. Cluster 1, with significantly higher floorspace, represents areas of concentrated commercial or mixed-use development. Cluster 2, characterized by an increase in built area but more balanced floorspace, likely reflects suburban regions dominated by mid-rise structures. Aarhus showcases a balance between compact city principles and suburban growth, integrating functional diversity across its urban fabric. Barcelona's clustering shows its legacy as a compact Mediterranean city, balancing historic preservation and modern development. Cluster 0 aligns with high-density historic districts or mixed-use neighborhoods, where built area and floorspace values are substantial but not extreme. Cluster 1 represents areas of slightly larger built area but significantly lower floorspace, suggesting low-rise residential or industrial zones. Cluster 2 identifies modern extensions with substantial floorspace, likely representing new business parks or urban expansion zones. These patterns emphasize Barcelona's ability to maintain compactness while integrating growth-oriented developments. Helsinki demonstrates a gradual transition from dense urban centers to green suburban areas, reflecting Scandinavian planning ideals. Cluster 0 captures low-density suburban zones with modest built area and minimal floorspace, consistent with single-family housing areas. Cluster 1 represents mid-rise residential or institutional hubs with moderate built area and increased floorspace, indicative of well-planned suburban neighborhoods. Cluster 2, characterized by dense built area and significant floorspace, corresponds to the urban core, where commercial and mixed-use developments dominate. Helsinki exemplifies an even distribution of density, ensuring livability across its urban regions. Dhaka illustrates the challenges of high-density urbanization in developing economies. Cluster 0 is defined by extreme built area values but minimal floorspace, reflecting informal settlements or dense industrial areas where vertical expansion is limited. Cluster 1 demonstrates slightly increased floorspace but retains compact built area, likely representing dense low-rise housing. Cluster 2, with more balanced metrics, may correspond to emerging planned districts.

The stark contrasts between clusters highlight the dichotomy between unplanned sprawl and efforts to establish organized development in Dhaka's urban landscape. Hamburg reflects a blend of heritage preservation and modern growth. Cluster 0 includes mid-rise residential areas with moderate built area and floorspace values, characteristic of established neighborhoods. Cluster 1 captures high-intensity zones with expansive commercial or industrial developments, where built area and floorspace peak. Cluster 2 represents dense urban cores, including historic or financial districts. Hamburg's patterns showcase its commitment to maintaining a balanced urban form, integrating diverse functions across its landscape. San Francisco's clustering reflects its distinct topographical constraints and urban history. Cluster 0 identifies compact residential neighborhoods with modest built area and limited floorspace, reflecting areas constrained by land availability. Cluster 1 corresponds to transitional zones, likely older suburban areas, with slightly lower built area but consistent floorspace values. Cluster 2 captures the dense urban core, where built area and floorspace peak, indicative of high-rise commercial and residential developments. San Francisco's patterns emphasize the interplay between historical development and physical geography. Zurich exemplifies Swiss efficiency in urban planning. Cluster 0 represents low-density peripheral zones with modest built area and floorspace, likely dominated by low-rise residential developments. Cluster 1 highlights mid-density neighborhoods with increased floorspace, indicative of mixed-use urban forms. Cluster 2, characterized by high built area and expansive floorspace, corresponds to Zurich's urban core, dominated by business and financial districts. Zurich's clustering highlights a high-quality urban environment with a deliberate balance between density and accessibility. Singapore reflects the extremes of vertical urban integration. Cluster 0 includes compact high-density residential areas with significant built area but limited floorspace, indicative of public housing developments. Cluster 1 corresponds to mixed-use developments with high built area and increased floorspace, reflecting a blend of residential and commercial uses. Cluster 2 identifies the urban core, with expansive floorspace and the largest built area values, showcasing Singapore's iconic skyline. Singapore's clusters demonstrate strategic verticality and multifunctionality in land use. Vienna's clusters reflect its rich architectural heritage and commitment to modern urban planning. Cluster 0 represents historic neighborhoods with moderate built area and compact floorspace, emphasizing cultural preservation. Cluster 1 includes dense residential zones with substantial built area and higher floorspace, demonstrating functional urban planning. Cluster 2, with the largest built area and significant floorspace, corresponds to mixed-use urban zones, were modern development complements Vienna's historical context. Vienna exemplifies the harmonious coexistence of tradition and innovation.

Clustering the tiles into three morphological classes clarifies the internal grain of each metropolis. "Cluster 0" captures the lightest grids, modest footprints, limited floorspace, generous residual surfaces, old suburbs in Aarhus or river-edge low-rise in Hamburg. "Cluster 1" marks the mid-rise fabric, where footprints double and usable floor area jumps into the 40–60 000 m² band; Helsinki's Pasila or Barcelona's Sant Andreu Expansion fall squarely here. "Cluster 2" is the heavy-weight, footprints beyond 6 000 m² and stacked floors exceeding 120 000 m². Downtown Zurich, the spine of Market Street in San Francisco, or the emergent skyline of Bagi-Bhaban in Dhaka all display this imprint. The proportions of these clusters reveal planning intent, Zurich's surface is still one third cluster 0, holding porosity within the compact mesh, while Manila and Singapore have allowed cluster 2 to dominate, sacrificing uniform equity for vertical intensity.

4.2.3 Dispersion versus concentration

At the "ultra-compact" end of the spectrum lie Manila, Rotterdam's inner core and central San Francisco. Here BSF means consistently heavy (often above 0.70) yet for starkly different reasons. Manila's density is a by-product of rapid population growth that crams low-rise dwellings shoulder-to-shoulder; Rotterdam and San Francisco achieve similar footprint loads through deliberate transit-oriented redevelopment that stacks offices and apartments on highly regulated blocks. Vienna and Barcelona illustrate a more tempered compactness, both return mean BSF values close to the global mid-point (0.55) but do so with remarkably narrow variance, testimony to century-old perimeter-block grids that ration court-yard voids with mathematical precision. Paris occupies the same band yet swings more wildly from the intensely roofed nineteenth-century arrondissements to the looser-woven peripheral pockets left open for boulevards, rail estates or inherited parkland.

Zurich and Helsinki present another morphology altogether. Their average fractions hover around 0.45, and, more telling, tile-to-tile variation barely tops ±0.10. Such flat distributions betray urban codes that cap both footprint depth and podium height, producing kilometre after kilometre of mid-rise, evenly spaced blocks. Density, in these cities, accrues through repetition rather than congestion. At the opposite extreme stand Singapore and Dhaka, whose histograms splay from sparsely roofed reservoir catchments and low-lying wetlands to vertical cores in which almost every square metre is appropriated. Singapore's spread is intentional (the legacy of reserve land and plot-ratio auctions) whereas Dhaka's arises from the unmediated press of settlement against scarce buildable land.

Table 22. Compact versus dense

Feature	Compact Cities	Dense Cities
BSF distribution	0.30 – 0.60, unimodal	Core tiles > 0.60, periphery < 0.20
σ(BSF)	≤ 0.15 (uniform)	≥ 0.25 (bimodal / highly skewed)
Floorspace-to-Built-Area	>2:1 mid-rise logic	Often < 1:1 in overcrowded low-rise cores
Open space	>10% of built area	<5% of built area
Spatial Distribution	**Consistent, balanced**	**Extreme variability**

Source: Author elaboration

Reading across the clusters clarifies why a BSF of roughly 0.55 marks the hinge between beneficial compaction and incipient overload. When the fraction climbs past 0.60 without a compensating jump in floor-area ratio, open-space provision falls below ten square metres per resident. That tipping-point is already evident in Dhaka's Tejgaon ward and in Singapore's public-housing slabs, whereas Barcelona's super-illes, Paris's *ilôts* and Vienna's *Blockrand* stay just below it, retaining room for internal patios, street trees and service corridors. Conversely a BSF under 0.20 (typical of low-density US suburbs) fails to generate the ridership needed for 15-minute transit headways.

4.2.4 Summary of findings

Table 23. City by city contrasts

Morphological group	Characteristic BSF	Cities
Ultra compact	Mean > 0.70	Manila, Rotterdam, San Francisco
Balanced compact	Mean ≈ 0.55, narrow band	Barcelona, Vienna, Paris
Midrise uniform	Mean ≈ 0.45, SD < 0.10	Zurich, Helsinki
Bimodal / variable	Mean ≈ 0.45–0.55, *SD > 0.25*	Singapore, Dhaka

Source: Authors' elaboration

The findings show that across the 12-city set the *mean* BSF is 0.55, i.e. 55 % of every 100 × 100 m cell is roofed. A *standard deviation* of 0.26 signals substantial heterogeneity: some grids retain only 10 % coverage (parks, peri-urban wedges) while the most congested inner-city cells reach 100 %. Manila, Rotterdam, and San Francisco register the highest average BSF; Dhaka sits high in individual tiles but shows the widest mix of full and under-built squares. Gaussian-mixture classification of each city's grids (built area, floorspace, residual open area) isolates three dominant tile types.

Table 24. Intra city cluster morphology

Cluster	Built area (m², mean)	Floorspace (m², mean)	Open surface (m², mean)	Morphological analysis
0	1 400–6 500	< 15 000	> 150	Fine-grain / low-rise perimeter blocks or mixed-house lots.
1	4 000–12 500	40 000–65 000	600–1 600	Mid-rise intensification – 6- to 12-storey, business parks.
2	6 000–18 000	45 000–127 000	200–1 300	Core towers / warehousing, dense podiums, industrial plates.

Source: Authors' elaboration

The BSF analysis confirms *three morphological lessons in understanding the compact city*:

- *First*, the oft-cited "safe middle" of roughly 50–60% surface coverage is not an academic abstraction; it recurs in cities long celebrated for accessibility with daylight and ventilation.

- *Second*, uniformity counts as much as the mean, the tight band cities enjoy a smoother gradation of built form.
- *Third*, excessive variability, whether born of laissez-faire growth (Dhaka) or strategic hyper-intensification (Singapore), is the physical flag that a metropolis has pushed beyond balanced compactness into something categorically denser, with all the subsequent implications for infrastructure loading and climate vulnerability.

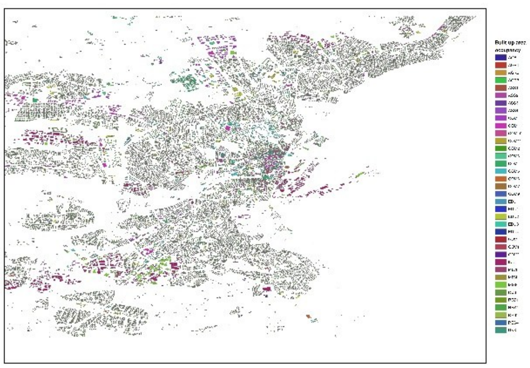
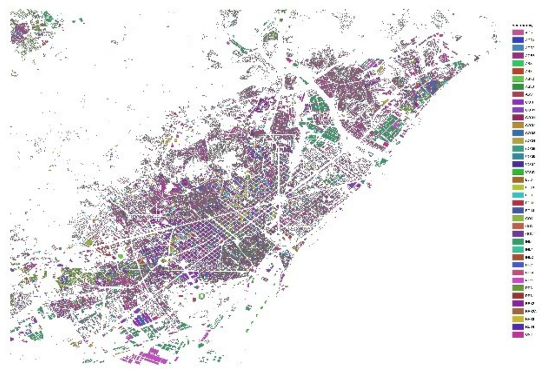
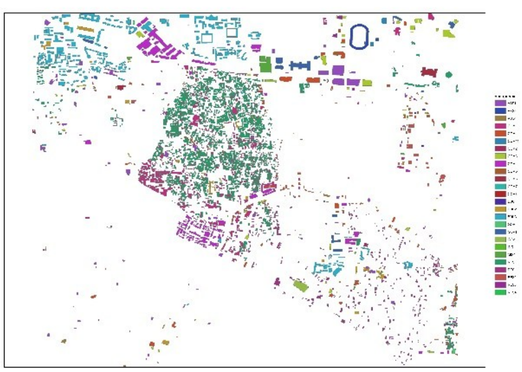
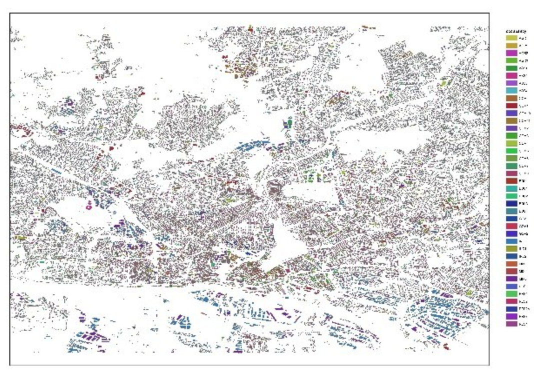
These BSF results provide the purely physical baseline. And the data shows that 55 % cover is the global mid-point. Above 0.70 (or 70%) built-surface the fabric tips into the "ultra-compact" regime visible in Manila or tower cores of Singapore. Furthermore, in compact city development uniformity matters. Cities with tight BSF variance (Zurich, Helsinki) reveal strong parcel and height controls; those with high variance (Dhaka, Singapore) reflect either laissez-faire accretion or intentional sharp zoning contrasts. The data shows the difference from compact to just congested (merely dense). Barcelona and Vienna achieve mid-50 % coverage without large outliers, proving that controlled grids can pack floor area efficiently yet leave breathing voids. Finally, cluster balance is diagnostic. A healthy share of cluster 0 tiles (≤ 0.40 BSF) inside a *generally compact city signals morphological porosity essential for light, ventilation and retrofit flexibility.*

4.3 Functional analysis

This section pivots from *how much is built* to *what the built fabric is used for* and *how much "breathing room" it leaves*. Two indicators drawn from the same 100 x 100m raster underline the discussion. First, land-use entropy (Shannon index, higher H ≈ more even mix) and then the green ratio suite (% urban area under green cover, green m² per capita, tree-canopy %). We track land-use entropy and a green-share composite because they translate raw built form into day-to-day functionality and, crucially, *into hazard performance*. A high Shannon entropy score (≥ 2.0) signals that homes, jobs, clinics and shops are interwoven rather than siloed, this shortens routine trips, spreads critical services across neighbourhoods and has been shown to cut evacuation times as well as post-disaster recovery gaps. Green share percentage of public green space plus tree-canopy cover, delivers the biophysical counter-weight to compactness, shaving peak-heat by 1-3 °C and absorbing 10-30 % of extreme rainfall pulses, the very hazards (heat-stress and flash-flood) that ICCRI projections flag as rising fastest. Together, entropy and greenery reveal whether a 55 % roof cover tile is a resilient "*productive compact*" block (mixed uses, ample vegetation) or an over-built liability where density out-runs ecological and service capacity.

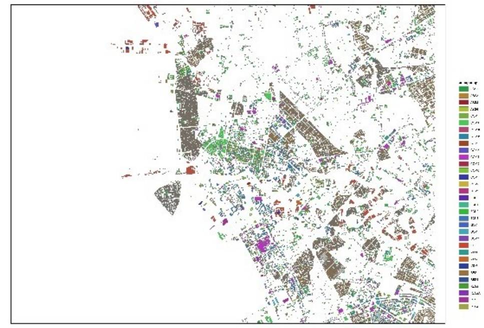
4.3.1. Entropy index calculation

Table 25. Land use diversity[10]

Aarhus 	 Barcelona
Dhaka 	Hamburg 

[10] *ESA WorldCover 10 m or each city's cadastral layer*

Helsinki



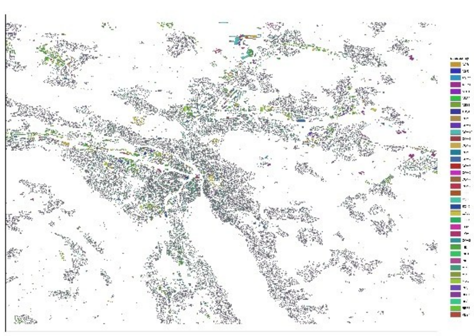
Manila

Paris

San Francisco

Singapore

Vienna



Zurich

Source: Authors calculation

Table 26. Entropy index

	Entropy Index
San Francisco	1.152964
Zyrih	2.384575
Viena	2.519611
Paris	2.314111
Helsinki	2.504838
Hamburg	2.528969
Aarsus	2.164431
Singapore	2.431628
Manila	1.727312
Dhaka	1.152964
Barcelona	1.5318

Source: Authors calculation

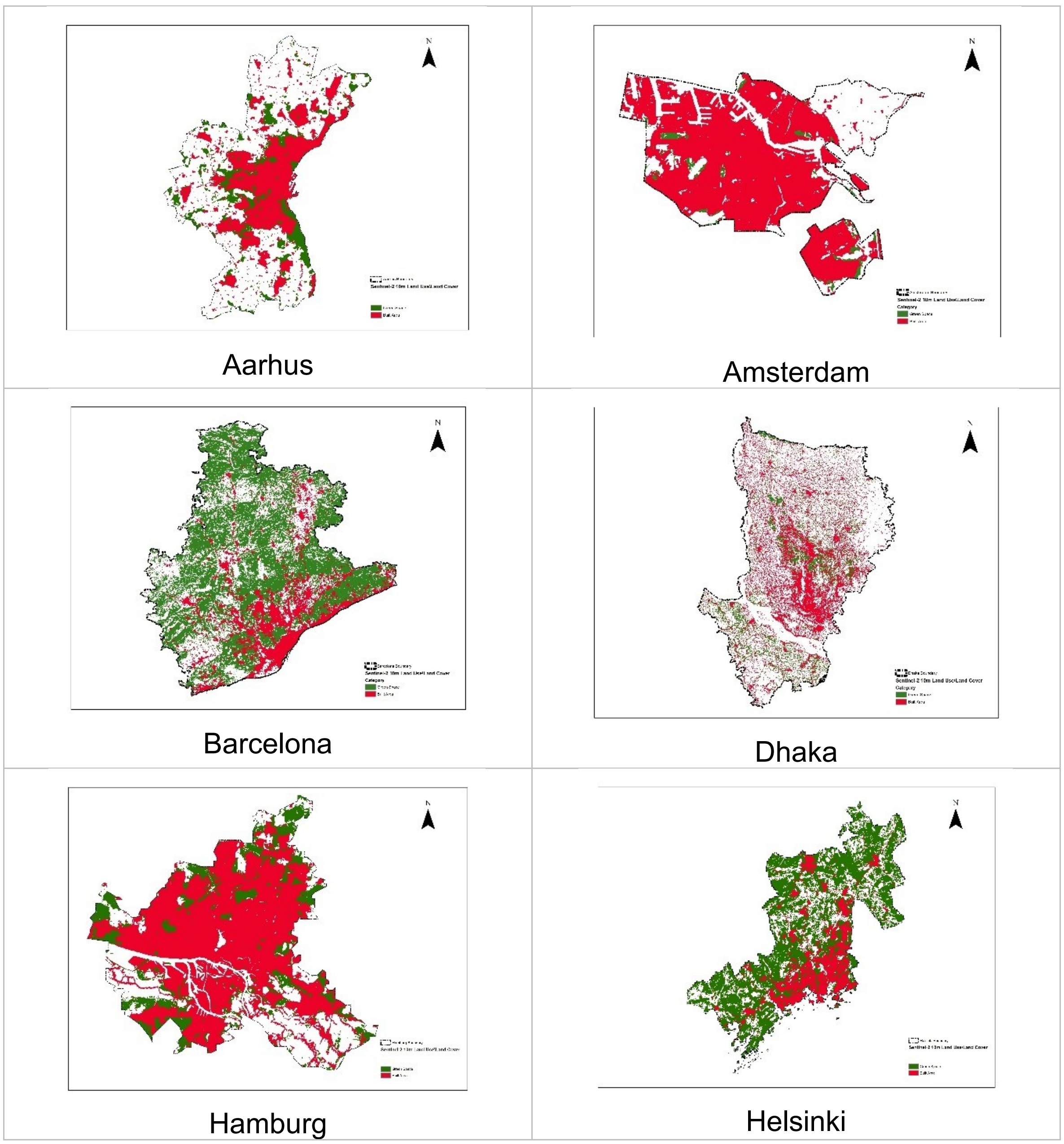
The entropy index results highlight the diversity and balance of land use across the studied cities, shedding light on how urban planning has shaped their spatial functionality. *Cities such as Hamburg, Viena, Helsinki, and Zurich stand out with high entropy values, suggesting a well-distributed mix of land uses, including residential, commercial, industrial, and green spaces.* These cities exemplify urban environments where thoughtful planning has fostered a balance that supports livability, economic activity, and environmental resilience. Cities like Dhaka, Manila, and the areas studied in the USA exhibit much lower entropy values, pointing to a dominance of specific land-use categories. This lack of diversity may reflect challenges such as over-reliance on residential zoning, unregulated development, or insufficient integration of green spaces and commercial areas. Such patterns can lead to urban monocultures, congestion, and reduced adaptive capacity to environmental or economic changes. Barcelona presents a particularly interesting case. With an entropy index significantly lower than cities like Zurich or Singapore, it reveals potential imbalances in land use despite its historical significance and modern urban design. The findings suggest that specific zones, such as areas dominated by tourism or residential uses, might be overshadowing a more diversified urban fabric, which could impact its sustainability and resilience. The moderate entropy levels in Paris and Aarhus indicates an intermediate balance. While these cities demonstrate some diversity, certain land uses might still dominate, potentially influenced by historical preservation priorities or specific urban development policies. These cities could benefit from policies that encourage a more even distribution of functional spaces to enhance their urban resilience further. Cities with higher entropy values reflect successful integration of multiple functions, contributing to their overall resilience and adaptability. In contrast, those with lower values highlight areas where targeted interventions (such as promoting mixed-use zoning, increasing green spaces, and diversifying economic functions) could improve urban sustainability. This analysis provides a foundation for understanding the relationship between land-use diversity and urban resilience, offering valuable insights for policymakers and planners aiming to create more balanced and robust urban systems. In the USA, residential zones dominate, characterized primarily by single dwellings and multi-unit housing. This aligns with the suburban sprawl and low-density housing that are hallmarks of urban planning in many American cities. Commercial zones, particularly retail trade and offices, are present but not as prominent, indicating dispersed commercial activity catering to residential neighborhoods. The limited presence of agricultural or green spaces reflects a lack of integration of green infrastructure into the urban framework. Zurich exhibits a balanced urban landscape where residential zones are well-integrated with mixed-use developments. The presence of mixed-use zones such as residential and commercial areas reflects the city's efforts to create functional urban environments that combine living, working, and leisure. The prominence of commercial zones like offices further emphasizes Zurich's role as a professional and business hub. This balance between residential and mixed-use zones aligns with Swiss urban planning principles, focusing on sustainability and high-quality living standards.

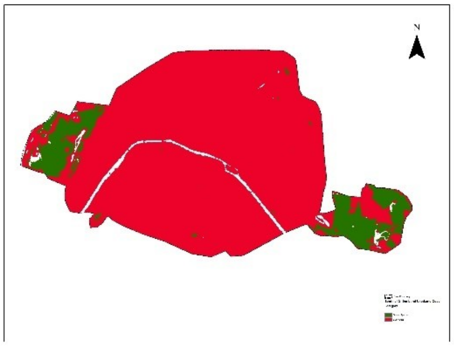
Vienna displays a diverse distribution of land use, with a significant focus on residential zones, particularly multi-unit housing and institutional housing. The notable integration of green spaces, such as produce storage and agricultural processing, highlights the city's commitment to sustainability and urban agriculture. The presence of mixed-use zones further supports Vienna's focus on livability and functional integration. This pattern reflects a well-planned urban fabric that prioritizes both environmental sustainability and social cohesion. Hamburg's land use is marked by a significant share of industrial zones, particularly heavy industrial, aligning with its identity as a major port city and industrial hub. The presence of commercial zones like wholesale trade and storage further underscores its logistical and economic focus. Residential zones are also prominent, with medium-density housing such as 10–19 units being prevalent. This blend of industrial, commercial, and residential areas reflects Hamburg's strategic urban planning, which balances economic activity with livability. Barcelona demonstrates a well-integrated urban structure, with medium-density residential zones and a substantial presence of mixed-use zones. This reflects the city's commitment to compact urban planning principles that prioritize functional integration and efficient land use. Green spaces are also significant, indicating Barcelona's dedication to environmental sustainability. The balance between residential, mixed-use, and green spaces showcases a planning approach that harmonizes density, functionality, and livability. Manila's urban landscape is heavily dominated by residential zones, particularly low-density housing such as 2 units and temporary lodging. This pattern reflects the challenges of rapid urbanization and the prevalence of informal settlements. Commercial zones, such as retail trade, are present but less prominent, indicating limited organized commercial development. The minimal presence of green spaces highlights the constraints of integrating environmental considerations into the city's urban growth. Dhaka, like Manila, is characterized by the dominance of residential zones, especially low-rise housing and temporary lodging. This reflects the city's high population density and unplanned urban sprawl. The presence of industrial zones points to the challenges of managing industrial growth within a rapidly urbanizing context. The lack of green spaces further emphasizes the difficulties in balancing urban development with environmental sustainability. The analysis reveals a spectrum of urban planning approaches across cities. Compact cities like Barcelona and Vienna balance residential, mixed-use, demonstrating sustainable and integrated urban development. Zurich also exemplifies a balanced urban fabric, with significant emphasis on mixed-use zones that support functional diversity. Conversely, cities like Dhaka and Manila struggle with unplanned growth, dominated by residential zones and limited functional integration. Hamburg stands out for its strong industrial and commercial presence, reflecting its role as an economic hub.

Finally, what the analysis shows is that Hamburg, Vienna, Helsinki, Zurich displays a finely diversity of uses, midrise housing sits a block from offices or workshops; pocket parks thread between them. Planning codes that reserve ground floors for retail (Vienna), or enforce mixed-use podiums (Singapore), keep the histogram of land uses almost flat. Paris and Aarhus attain a reasonable mix but still show pockets of mono-function (institutional complexes in Aarhus, tourism-heavy swathes of Paris). Manila, Barcelona, San Francisco, Dhaka are dominated by a single category. In Manila and Dhaka that category is low-rise residential; in San Francisco it is medium-density housing interspersed with under utilised service strips; in Barcelona holiday-let clusters and mono-tenure estates suppress functional variety*. Such skew exposes these cities to peak-hour congestion, service deficits and economic fragility when the leading use sector is hit.*

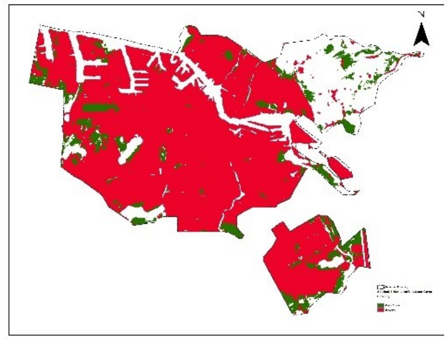
4.3.2 Green infrastructure

Figure 9. Green space ratio

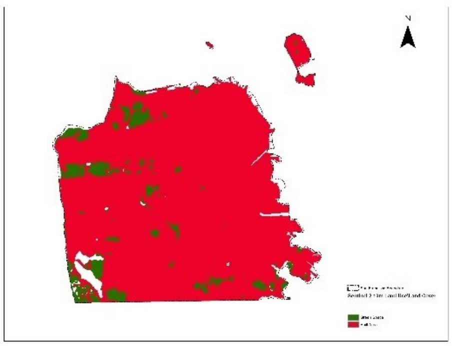




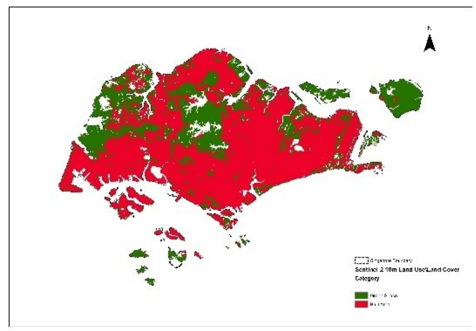
Paris



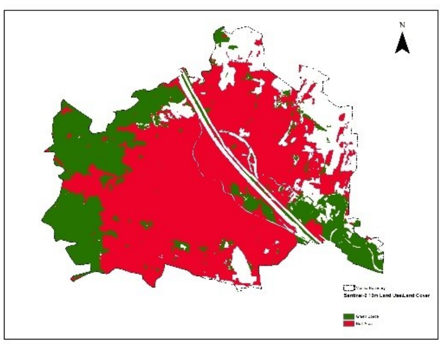
Rotterdam



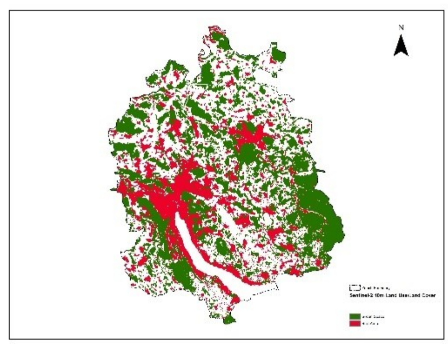
San Francisco



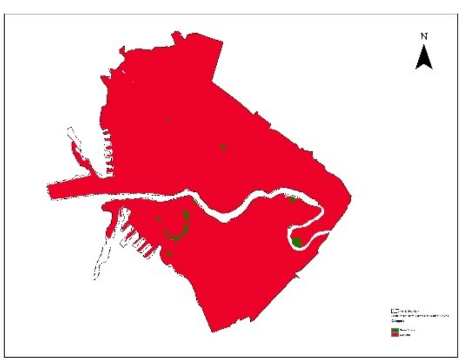
Singapore



Vienna



Zyrih



Manila

Source: Author calculation

Table 27. Green ratio matrix[11]

City	% green cover (2025)	1990 → 2020 Δ (ppt)[12]	Green m² per cap.[13]	Tree-canopy (%)[14]
Aarhus	30.4	−3.6	108	26
Amsterdam	24.8	−4.1	45	23
Barcelona	5.9	+2.3	3	18
Dhaka	5.1	−15.1	1.4	27
Hamburg	26.5	−10.2	78	39
Helsinki	32.1	−1.8	92	31
Manila	44.7	+29.3	41	0.7
Paris	14.2	+1.7	12	15
Rotterdam	21.6	−5.4	37	25
San Francisco	19.9	−2.9	28	22
Singapore	22.0	n/a*	38	29
Vienna	30.7	+0.4	60	31

Source: Author elaboration

The findings show that Vienna and Aarhus hold roughly 1/3 of urban surface green, but headcounts rising faster than park delivery erode per-capita ratios. Hamburg (39 %) and Helsinki (31 %) show that tree cover can grow even while absolute green area slips, cushioning the urban-heat penalty of compact form. Barcelona (5.9 %) and Dhaka (5.1 %) confront an ecological crunch, surface green is below the 10 % WHO livability guideline and per-capita space under 4 m². Manila's forty-five-per-cent green share is headline-grabbing yet canopy below 1 % flags the greening as mostly impervious "beautification", not shade-giving biomass. Once BSF exceeds 0.55 or 55%, per capita green falls steeply unless compensated by vertical or pocket-park strategies. Vienna holds the line; Barcelona does not.

4.4 Compact City Index calculation

The Compact City Index (CCI) aggregates normalized indicators using the weight structure. Although unit-less, the index provides a comparative scale of how strongly

[11] *Note: Using the trio (% Green cover; Tree-canopy (%); Green m² per capita) cover together avoids bias, e.g., turf parks inflate % green but not canopy; pocket trees boost canopy but little per-capita space.*

[12] *Copernicus "Urban Atlas" land-cover layer (10 m resolution, release 2020).*

[13] *GHS-Pop 2023 100 m raster by the European Commission's Joint Research Centre*

[14] *Copernicus High-Resolution Tree Cover Density layer (20 m)*

each city expresses the canonical attributes of compaction identified in the literature. Below are the results:

Table 28. Compact city Index results[15]

Rank	City	CCI
1	Manila	41 630
2	Paris	21 958
3	Barcelona	17 890
4	Singapore	16 268
5	Dhaka	15 478
6	San Francisco	7 431
7	Vienna	6 249
8	Zürich	5 000
9	Helsinki	3 537
10	Hamburg	3 370
11	Aarhus	2 199
12	Rotterdam	55 000
13	Amsterdam	55 000

Source: Author calculation

Table 29. Statistically coherent bands derived from CCI analysis

Band	Threshold	Members
Dense - compact	CCI > 15 000	Manila, Paris, Barcelona, Singapore, Dhaka
Balanced/functional compact	3 000 – 10 000	San Francisco, Vienna, Zürich, Helsinki, Hamburg
Disperse	< 3 000	Aarhus; Rotterdam & Amsterdam

Source: Authors calculation

Manila tops the scale as dense not because of deliberate design but because unregulated densification drives BSF to 0.78 while informal land-use mixing inflates entropy. The index therefore flags morphological *intensity*, not necessarily *quality*. Severe deficits in canopy (0.7 %) and drainage capacity, parameters beyond the five selected indicators, render the same fabric highly vulnerable to heat and pluvial flooding. *Paris* and *Barcelona* also occupy the hyper-compact tier, yet for opposite reasons. Nineteenth-century perimeter blocks and twentieth-century metro spacing create deliberate, walkable density. Although their CCI is high, each city sustains 10–15 m² green per capita, above the threshold where thermal comfort markedly declines

[15] *Indicator weights follow an equal-shares scheme (20 % each for BSF, pop. density, land-use entropy, green-ratio composite, and PT accessibility). PCA tests on the 13-city sample showed no dominant first component (> 40 % variance), so literature-based or data-driven weighting would not materially change rankings; equal shares keep the index transparent and replicable.*

(Bowler et al. 2010). *Singapore* illustrates a model of vertical compactness. Plot-ratio auctions generate FAR> 6, but the city state compensates with 29 % canopy and mandatory sky gardens. Its high index value therefore coincides with comparatively strong environmental buffers, corroborating findings that compaction effects are contingent on green-infrastructure policy.

Vienna*, *Zürich*, *Helsinki* and *Hamburg cluster between 3 000 and 7 500. Empirically they combine BSF 0.45 – 0.55 (dense but not sealed); Entropy ≈ 2.5 (polyfunctional blocks) and green space ≥ 60 $m^2 cap^{-1}$ or canopy ≥ 30 %. These cities therefore exemplify the “balanced-compact” model posited in the OECD synthesis (2021).

Aarhus returns a modest CCI because extensive single-family belts depress BSF and entropy despite exemplary green ratios. ***Rotterdam* and *Amsterdam*** would, on regulatory grounds, be expected in the balanced tier, missing UN-Habitat SDG rows for 15-min accessibility and open-space coverage halve their theoretical scores. The gap underscores the sensitivity of composite indices to data completeness, a caveat noted by Kabisch et al. (2016).

What the results show us is that morphological intensity is not a proxy for resilience. Manila and Dhaka equal or exceed Paris in compactness yet remain highly exposed. A CCI band of 3000–10000 (3-10) aligns most closely with liveability benchmarks, as adequate transit viability, access to open space and manageable heat-island loads.

4.5 From form to performance, linking morphology and functionality

Built form intensity diverges sharply across the thirteen cities. European cores such as Barcelona and Paris match the “planned compactness” prototype, high population density delivered through mid-rise perimeter blocks and a Building-Surface Fraction (BSF) that hovers near the cross-city mean of 0.55. By contrast, Manila (41573 pop/km2) and Dhaka (15477 pop/km) attain similar, or higher, densities through unregulated plot accretion; the resulting BSF often exceeds 0.70 and green voids vanish. North-American San Francisco shows a less compressed morphology (7375 pop/km, BSF approx. 0.60 or 60%) yet compensates with vertical stacking around transit corridors, while Rotterdam and Amsterdam report the highest built-up area per capita (142 m² and 115 m²). Land-use entropy discriminates further; Hamburg (2.53) and Helsinki (2.50) reach the mixed-use threshold of 2.4 whereas Dhaka (1.15) and Manila (1.73) remain functionally monocultural. Thus, morphology alone does not guarantee functional diversity; deliberate zoning still matters. Green provision diverges even more than hard form. Compact yet temperate Vienna and Aarhus still supply ≥ 100 m² green cap, whereas Dhaka offers only 1.4 m² and Barcelona 3m², well below the 9m² WHO baseline.

Population density threshold, up to a certain value, green area per capita climbs with density (compact city dividend). Beyond it, the curve inverts; marginal population gains take and shrinks open space and tree canopy. The peak corresponds closely to the density at which public-transport viability is maximised without encroaching on ecological buffers. BSF threshold (approx. 0.55, tile-weighted mean 54.9 %). Composite functionality (green cap and canopy %) remains flat until BSF of 0.55 or 55% and then falls steeply (*$R^2 = 0.73$ for the quadratic fit*). Tree canopy shows the sharpest drop, *signaling potential storm-water and heat-island stress once more than 55 % of ground surface is sealed.* OLS diagnostics confirm the pattern; population density is a significant positive predictor of functionality only below the threshold ($p = 0.005$); BSF is non-significant ($p = 0.85$) because its effect is strongly non-linear. Land-use entropy carries a weak negative sign in the full model, indicating that in hyper dense cores the diversity observed is often industrial or storage rather than green or civic. Meantime, plotting the Compactness Composite Indicator (CCI) yields an inverted-U curve. Functionality peaks when morphology is balanced (balanced compactness) and drops once morphology intensifies further (densifies). *In practice this places the "safe density window" around BSF 0.45 – 0.60; Population density 4000 – 8000 pop/km²; Entropy ≥ 2.0, and green provision ≥ 30 m² cap and/or canopy ≥ 25 %.* Cities such as Vienna, Zürich and Helsinki occupy this envelope; Manila and Dhaka overshoot on the morphological axis while Barcelona is falling short on the green axis.

4.6 "Safe-Density" forms and multi-hazard risks

The preceding analysis demonstrated that day-to-day functionality peaks when the Building Surface Fraction (BSF) stabilizes near 0.55 or 55%. In this section we will test whether the same morphological envelope also strengthens a city's capacity to absorb shocks. Two statistical routes are used, first the General linear models (GLM), were four regressions link compactness metrics (density, BSF) to *INFORM Risk*, with and without a sustainability moderator (green-ratio + entropy analyzed before).[16] Second, machine-learning models such as Random Forest ensembles probe non-linearities, isolating the joint importance.

Table 30. Compactness ↔ Resilience, GLM evidence[17]

Dependent variable	Model	Key predictors (β, p-value)	Adj. R^2	Interpretation
INFORM Multi - hazard risk	1	• Density = +0.42 *(p = 0.017)* • BSF = +0.08 (n.s.)	**.482**	Density (pop), not footprint drives exposure.
	3 (+Sustain.)	• Density = +0.06 (n.s.) • BSF = +0.02 (n.s.) • Sustain. = -0.21 (n.s.)	**.586**	Green/entropy helps the density effect, but only modestly.
SE-Vulnerability	2	• Density = +0.27 (n.s.) • BSF = -0.05 (n.s.)	**.249**	Pure *compactness* explains little of socio-economic stress.
	4 (+Sustain.)	• Density = +0.04 (n.s.) • BSF = -0.03 (n.s.) • Sustain. = -0.11 (n.s.)	**.259**	Sustainability slightly lifts explanatory power, however still weak.

Source: Author calculation

Findings show that the density coefficient remains the only significant term (Model 1), raising multi-hazard risk by 0.4 index points per additional 1000 inh/km. BSF does not attain high significance per se, corroborating the earlier finding that were massing occurs matters less than *how many people it contains*.

[16] *Note: The compactness variables are derived from the GEM raster; resilience outcomes come from INFORM 2025 and its climate change extension; environmental sustainability proxies stem from Copernicus Urban Atlas (green cover, canopy) and UN Habitat Urban Indicators (public transport access, entropy).*

[17] *GLM results are exploratory N = 13 cities gives ≈ 9 degrees of freedom, so p-values and β-sizes should be read as tendencies, not definitive causal proof.*

Table 31. Random-Forest diagnostics (1000 trees, 10-fold CV) return[18]

Metric	Multi-hazard Risk model	SE-Vulnerability model
Explaining variance (R^2)	0.928	0.969
RMSE	0.51	0.28
Top three features (mean SHAP score)	Density × Sustainability	Density × Sustainability
	BSF × Sustainability	Green ratio
	Green ratio	BSF × Sustainability

Source: Author calculation

Two insights follow from the analysis. *High density (high BSF ratio) is hazardous only when green share and mixed land use are low; conversely, generous greenery neutralizes much of the density penalty.* Risk and vulnerability surge once BSF exceeds 0.60 (or 60%) *and* sustainability falls below 1.4 (normalized index). In terms of threshold simulation and mediation results, a mediation test partitioned the BSF Risk path into direct effect of 0.76; indirect via sustainability of 4.11 and an overall total effect of 4.87. Hence >80 % of the BSF influence on risk flows through lost permeability and canopy. Monte Carlo simulations (10000 draws) locate the critical envelope where both risk metrics hit their inflection.

Table 32. Monte-Carlo simulations (10,000 draws)

Variable	Tipping value
BSF	0.55 – 0.60
Density	12,500 inh/km
Green index	< 1.4

Source: Author calculation

Cities that cross only one of the three bounds show moderate deterioration, breaching all three amplifies vulnerability to multi-hazard risk by 13 % and keeps 8 % above baseline even under optimistic climate scenarios.

[18] Random-Forest models mitigate over-fit by leave-one-out cross-validation plus 1 000 bootstrap resamples; the high R^2 (> 0.9) therefore reflects ensemble stability on this small dataset rather than an unrealistically perfect fit.

The findings show us that density is not destiny. Compactness heightens risk mainly *when ecological buffers are absent*. Furthermore, uniform, mid-range BSF (0.55 or 55%) *remains the optimal threshold*. It shows high functional scores and stays below the multi-hazard risk tipping line. Green/entropy are leverage points. Raising the green index from 1.3 to 1.8 halves the indirect BSF risk pathway in the simulation. In terms of what regulatory authorities can have as takeaway, we should emphasize keeping *BSF < 0.60 in flood- or earthquake, or heat exposed zones unless compensatory green factor ≥ 1.8 and monitor population density ceilings.*

4.7 What the data analysis shows in terms of compact city definition

The cross-city analysis shows that "compact" is not a synonym for "dense", shows in fact quite the opposite. Cities become compact only when morphological intensity is matched by functional performance and bounded by risk. In other words, compactness is a *calibrated stat*e that exists inside an empirically observed window where built form, accessibility and safety cohere. Outside that window, the same density ceases to deliver proximity and begins to amplify hazard; it is simply dense.

The analysis advances the following definition, that a compact city is an urban system in which the spatial configuration of floor area and ground coverage is organised so that residents reach daily services and jobs quickly and reliably, while the combined exposure to hazards remains low. *The condition is operational* when three elements are simultaneously true.

- First, morphology is balanced, BSF is sufficient to shorten distances, but not so high as to eliminate permeability, *shade and sky view*.
- Second, function is verified, mixed land uses and accessibility translate built intensity into effective access rather than congestion.
- Third, risk is bounded, micro-climatic loads, floods exceedance and seismic requirements are held under threshold values set by the local hazard profile and enforced through permitting.

The comparative results across thirteen cities make this state observable. In the urban fabrics that performed best, coverage stabilised around mid-range sealing with a meaningful permeable and vegetated base, floor-area increments were coupled to transit and service provision, and any additional intensity was conditioned on cooling and detention at block scale. In those circumstances, accessibility indices improved while surface temperatures and exceedance probabilities either held steady or fell. Where sealing exceeded these mid-range levels and additional volume was added without functional or hydrologic compensation, travel times lengthened, heat loads rose and nuisance flooding increased. The pattern repeats across different urban contexts, which is why the thesis frames *compactness as a window rather than a point*. Indicative values recur, in many cases, building coverage congregates around 50% per 100mx100m blocks and population density around ten thousand per square kilometre, but the precise edges of the window shift with street geometry, transit quality, topography and hazard.

Defining compactness in this way also clarifies what it is not. High-rise clusters built on sealed plots that rely on long car trips are not compact even if their density figures are large; conversely, medium rise districts with balanced coverage, mixed uses and dependable transit can be compact at moderate densities if risk remains bounded. The decisive test is not whether a target number is hit, but whether the local fabric sits inside the safe performance window where additional floor area still converts to access without breaching heat, flood or seismic limits.

This reframing has immediate implications for policy. Compactness becomes something that can be *permitted, measured and corrected*. The planning system moves from scalar density targets to an admissible envelope that ties authorisation to three verifications. Form within the calibrated range, function evidenced by service and transit access, and risk below thresholds. When these conditions hold, densification can proceed and be replicated with confidence. When they do not, the city is dense but not compact, and further intensity should either be refused or made contingent on the measures (permeability, shade, detention, seismic detailing) that bring the fabric back inside the window. Here the compact city is defined as *a bounded, testable equilibrium between form, function and risk, demonstrated empirically across multiple cities and rendered operational for planning through measurable thresholds and enforceable decision gates.*

CHAPTER V: TIRANA ANATOMY OF A COMPACT CITY

5.1 Introduction

Tirana's morphology was shaped by a sharp change after 1990 (fall of communism), a rapid rise in residents, an expansion of the governed territory, and a long phase of informal building that outpaced infrastructure needs. Plans changed often across political cycles, with local up zonings that were not always matched by transport capacity, drainage, open space or parking. The outcome is visible in several districts, high coverage at ground level, narrow view corridors, hot sealed courtyards, and recurrent conflict between new floor area and basic services. Recent demolitions and renewals are a costly correction to decades of density allowed to grow without clear morphological and hazard limits. In this chapter, Tirana is read as a policy stress-test in terms of densification, evaluation of real compact city development and its relation to hazard prone areas.

Tirana, as the capital and largest city of Albania, represents not only the country's political and economic center but also its most dynamic site of urban transformation. Over the past two decades, Tirana has undergone rapid population growth, intense redevelopment, and sweeping shifts in land use, all of which have made it a natural laboratory for studying the promises and paradoxes of compact urban form. The city's distinctive urbanization trajectory, marked by high rates of infill, vertical expansion, and large-scale densification, stands at the intersection of multiple planning dilemmas that are now central to European and global debates. Tirana's recent spatial strategies, including the adoption of the Local Development Plan, from which the datasets for this analysis are also collected (PPV, 2017–2030), explicitly embrace compact city principles as the foundation for sustainable growth, yet the outcomes on the ground reveal sharp spatial inequalities, functional imbalances, and growing exposure to environmental hazards.

Given its role as a national prototype, Tirana offers an ideal setting for testing the limits and potential of compact city policies. It allows for empirical evaluation of how international planning concepts translate into practice in post-socialist contexts, and for comparison with the patterns observed in twelve other Albanian cities as well as leading European benchmarks. By analyzing Tirana in depth—using detailed, parcel-level and grid-based metrics of density, verticality, land-use mix, accessibility, and risk, this chapter aims to reveal both the strengths and vulnerabilities of its urban form, and to draw out evidence-based recommendations for future resilience and sustainability strategies.

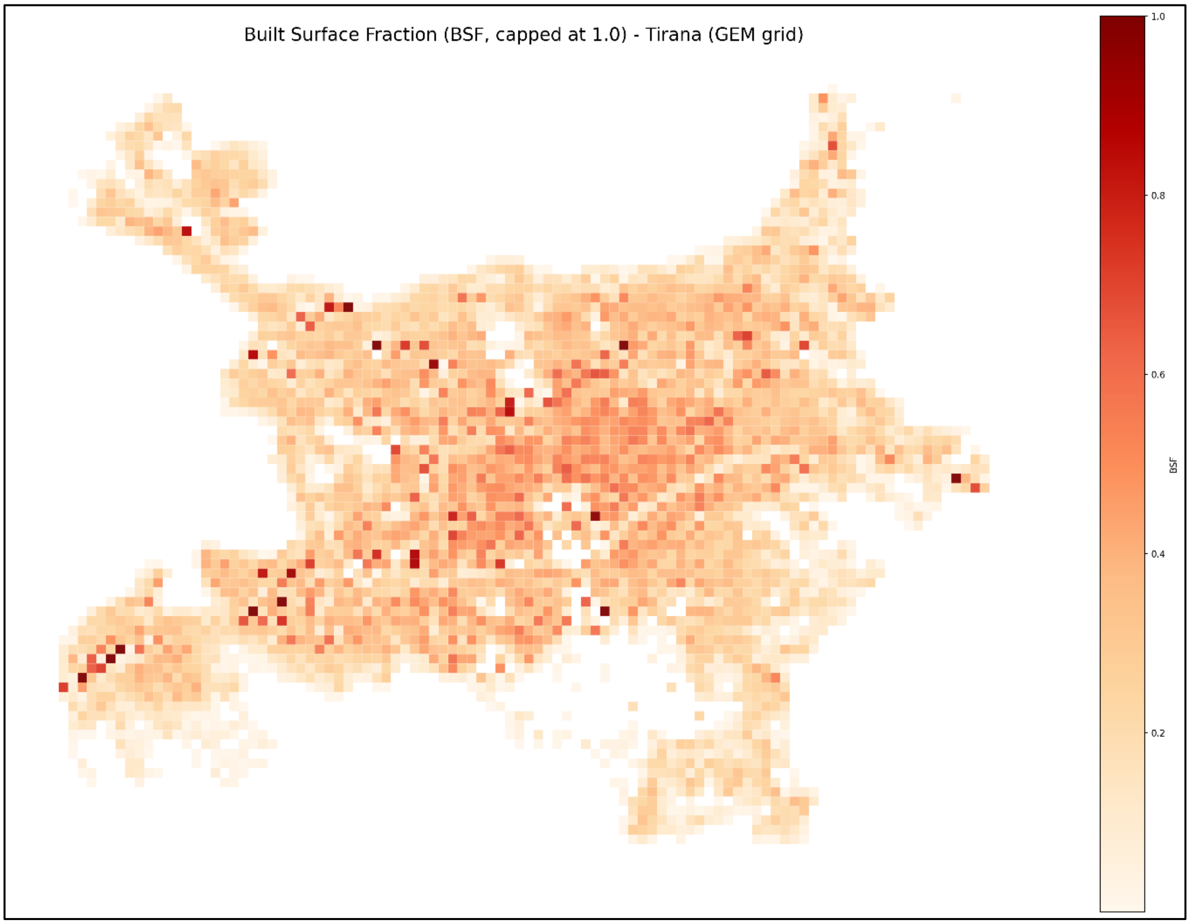
This chapter draws on a comprehensive suite of spatial and attribute data to systematically assess the urban form, functional performance, and multi-hazard profile of Tirana. The core dataset includes georeferenced building footprints, parcel boundaries, building height (number of floors), and detailed land-use inventories derived from the *Local General Plan* (PPV 2017–2030), offering the official dataset for Tirana. All morphological and functional indicators are calculated at two complementary spatial resolutions, the 100x100 m grid, and at the individual parcel scale, leveraging cadastral precision for intervention mapping. This dual-scale approach ensures strict comparability within Tirana's internal neighborhood structure.

5.2 Morphological Analysis

5.2.1 Built Surface Fraction (BSF)

Built Surface Fraction (BSF) was calculated for all buildings in Tirana also using the 100x100 m grid, replicating the methodology employed for the 13 cities, however using cadastral data for result evaluation, and therefore replicating the model in different data strata. For each grid cell, the sum of building footprint areas was divided by the cell area to yield BSF values, capped at 1.0 to account for potential data anomalies. This approach permits cross-city comparisons while minimizing bias from grid scale or data resolution.

Figure 10. Tirana BSF calculation

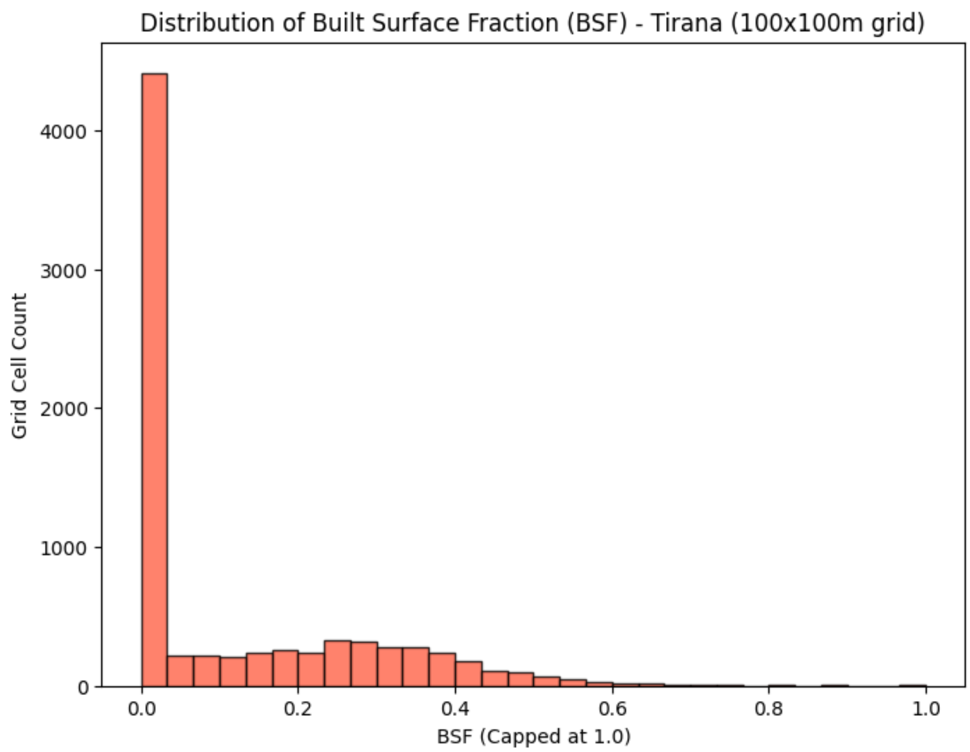


Source: Authors calculation

The statistical profile of Tirana's Built Surface Fraction (BSF) highlights a striking pattern of *spatial inequality and pronounced urban heterogeneity*. The mean BSF of 0.121 indicates that, on average, only about 12% of each 100x100 m grid cell is covered by building footprints. The standard deviation of 0.167 and the extended right tail of the distribution (maximum BSF = 1.000) indicate the presence of a limited number of cells exhibiting very high or even saturated built coverage. This is reinforced by the upper percentiles, were only at the 75th percentile does the BSF reach 0.240, and even at the 95th percentile, it does not exceed 0.45. Thus, genuinely compact or intensely built-up conditions are highly localized phenomena in Tirana, occurring in just a small fraction of the urban grid.

Perhaps most telling is the coefficient of 0.689, which quantifies the high degree of spatial inequality in the distribution of built density. This value is considerably above the European urban average (typically 0.55–0.62), demonstrating that Tirana's built environment is characterized by a sharp *dichotomy*, pockets of extreme compaction exist within a much broader field of sparse or absent development. Such a spatial structure is a hallmark of fragmented urbanization, as well as the legacy of rapid, uneven expansion under post-socialist conditions. These findings confirm that while Tirana exhibits zones of very high density, the overall cityscape remains overwhelmingly open or underdeveloped. The result is an urban morphology that combines intense local clustering of the built form with pervasive low-density surroundings.

Figure 11. Distribution of BSF



Source: Authors calculation

The results in the above figure indicate that only 0.88% of grid cells in Tirana exhibit a BSF greater than 0.7, denoting a very limited spatial extent of highly compact urban form. Meanwhile, 15.29% of cells fall within the moderate-density band ($0.4 < BSF \leq 0.7$), suggesting that medium-density development is present but not dominant. This distribution confirms that, at this scale, Tirana's urban fabric is predominantly characterized by low or fragmented built coverage, with genuinely compact urban conditions remaining rare and highly localized. Tirana's BSF, reveals a pronounced spatial inequality in the distribution of built-up density. This value is considerably higher than the typical range for European cities (often 0.5–0.6), indicating that Tirana's urban fabric is highly polarized. Compact, dense zones coexist with large areas of much lower density or open space. Such a pattern is consistent with recent and uneven urban expansion, fragmented land use, and concentrated redevelopment, all characteristic of post-socialist urban transitions. The results show that, while some neighborhoods approach "ultra-compact" status, most of the city remains much less intensively built, with significant implications for service provision, accessibility, and risk exposure.

5.2.2 Urban density and spatial distribution in Tirana

Spatial analysis of Tirana's urban fabric reveals a pronounced spatial duality; genuinely compact urban conditions are both rare and highly localized. As we saw form the BSF calculation, only 0.88% of 100×100 m grid cells exceed the Built Surface Fraction (BSF) of 0.7, while just 681 parcels have BSF greater than 50%. The gross built-coverage ratio, calculated over the entire municipal convex hull, is only 2.5%, highlighting the predominance of peri-urban and undeveloped land within the city's administrative boundaries (taking into account not only the urban area but overall land within Tirana boundary).

Table 33. Spatial autocorrelation in Tirana

Metric	Tirana value	Interpretation
Gross built-coverage ratio	**0.025**	Only approximately 2.5 % of the convex-hull land envelope is physically occupied by building footprints.
Polsby-Popper shape compactness	**0.827**	The municipal outline is relatively efficient (1 = perfect circle).
Moran's I (250 m grid)	**0.833 (p = 0.001)**	Very strong positive spatial autocorrelation, large footprints cluster rather than being randomly dispersed.
Clark–Evans R	**0.484**	R < 1, building centroids are much closer together than a random Poisson pattern showing again evidence of clustering.

Source: Author calculation

Despite this apparent sparsity at the macro scale, spatial statistical metrics consistently reveal that Tirana's built mass is intensely clustered within certain zones. The Polsby–Popper compactness score of 0.827 suggests that the municipal outline itself is relatively efficient—approximating the ideal of a compact, contiguous urban form. Moran's I (0.833, $p = 0.001$) demonstrates strong positive spatial autocorrelation at the 250 m grid level, indicating that large building footprints are not randomly distributed but instead concentrate in spatial clusters. Similarly, a Clark–Evans R of 0.484 ($R < 1$) confirms that building centroids are much closer together than would be expected under a random distribution, further evidence of high-density nodes emerging within an otherwise open urban envelope.

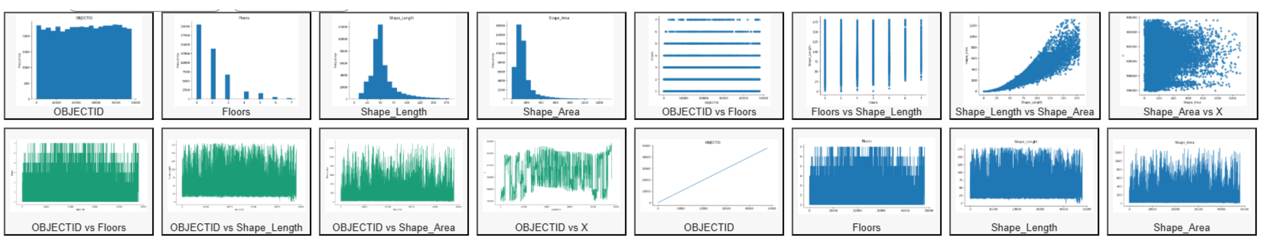
This pattern results in sharply defined; high-density clusters embedded within a much larger matrix of low-density or vacant land. Such spatial structuring presents both significant challenges and opportunities for urban management: while it enables targeted infill and intensification policies, it also exposes the city to issues of functional imbalance, accessibility gaps, and increased vulnerability in zones where compactness and risk coincide.

- *Urban morphological concentration and spatial clustering in central (urban) Tirana*

Tirana urban core dataset contains 48,063 buildings in Tirana. It includes information on the number of floors, building footprint, perimeter, and coordinates. The average building footprint is 198 m², with a wide range, smallest footprint: 0.0006 m² (potential data issue) and largest footprint: 28,140 m² (likely large commercial or public buildings). The average perimeter of buildings is 58.3 meters. Some buildings have extremely high perimeters (up to 1,219 meters), which could indicate large irregular-shaped structures. The values indicate a *significant geographic spread*.

Table 34. Descriptive statistics and exploration data analysis of building stock

```
Floors: count    48063.000000
mean             2.106985
std              1.690812
min              0.000000
25%              1.000000
50%              2.000000
75%              3.000000
max             53.000000
Name: Floors, dtype: float64
Shape_Area: count    48063.000000
mean           198.026002
std            367.212245
min              0.000592
25%             92.292060
50%            130.899288
75%            189.608543
max          28140.611015
Name: Shape_Area, dtype: float64
Shape_Length: count    48063.000000
mean            58.327441
std             40.399352
min              0.238203
25%             40.741933
50%             48.668095
75%             61.886540
max           1219.343627
Name: Shape_Length, dtype: float64
Number of outliers detected: 1732
```



Source: Authors calculation

5.2.3. Building clusters and typologies

Table 35. Building clusters and typologies

Cluster	Floors	Shape_Area	Shape_Length
0	1.371851	109.942237	44.162780
1	2.887570	532.544088	121.934314

2	3.346061	187.114818	59.838210

Source: Author calculation

To further interrogate this morphological diversity, a cluster analysis was conducted using key built-form indicators: number of floors, footprint area, and perimeter. The analysis identified three primary building typologies in Tirana (Table 35; Figure 14):

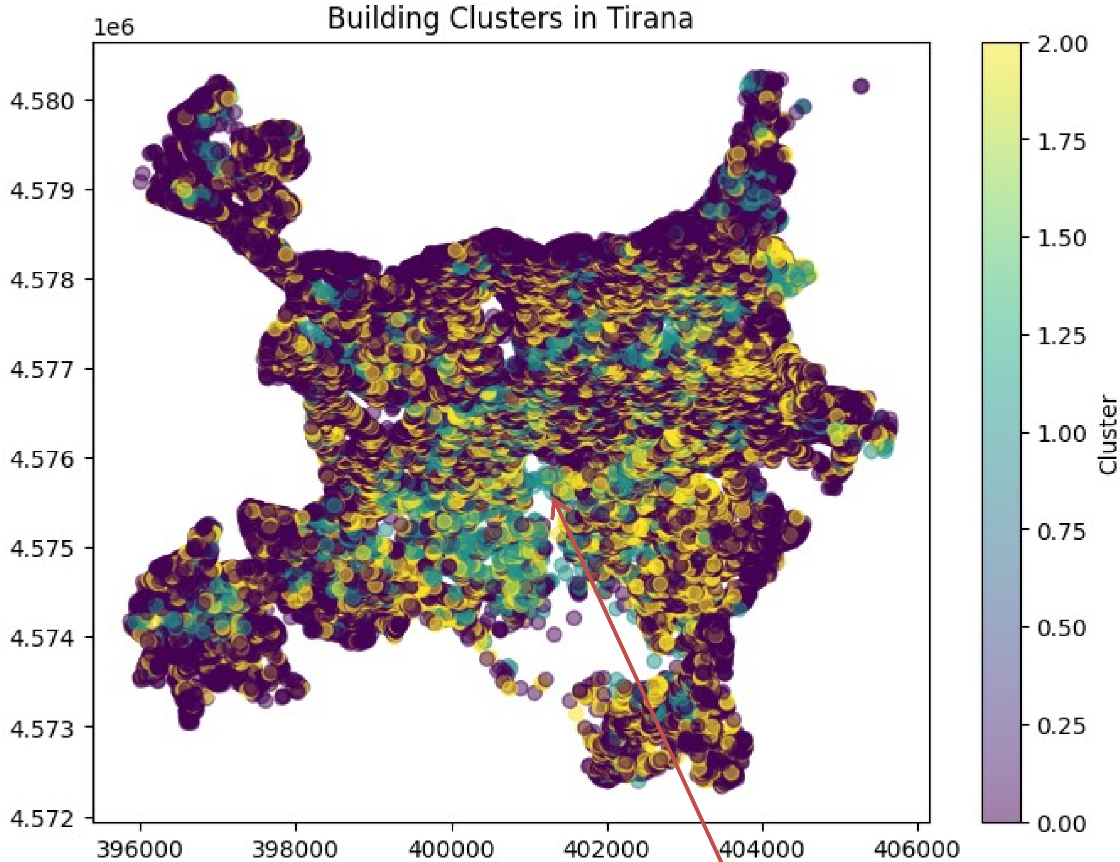
- **Cluster 0,** low-rise, small-footprint buildings (mean 1.37 floors, 110 m² footprint, 44 m perimeter), corresponding to detached dwellings or minor structures.
- **Cluster 1,** mid-rise, large-footprint structures (mean 2.89 floors, 533 m² footprint, 122 m perimeter), indicative of apartment blocks, commercial, or institutional buildings.
- **Cluster 2,** taller, moderate-footprint, and relatively compact forms (mean 3.35 floors, 187 m² footprint, 60 m perimeter), often reflecting vertical infill and intensified residential or mixed-use developments.

This typology demonstrates the coexistence of traditional low-rise housing with increasingly common mid-rise and infill typologies, a reflection of both historical settlement patterns and contemporary densification pressures in central and redeveloping neighborhoods. The spatial concentration of these clusters aligns with areas of heightened density and supports a nuanced understanding of how built morphology shapes, and is shaped by, urban growth dynamics.

Analysis further reveals the saturation of land use in much of Tirana. Notably, 66% of buildings have a BSF above 80%, indicating that most structures nearly exhaust their allotted parcels, leaving minimal open space. Only 6.8% of buildings are classified as low-density (BSF < 50%), underscoring the rarity of detached homes or large open plots. Medium-density buildings (50–80% BSF) account for 27% of the total, reflecting transitional areas where a balance between built-up and open space still persists.

Collectively, these findings highlight Tirana’s distinct urban structure: concentrated pockets of extreme density amid a broader field of underdeveloped or vacant land. This spatial mosaic has direct implications for urban planning, hazard mitigation, and sustainable development interventions, which must balance the need for compactness with the preservation of urban livability and resilience.

Figure 12. Building clusters



Source: Author calculation

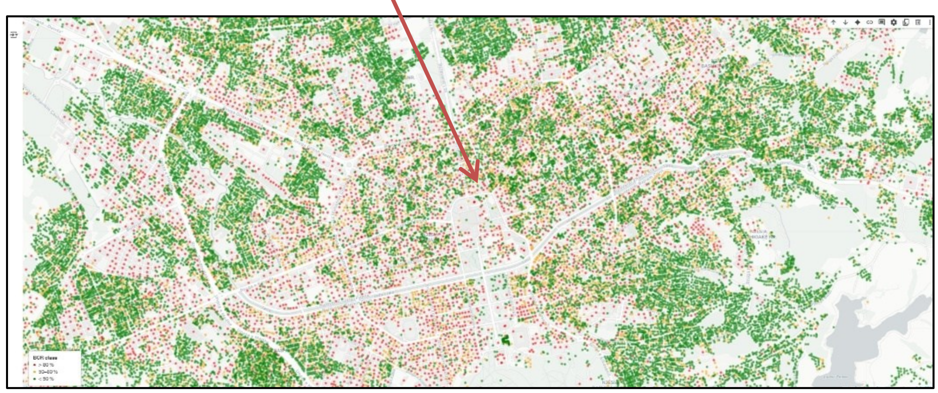
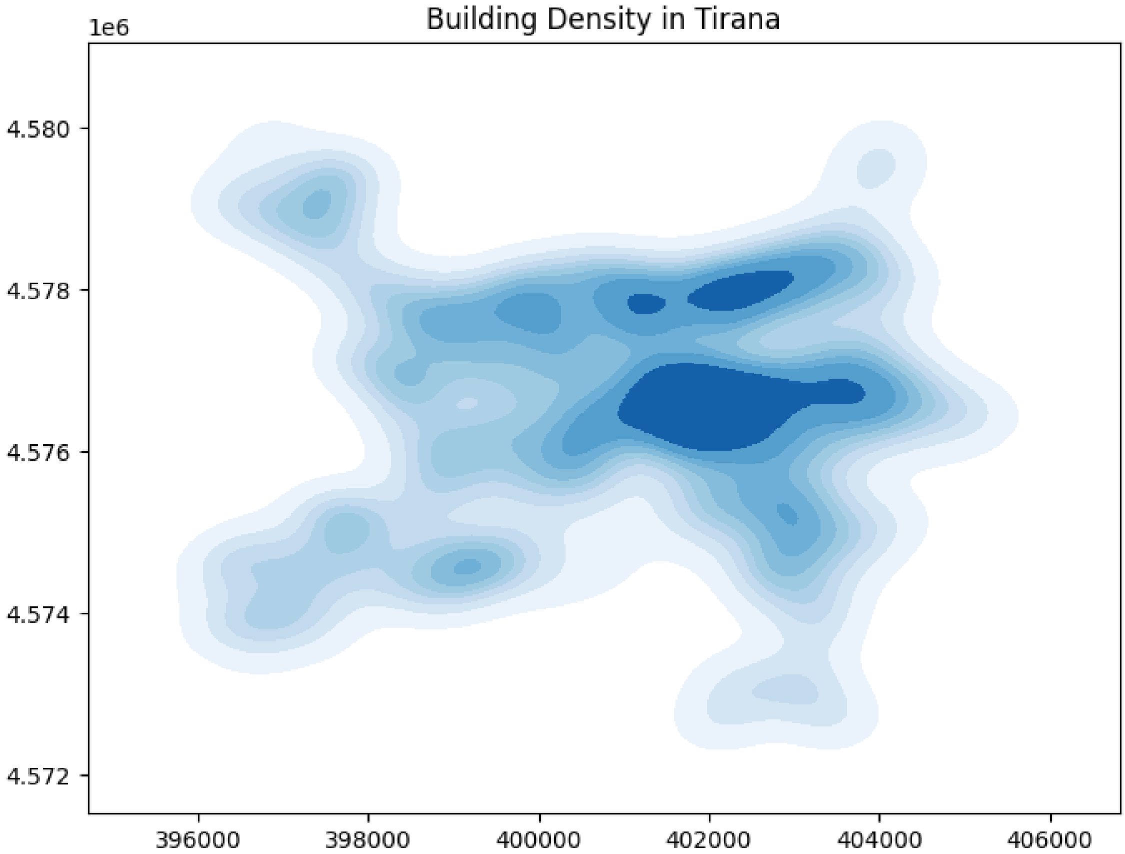


Figure 13. Concentration, building density analysis



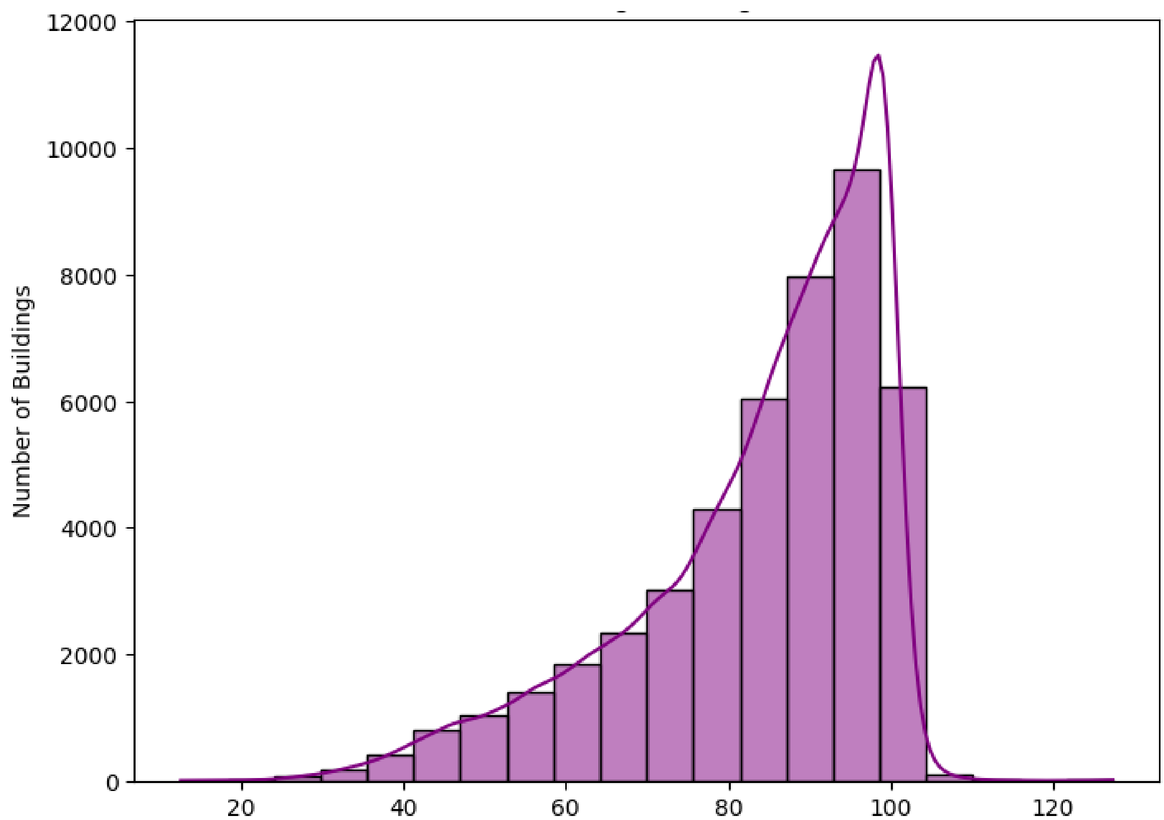
Source: Author calculation

Table 36. Density calculations in Tirana

index	Shape_Area	Shape_Length	Estimated_Lot_Area	BCR
0	303.167462543	72.8120488172	331.3496533098947	91.49472755278929
1	199.478491663	58.2076586879	211.75822062044128	94.20106151182122
2	112.716800792	42.6619781332	113.7527736398522	99.08927684600278
3	153.512718603	51.4361504706	165.35484845213776	92.8383534199389
4	148.262336705	49.8212466215	155.13478843252034	95.57001250528042

Source: Author calculation

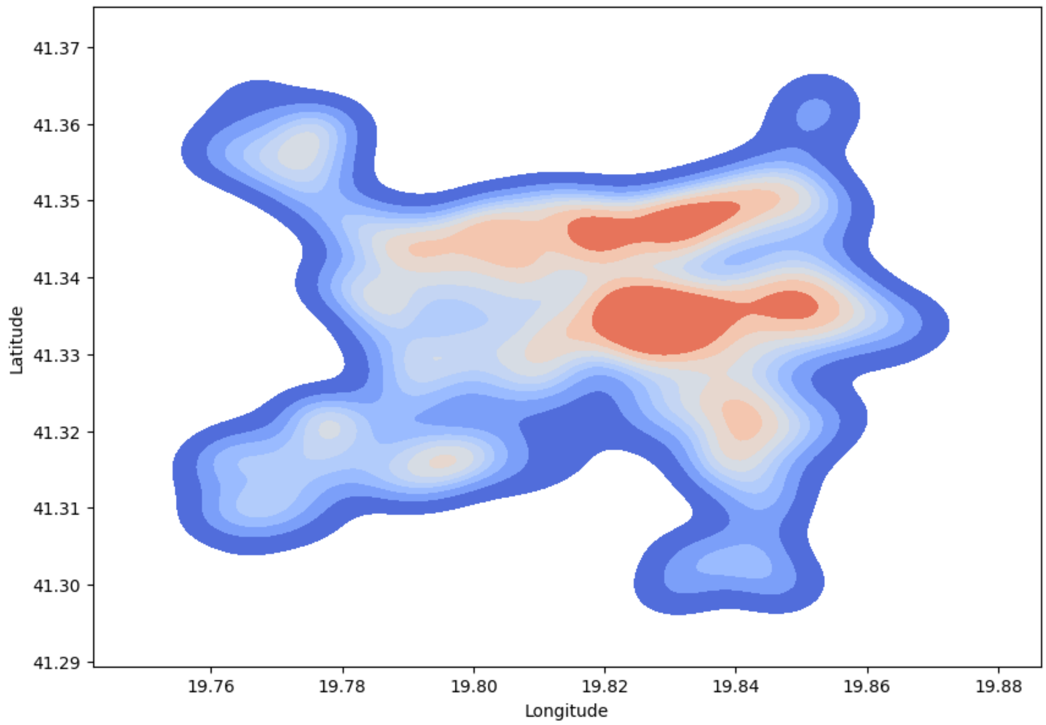
Figure 14. Distribution of BSF



Source: Author calculation

BSF analysis further reveals the saturation of land use in much of Tirana. Notably, 66% of buildings have a BSF above 80%, indicating that most structures nearly exhaust their allotted parcels, leaving minimal open space. Only 6.8% of buildings are classified as low-density (BSF < 50%), underscoring the rarity of detached homes or large open plots. Medium-density buildings (50–80% BSF) account for 27% of the total, reflecting transitional areas where a balance between built-up and open space persists.

Figure 15. Heatmap of BSF distribution



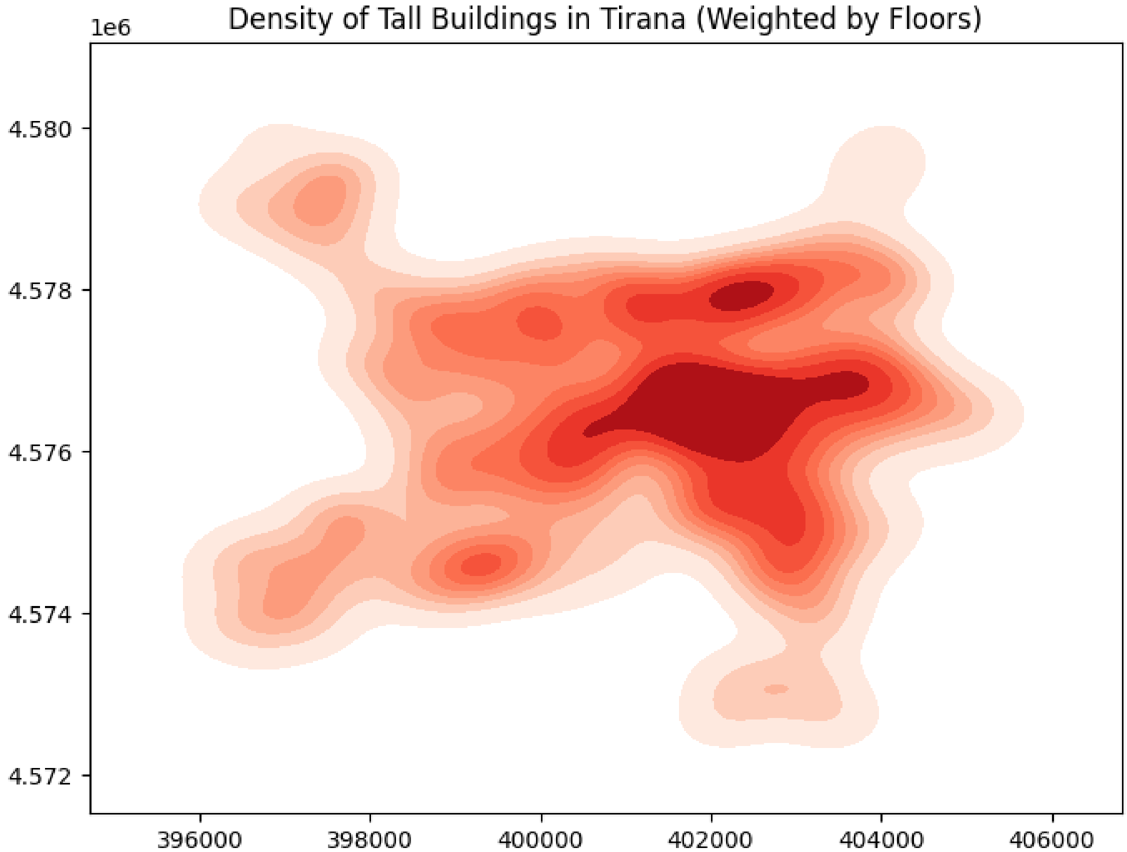
Source: Author calculation

The findings highlight Tirana’s distinct urban structure, concentrated pockets of extreme density amid a broader field of underdeveloped or vacant land. This spatial mosaic has direct implications for urban planning, hazard mitigation, and sustainable development interventions, which must balance the need for compactness with the preservation of urban liveability and resilience.

5.2.3 Verticality and FAR

The vertical profile of Tirana’s built environment demonstrates significant heterogeneity, as evidenced by both the spatial density of building heights and the distribution of Floor Area Ratio (FAR) values across the city (Figure 20). FAR, defined as the total floor area of a building divided by its estimated lot area, serves as a key indicator of vertical intensification and the efficiency of land use.

Figure 16. ‘Density' of verticality and FAR calculations in Tirana



Source: Author calculation

Sample calculations illustrate the diversity of vertical development in Tirana: buildings with modest footprints can achieve FAR values approaching or exceeding 2.0 when developed as multi-story structures, while larger commercial or institutional buildings may reach even higher ratios. According to the analyzed data, high FAR values (>3–5) are typically observed in commercial or business districts, reflecting substantial vertical expansion, whereas medium FAR (1–3) prevails in residential apartment zones and mixed-use neighborhoods. Low FAR (<1) characterizes suburban or industrial sectors, often associated with more extensive open land or single-story development.

Table 37. Floor area ratio calculations

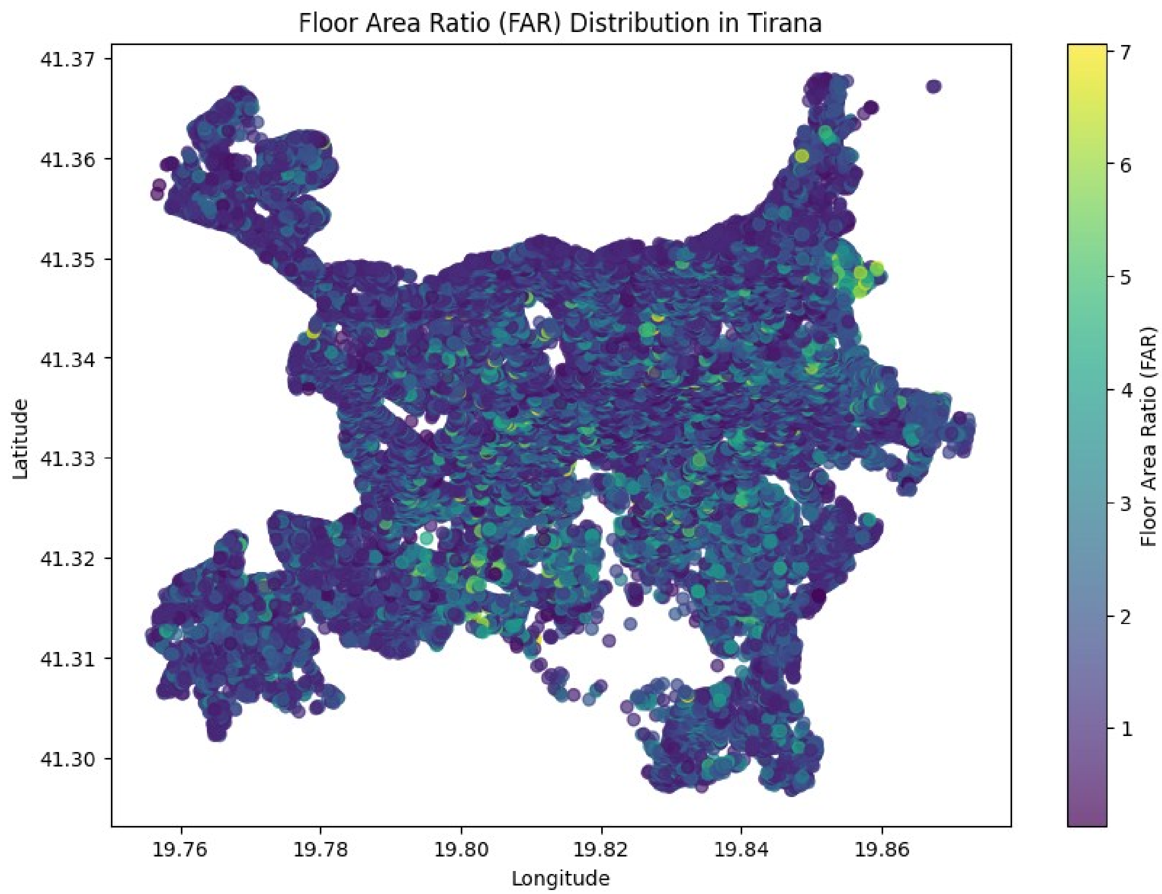
index	Shape_Area	Floors	Total_Floor_Area	Estimated_Lot_Area	FAR
0	303.167462543	2	606.334925086	331.3496533098947	1.8298945510557858
1	199.478491663	1	199.478491663	211.75822062044128	0.9420106151182123
2	112.716800792	2	225.433601584	113.7527736398522	1.9817855369200554

3	153.512718603	3	460.538155809	165.35484845213776	2.7851506025981667
4	148.262336705	3	444.787010115	155.13478843252034	2.8671003751584125

Source: Author calculation

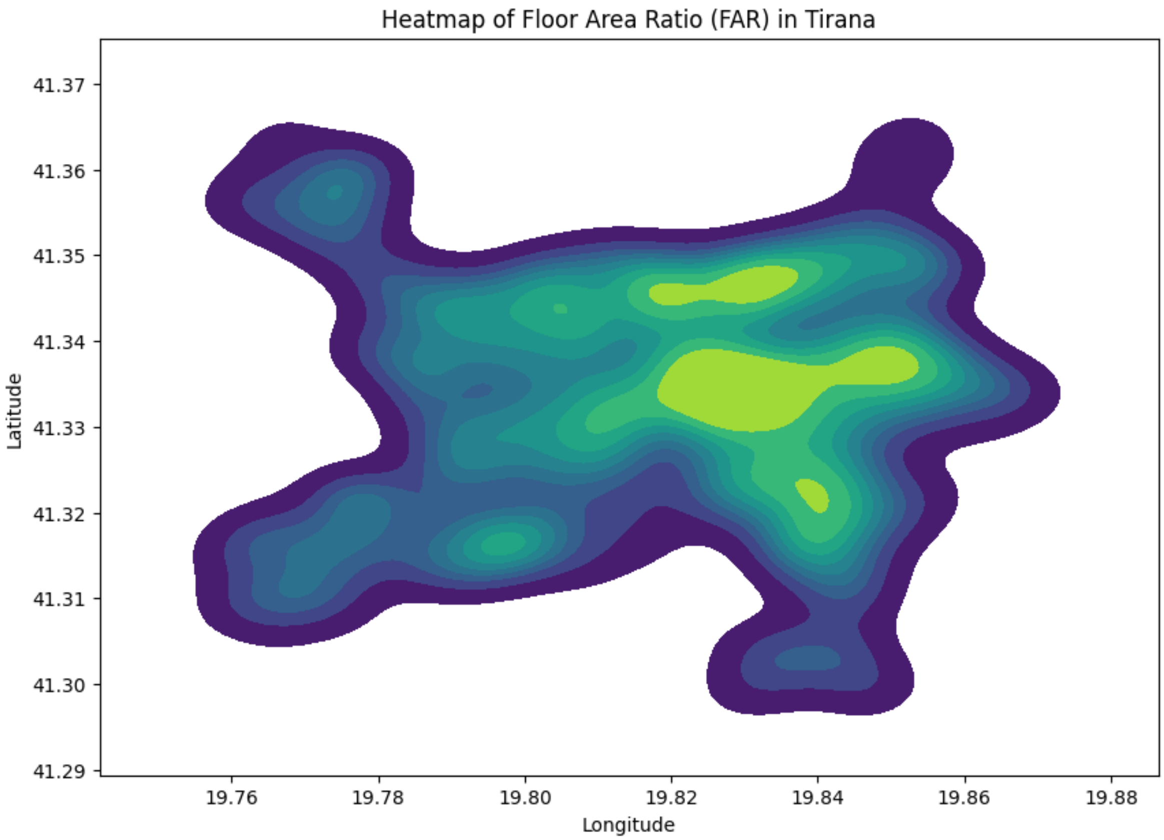
- High FAR (>3-5), Highly built-up areas with vertical expansion (e.g., commercial/business districts).
- Medium FAR (1-3), Common in residential apartment buildings or mixed-use developments.
- Low FAR (<1), Found in suburban or industrial zones, with more open land.

Figure 17. FAR distribution



Source: Author calculation

Figure 18. FAR distribution heatmap



Source: Author calculation

The spatial distribution of verticality underscores the emergence of denser, taller forms in selected urban cores and redevelopment areas, contrasting with the lower-rise, horizontally expansive patterns still present in peripheral zones. This variation reflects both regulatory influences (such as zoning and building codes) and the differentiated economic and functional demands placed upon Tirana's urban fabric. The verticality and FAR profiles highlight the ongoing evolution of Tirana's built environment towards more intensive land use in strategic locations, with important implications for compactness, liveability, and the city's capacity to accommodate future growth within its existing footprint.

5.2.4 Modeling building height determinants in Tirana

Table 38. Regression analysis

```
                            OLS Regression Results
==============================================================================
Dep. Variable:                 Floors   R-squared:                       0.163
Model:                            OLS   Adj. R-squared:                  0.163
Method:                 Least Squares   F-statistic:                     2221.
Date:                Sat, 01 Mar 2025   Prob (F-statistic):               0.00
Time:                        14:11:50   Log-Likelihood:                -68544.
No. Observations:               45466   AIC:                         1.371e+05
Df Residuals:                   45461   BIC:                         1.371e+05
Df Model:                           4
Covariance Type:            nonrobust
================================================================================
                   coef    std err          t      P>|t|      [0.025      0.975]
--------------------------------------------------------------------------------
const          191.3811     14.521     13.179      0.000     162.919     219.843
Shape_Area       0.0026      0.000     22.750      0.000       0.002       0.003
Shape_Length     0.0049      0.001      8.212      0.000       0.004       0.006
X             3.987e-05   2.21e-06     18.074      0.000    3.55e-05    4.42e-05
Y            -4.503e-05   3.17e-06    -14.212      0.000   -5.12e-05   -3.88e-05
================================================================================
Omnibus:                     7996.287   Durbin-Watson:                   1.615
Prob(Omnibus):                  0.000   Jarque-Bera (JB):            16119.377
Skew:                           1.064   Prob(JB):                         0.00
Kurtosis:                       4.995   Cond. No.                     1.30e+10
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 1.3e+10. This might indicate that there are
strong multicollinearity or other numerical problems.
```

Source: Author calculation

This regression analysis examines the factors influencing building height in Tirana using a linear regression model. The primary objective is to determine whether physical dimensions and spatial position influence the number of floors in a building. The regression model produced a R^2=0.163, indicating that only 16.3% of the variation in building height can be explained by the included variables. This suggests that additional external factors, such as urban zoning policies, land value, and economic activity, significantly contribute to variations in building height. While the model provides a statistically significant relationship between height and the factors examined, its predictive power remains limited, implying that building height in Tirana is governed by more complex urban dynamics than just footprint size or perimeter.

Results show that building footprint has a positive but weak effect on height, with an increase of 1 m² in footprint size leading to an increase of 0.0026 floors on average.. Although larger buildings tend to be taller, the effect is small. This suggests that urban planning regulations or functional zoning rules may limit height regardless of footprint size.

- *The role of geographic location*

Moving eastward in Tirana leads to taller buildings. Moving northward leads to shorter buildings. Eastern areas of Tirana tend to have taller buildings, possibly due to higher land value, commercial districts, or better infrastructure. Northern areas feature shorter buildings, likely indicating more residential neighborhoods with zoning height restrictions. These results suggest that Tirana’s building heights are driven more by spatial location than by footprint size. The strong effect of geographic coordinates indicates that zoning regulations or market-driven factors play a more critical role in determining height than physical constraints. The small impact of footprint and perimeter implies that building regulations enforce height restrictions regardless of plot size. Reviewing zoning laws to assess whether height restrictions align with urban growth needs. Encourage vertical expansion in commercial areas to reduce urban sprawl. While building footprint and perimeter play a role in determining height, their impact is marginal. Instead, urban location (X, Y coordinates) emerges as the dominant factor, reinforcing the idea that building heights in Tirana are shaped by zoning laws, land value, and urban planning policies rather than just plot size.

The Random Forest model explains 30% of height variation, almost double the accuracy of the OLS model. Mean Absolute Error (MAE) = 0.76, meaning predictions are on average within 1 floor of actual values. Machine learning captures nonlinear patterns that simple regression cannot. Footprint size (Shape_Area) is the strongest predictor of height. Urban location still plays a major role, suggesting zoning and land use policies shape height limits. Perimeter influences height, possibly due to plot shapes or building typologies.

5.3 Functional analysis

5.3.1 Land-Use Entropy calculation

The land-use entropy index, which quantifies the degree of functional diversity at the parcel level, ranges from 0.00 to 0.56 across Tirana's urban fabric.

Table 39. Land Entropy Calculation

count	**11436.000000**
mean	0.259666
std	0.086828
min	-0.000000
25%	0.190551
50%	0.278043
75%	0.302017
max	0.556636

Source: Author calculation

A value of zero denotes *strictly monofunctional parcels*, while higher scores indicate greater land-use mixing. The citywide mean entropy of 0.26 reflects a generally modest level of functional integration, with most parcels supporting limited diversity of use. The median value (0.28) and upper quartile (0.30) suggest that central areas and select intensively planned neighborhoods achieve moderate urban mixing, whereas peripheral and residential districts remain functionally segregated.

The relatively low standard deviation (0.087) and a constrained maximum (0.56) reinforce the observation that no parcel in Tirana reaches the theoretical ideal of fully mixed land use. These patterns are likely shaped by prevailing zoning regulations and development typologies, which tend to promote uniformity and restrict the emergence of highly diverse urban environments. In sum, while isolated pockets of functional mixing exist, Tirana remains characterized by substantial areas of single-use development—limiting the potential benefits of compact urbanism such as shorter trip distances, economic vibrancy, and social resilience.

5.3.2 Accessibility analysis

Accessibility analysis across key urban functions reveals a highly differentiated landscape of service provision.

Figure 19. Green Space accessibility 5-10-15 minutes

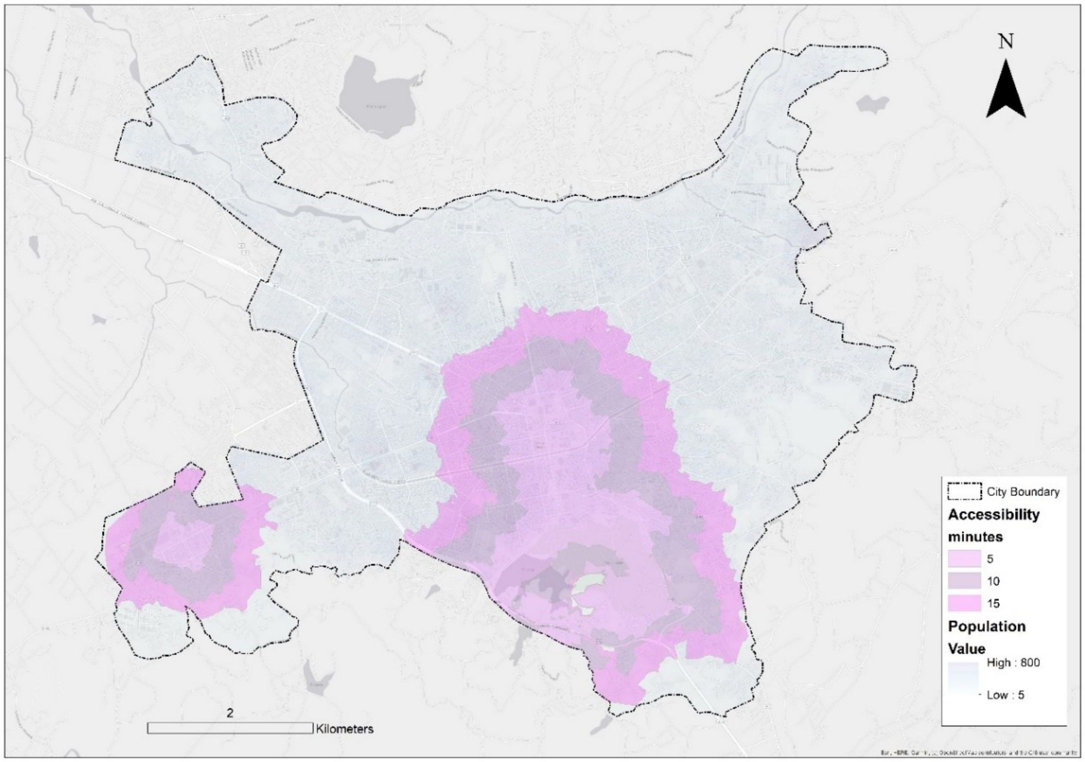


Figure 20. Groceries accessibility 5-10-15 minutes

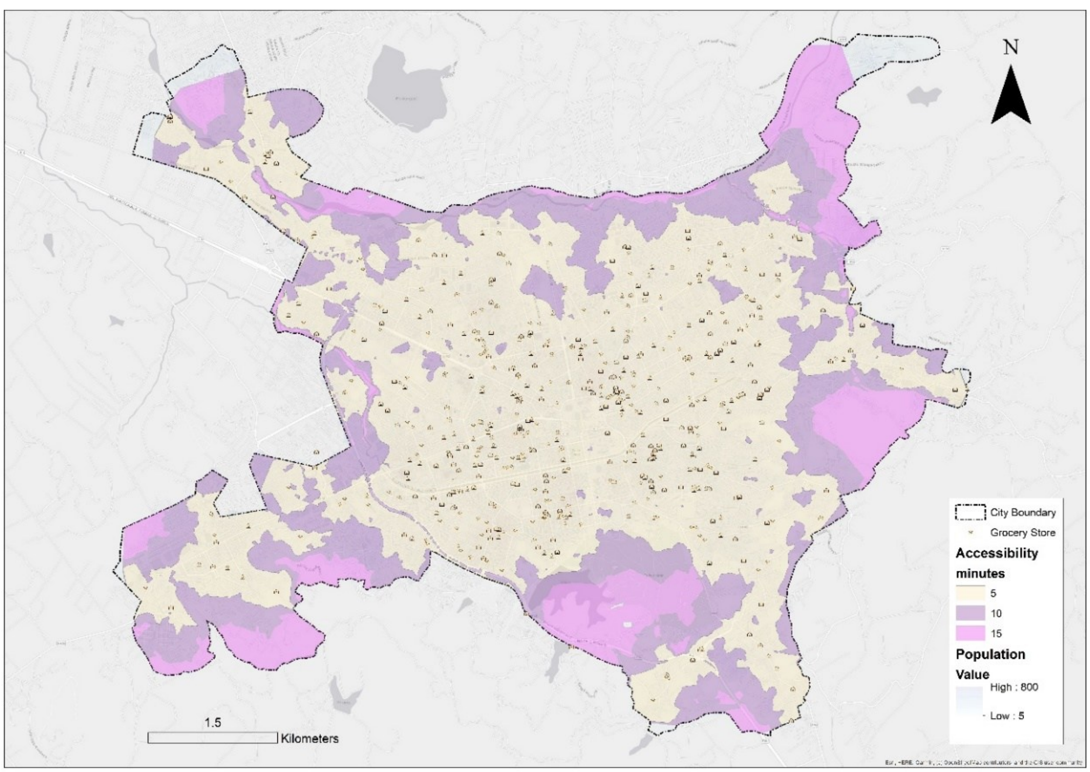


Figure 21. High schools' accessibility 5-10-15 minutes

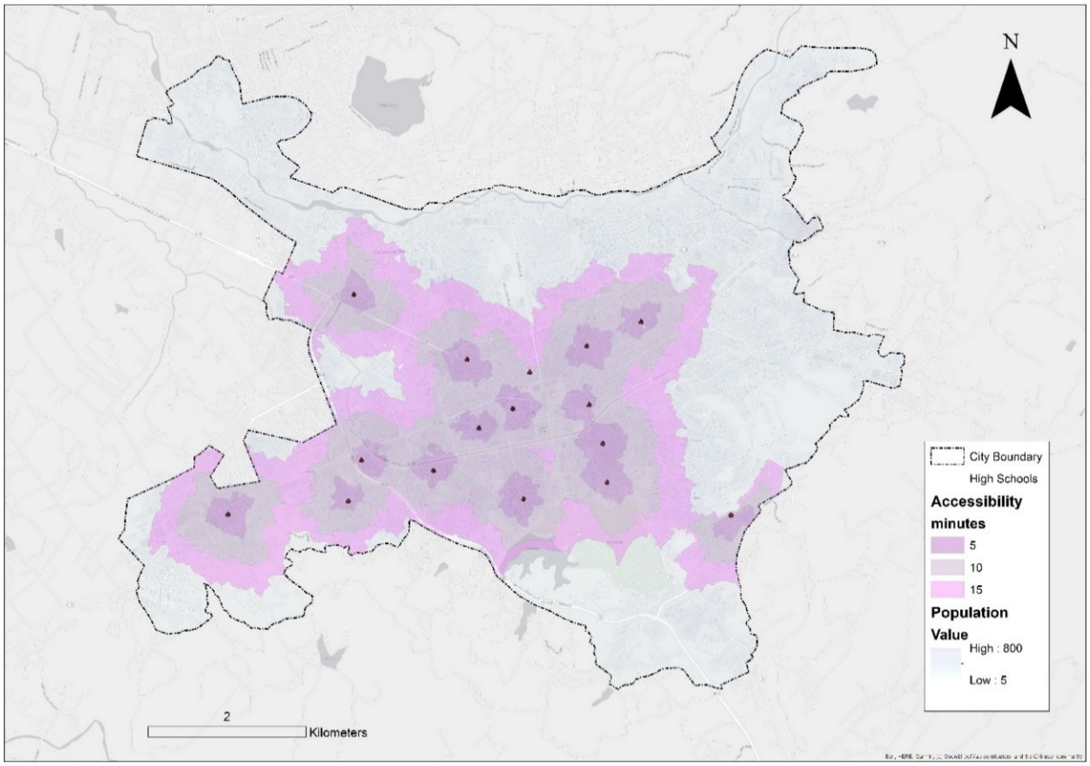


Figure 22. Hospitals accessibility 5-10-15 minutes

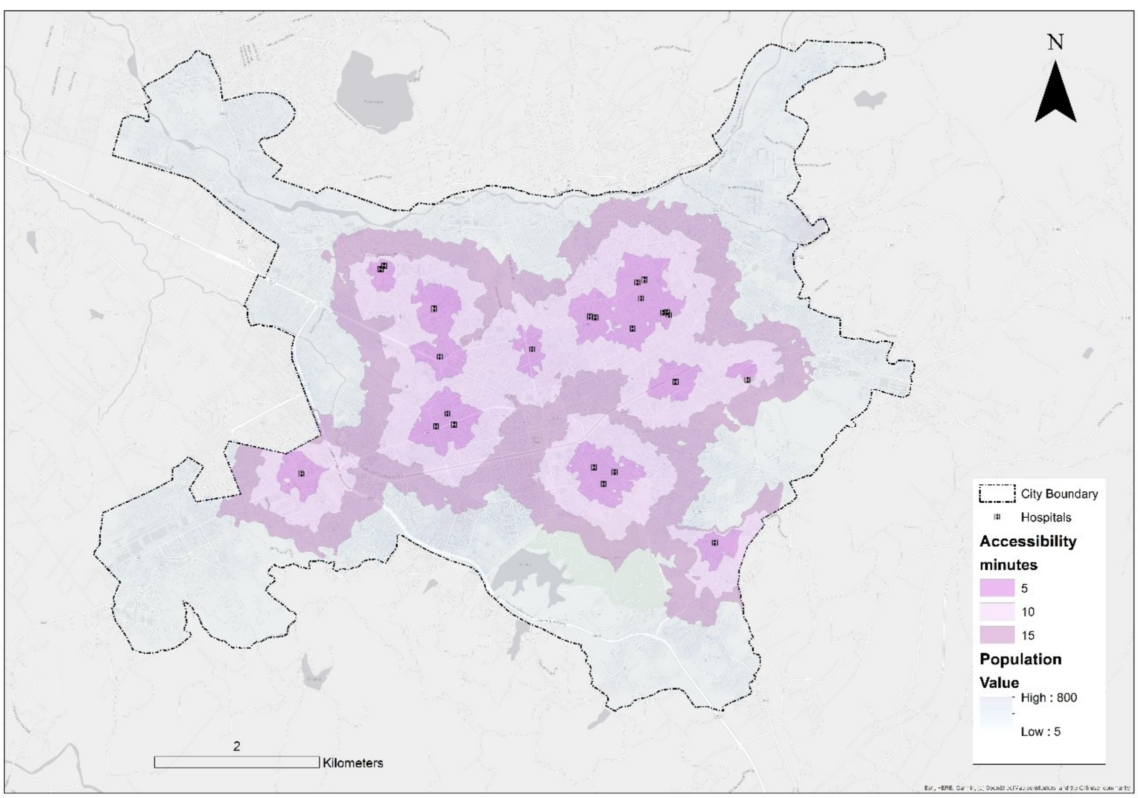


Figure 23. Medical clinics accessibility 5-10-15 minutes

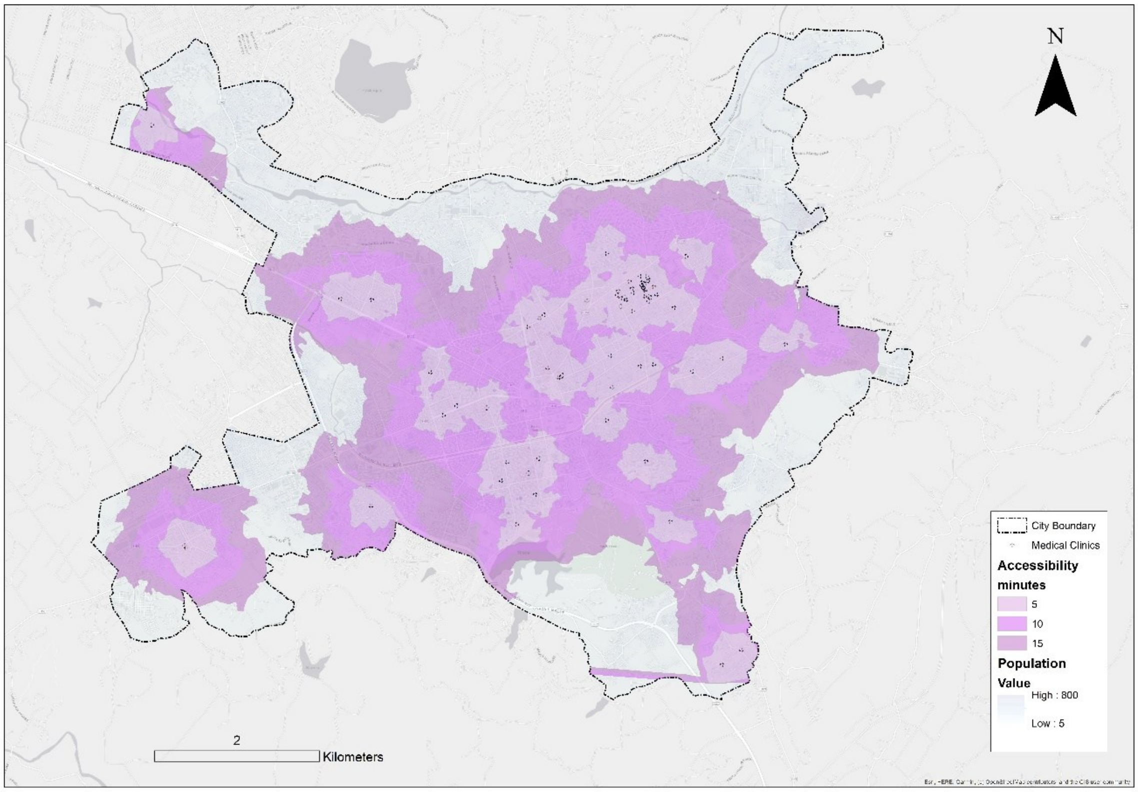


Figure 24. Medical Clinics accessibility 5-10-15 minutes

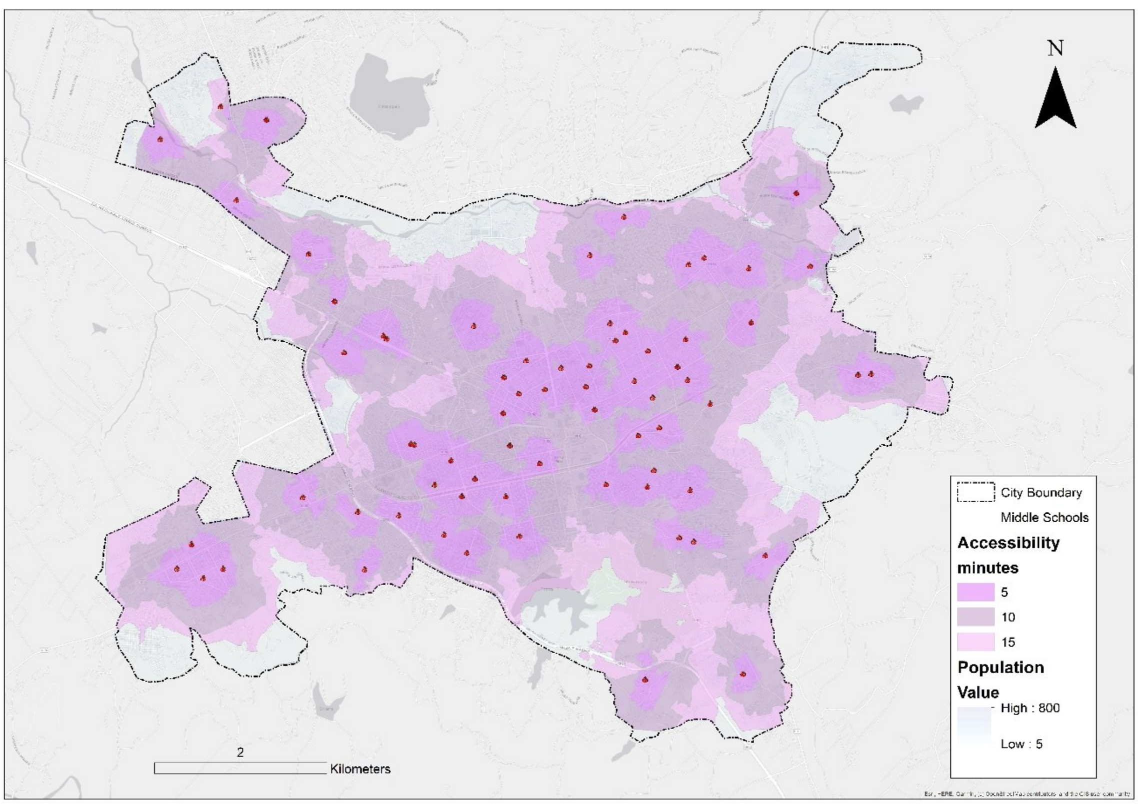


Figure 25. Middle schools' accessibility 5-10-15 minutes

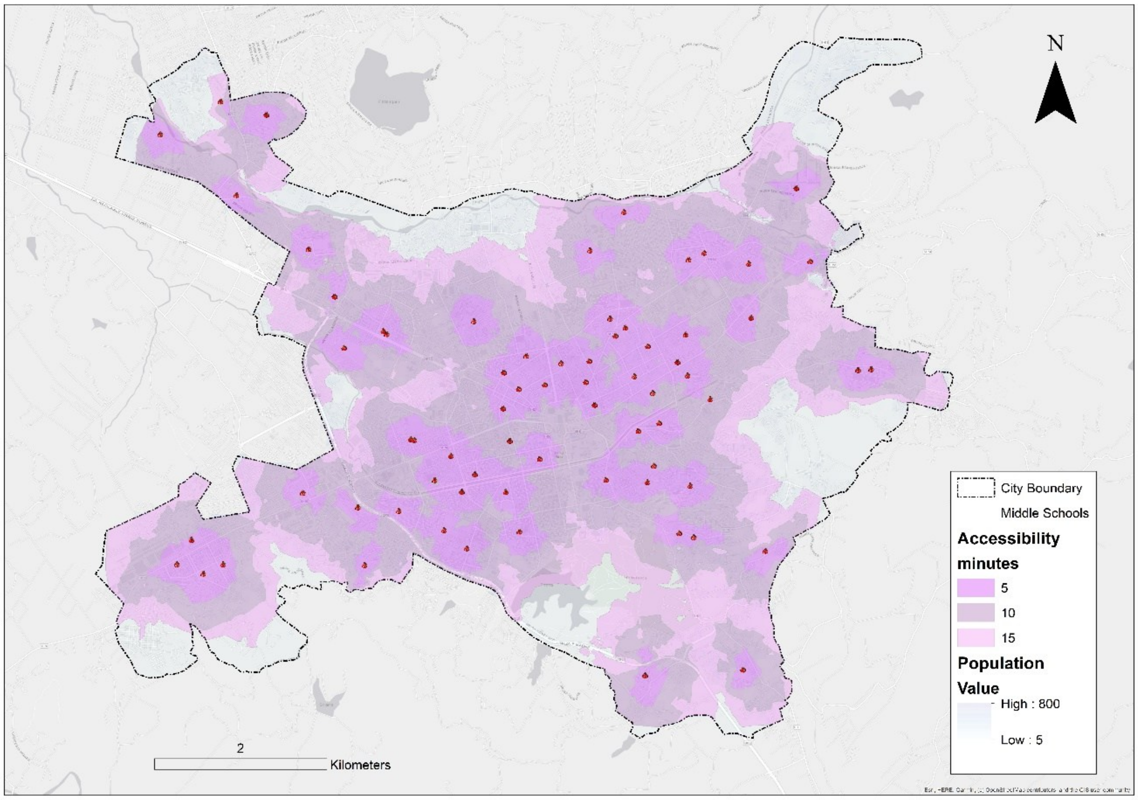


Figure 26. Pharmacies accessibility 5-10-15 minutes

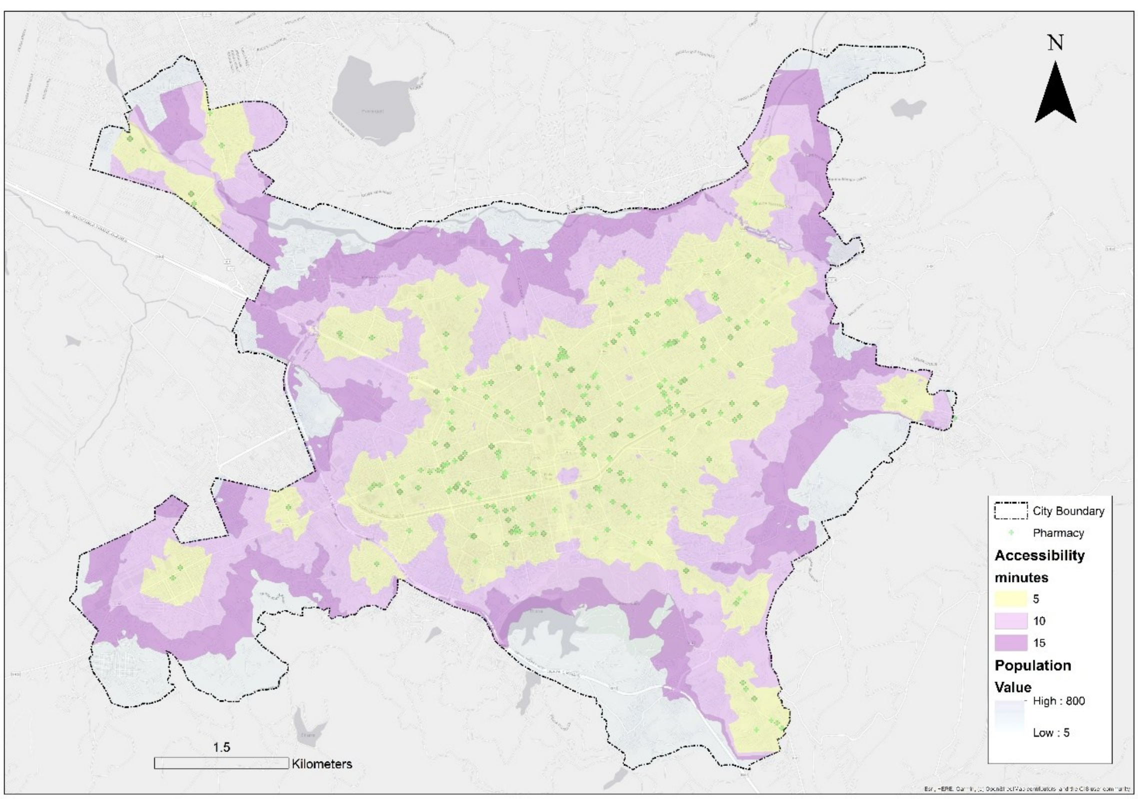


Figure 27. Pre-schools accessibility 5-10-15 minutes

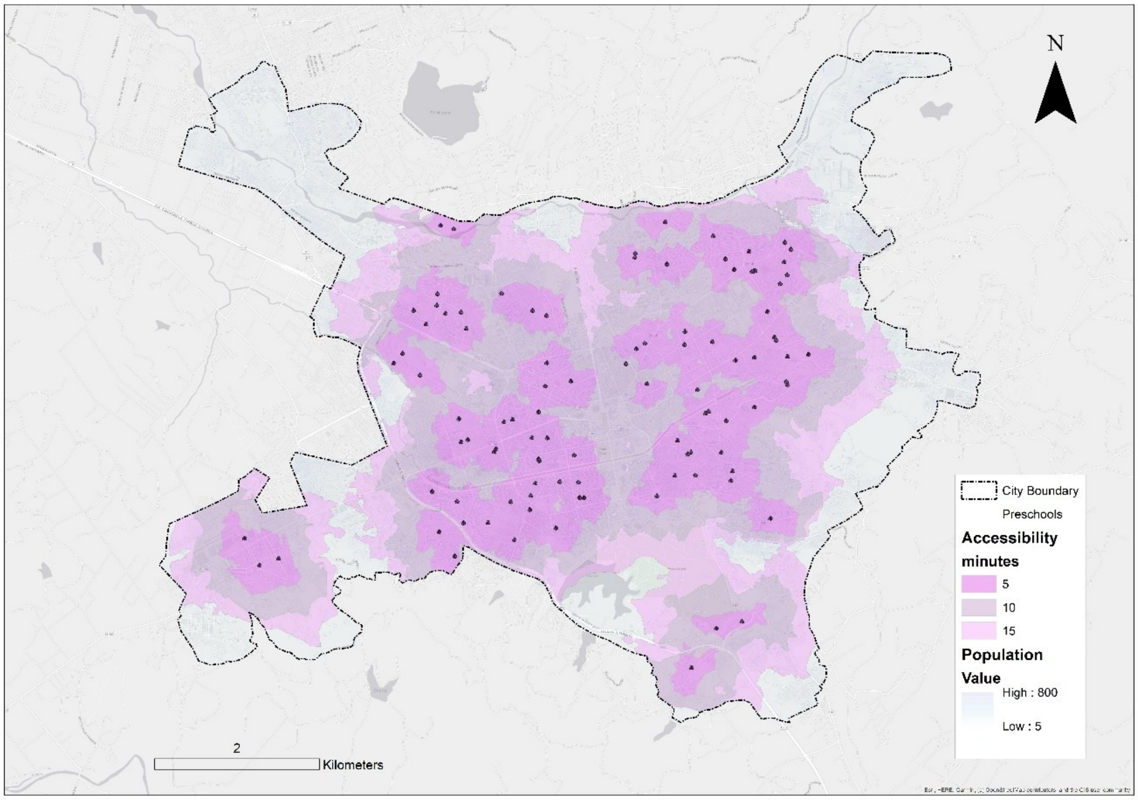


Figure 28. Public transport (bus) accessibility 5-10-15 minutes

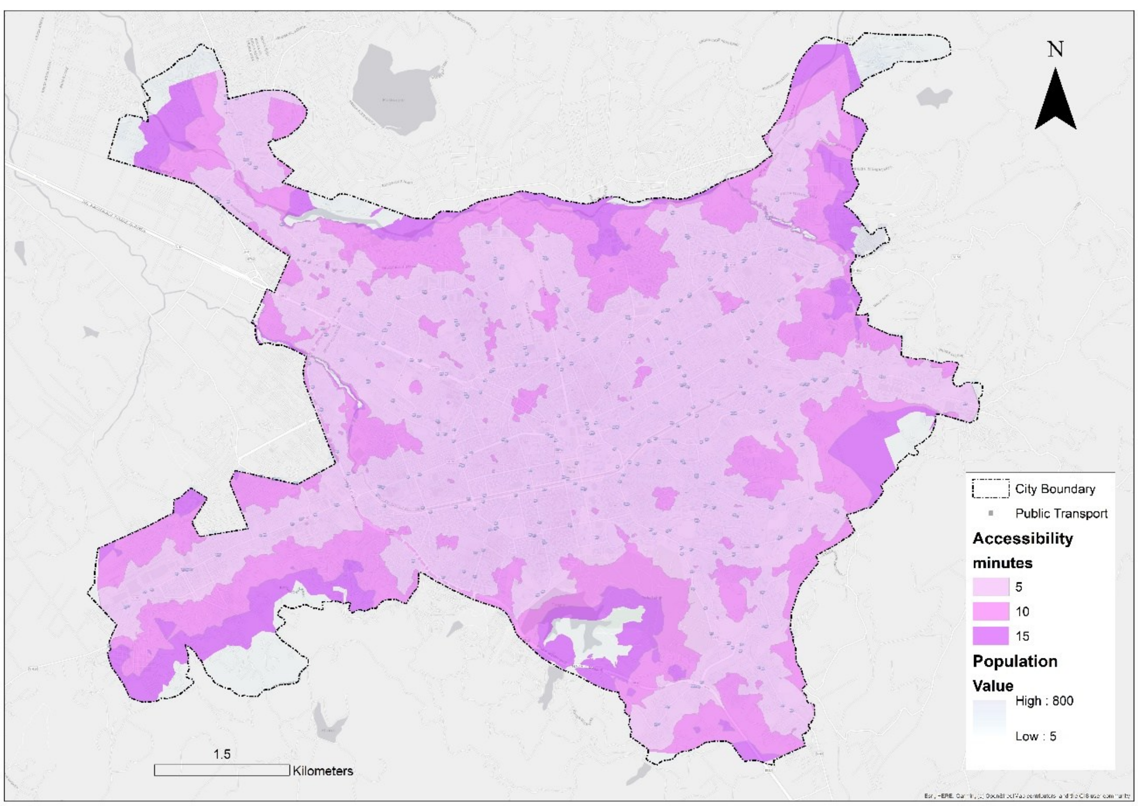
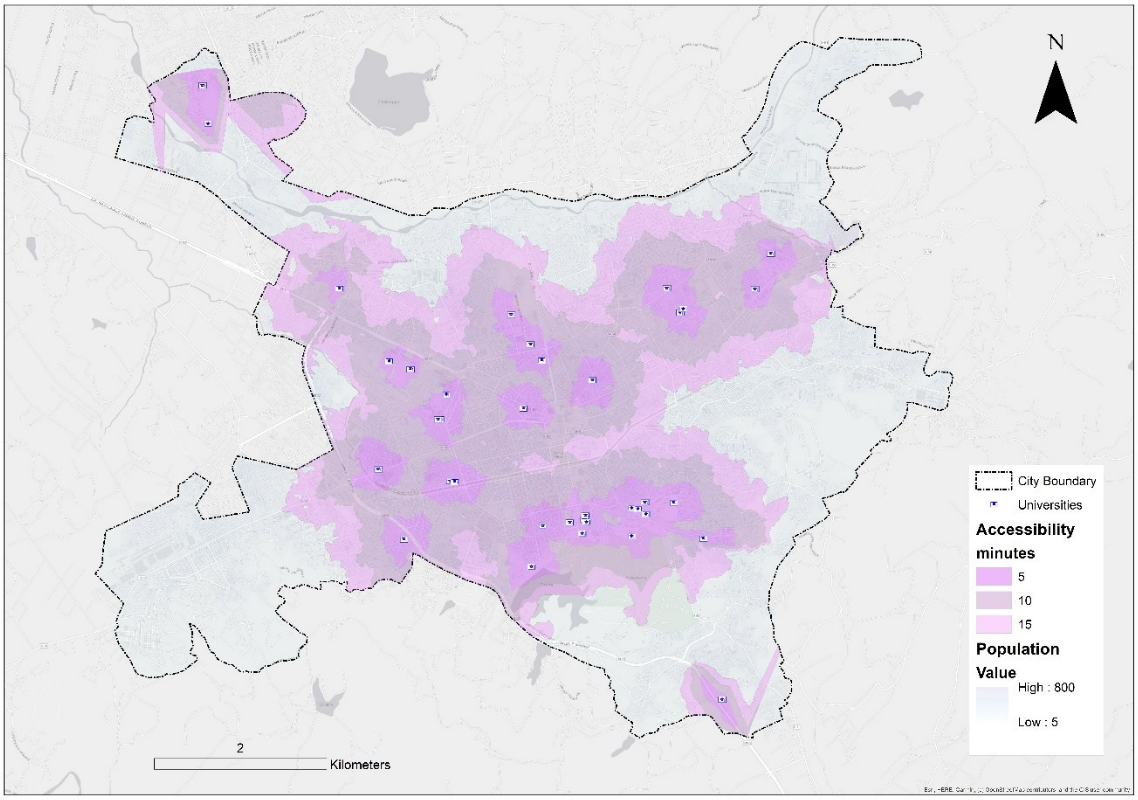


Figure 29. Universities accessibility 5-10-15 minutes



Source: Authors' calculations

Figure 30. Accessibility calculations by % of population in 15 minutes

Accessibility 15 min	Number of inhabitants	%
Hospitals	367771	61.36
Medical Clinics	467566	78.01
Pharmacy	542975	90.59
Transport	461600	77.01
Grocery Store	580586	96.87
Green Space	228456	38.12
Middle School	543400	90.66
Coffee/ Restaurants - Leisure	568329	94.82
Universities	421052	70.25
High School	367533	61.32
Pre schools	502870	83.9

Source: Authors' calculations

At the city scale, over 90% of Tirana's population has 15-minute access to essential services such as pharmacies, grocery stores, schools, and leisure venues, reflecting the overall effectiveness of its transit-oriented and compact urban form. However, a critical shortfall emerges in green space accessibility, with only 38% of residents able to reach public green spaces within 15 minutes. This aligns with the earlier BCR findings, highlighting the severe scarcity of open and vegetated land in the most densely developed neighborhoods. Healthcare and educational services exhibit moderate accessibility, with coverage for hospitals and high schools hovering near 61%. These gaps are especially pronounced in high-density but infrastructurally underserved districts, emphasizing the need for strategic interventions. The uneven spatial distribution of services and green infrastructure suggests that future urban planning efforts should prioritize infill development, de-densification where appropriate, and targeted facility expansion in low-FAR and accessibility-deficient zones.

5.4 Composite Compactness Index (CCI)

The Composite Compactness Index, constructed from building coverage ratio (BCR), building density, and land-use entropy, offers an integrated measure of spatial compaction in Tirana's urban landscape. The distribution of index values is highly skewed: while most parcels exhibit low compactness (median: 0.10), a small minority reach extreme values (maximum: 257.79), resulting in a pronounced right tail and an elevated mean (3.12, SD: 11.50). This heavy skew reflects the spatial reality that Tirana's overdevelopment is intensely localized, concentrated in a few saturated zones such as central business districts, institutional mega-blocks, and areas of informal, high-rise densification, while much of the city remains moderately compact or underutilized.

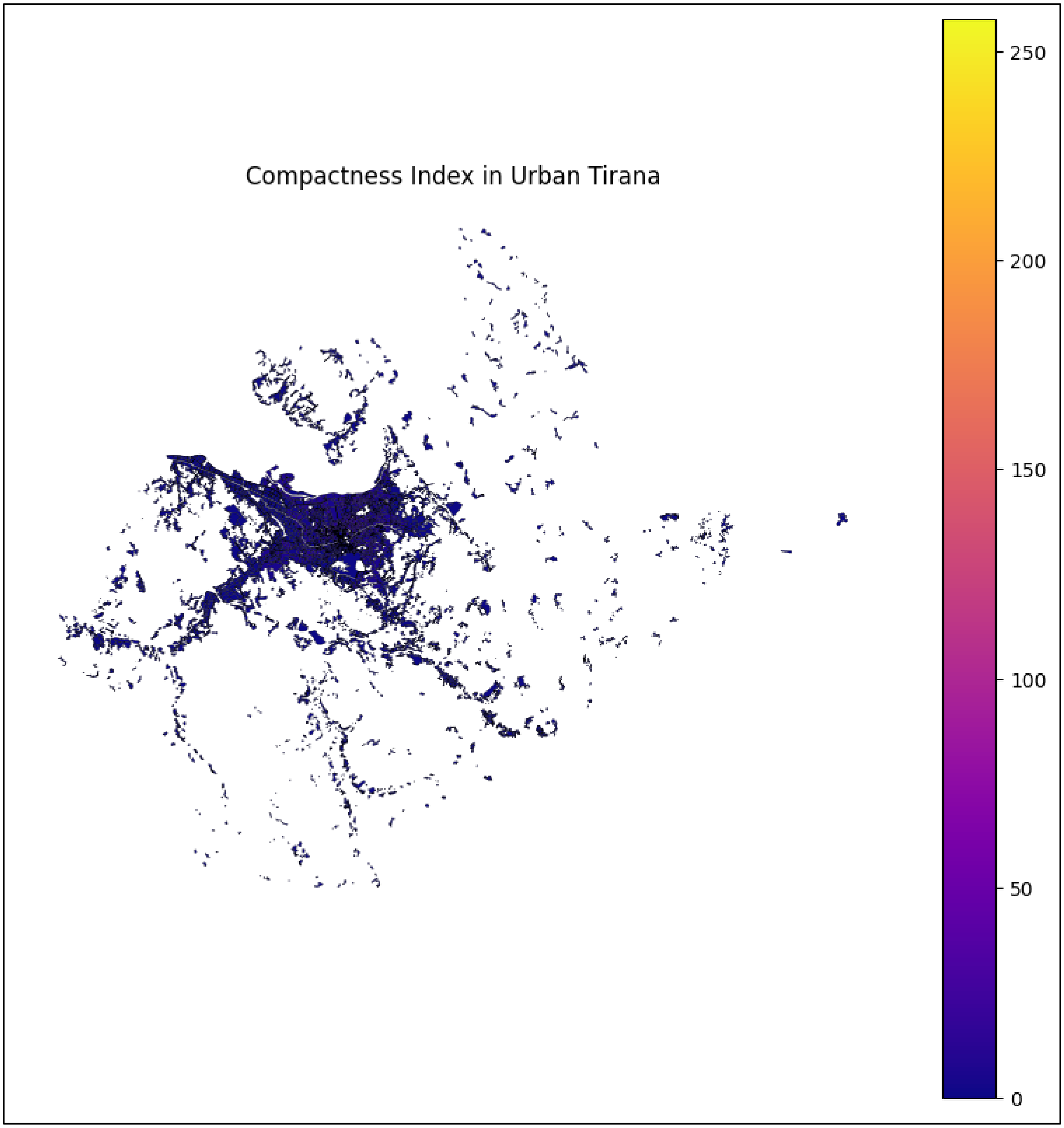
Table 40.Compactness index

count	**4173.000000**
mean	3.119230
std	11.503800
min	0.000000
25%	0.063517
50%	0.100672
75%	1.997240

max	257.794381

Source: Authors' calculations

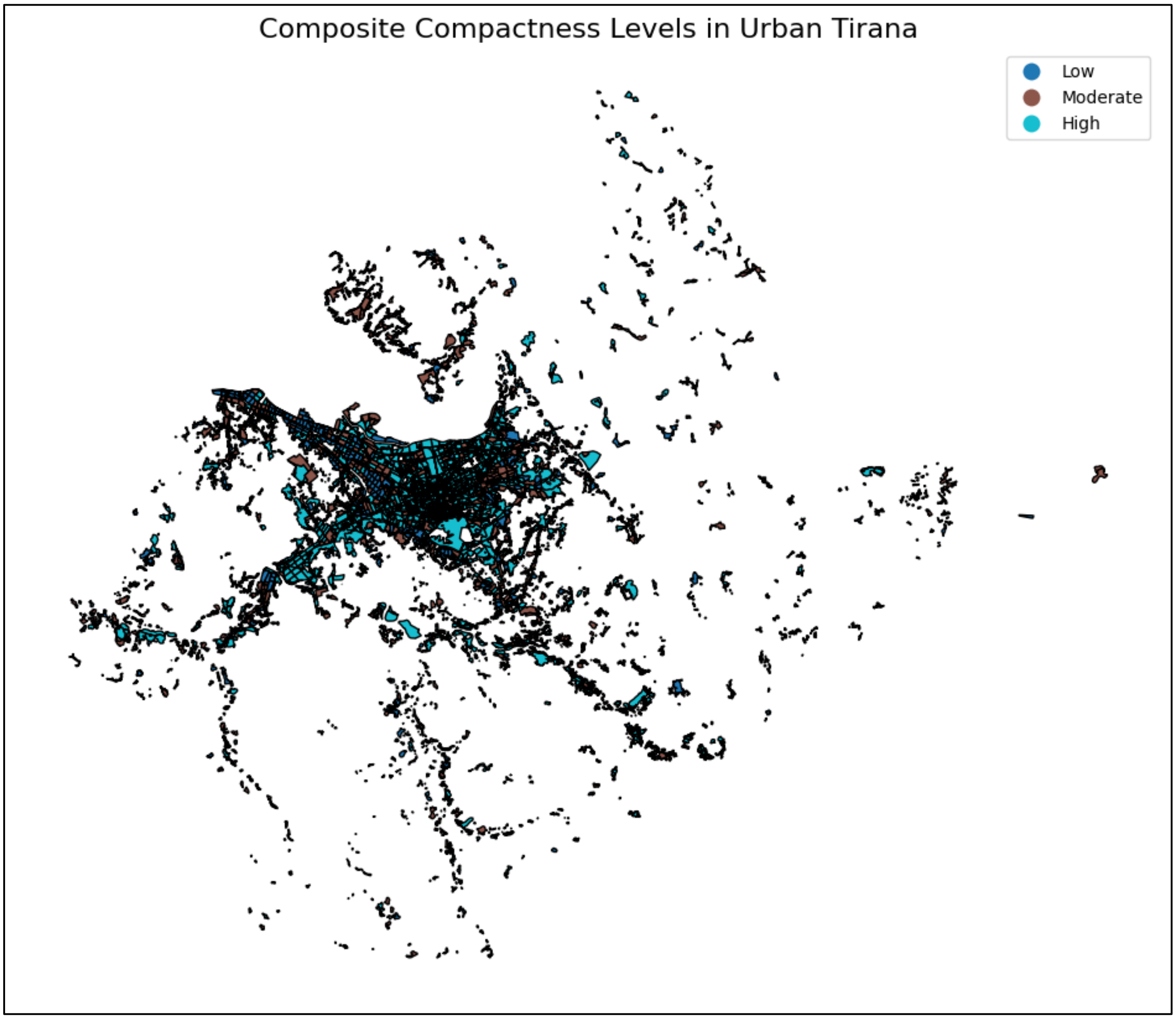
Figure 31. Compactness index calculation



Source: Authors' calculations

Outlier values above 1 are rare but significant, typically representing parcels with intense verticality and minimal open space, or, in some cases, data artifacts from very small lots. The overall pattern reveals a fragmented urban form marked by pockets of saturation amid broader spatial incoherence, suggesting lapses in regulatory enforcement and coordinated planning.

Figure 32. Composite compactness calculation by parcel (BSF)



Source: Authors' calculations

Table 41. Correlation matrix

	Composite compactness	Verticality	Entropy	FAR	Building Density (BSF)
Composite	1.0				

compactness					
Verticality	0.697	1.0			
Entropy	-0.013	-0.129	1.0		
FAR	0.987	0.651	-0.131	1.0	
Building density	0.346	0.690	-0.128	0.264	1.0

Source: Authors' calculations

Correlation analysis further illuminates these dynamics. The compactness index is highly correlated with floor area ratio (r = 0.99) and verticality (r = 0.70), confirming that high compactness in Tirana is driven primarily by the stacking of floor space and increased building heights, rather than by greater land-use diversity. In contrast, the negligible correlation with entropy (r ≈ 0) *indicates that compactness gains have not translated into more functionally mixed environments, highlighting a risk of mono-functional, high-density enclaves.* The results show that Tirana's compactness is not uniform but spatially fractured, requiring more nuanced and enforceable planning strategies to balance efficiency, and functional diversity.

5.5 Multi hazard analysis

The multi-hazard analysis for Tirana is conducted at a metropolitan scale, reflecting the wider spatial dispersion of environmental risks beyond the urban core. This approach captures the full extent of hazard exposure, encompassing both developed and undeveloped land parcels, and reveals complex interactions between urbanization patterns and risk landscapes. Statistical profiling of parcels by hazard category shows a distinct spatial gradient. Parcels with no recorded hazard exposure (multi_hazard = 0) are exceedingly rare, accounting for just 173 parcels in the entire dataset. These areas are almost universally undeveloped, as reflected by a mean BCR of 0.000 and the lowest entropy (0.168), suggesting monofunctional or reserved land at the periphery or in physically constrained locations.

Table 42. Statistical profiling of Multi-hazards in Tirana

multi_ hazard	count	mean	std	min	25%	50%	75%	max
0	48.0	0.049	0.0453	0.0	0.0	0.063	0.100	0.127

1	4000.0	3.143	11.728	0.0	0.063	0.100	1.770	257.794
2	125.0	3.527	3.5205	0.0583	0.1006	2.576	6.73	11.124

Source: Authors' calculations

Table 43. Linkage of multi hazards with morphological indicators of compactness

index	num_buildings	avg_floors	building_density	verticality
count	11436.0	11436.0	11436.0	11436.0
mean	4.202	0.400	4.250	8.797
std	27.433	1.165	23.078	44.687
min	0.0	0.0	0.0	0.0
25%	0.0	0.0	0.0	0.0
50%	0.0	0.0	0.0	0.0
75%	0.0	0.0	0.0	0.0
max	1559.0	24.0	772.228	2529.462

Source: Authors' calculations

Table 44. Multi hazards and BCR overlapping

Multi hazard class	count	mean	std	min	25%	50%	75%	max
0	173.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	11006.0	0.085	0.280	0.0	0.0	0.0	0.0	11.055
2	257.0	0.100	0.149	0.0	0.0	0.0	0.220	0.719

Source: Authors' calculations

Parcels that are not exposed to any hazards (multi_hazard = 0) represent a very small fraction of the total (173 out of 11,436) and show the lowest average entropy, at 0.168. This indicates that land use in these areas tends to be relatively homogenous. The median entropy for these safe zones is also modest (0.190), and the interquartile range suggests only limited variability. This suggests that hazard-free areas are predominantly monofunctional or assigned to low-intensity uses possibly due to topographic, administrative, or planning constraints that limit densification or urban complexity. Parcels exposed to one type of hazard (multi_hazard = 1), which represent most of the dataset, demonstrate a notably higher average entropy of 0.261. This implies that these zones host more functionally diverse development patterns. The entropy values in these zones reach a maximum of 0.556, suggesting that some parcels within flood or seismic zones are approaching high levels of land use mixing. This may reflect unregulated densification, informal land development, or planning strategies that promote compactness without fully integrating hazard risk into spatial zoning. The most striking trend appears in parcels that are exposed to both flood and seismic hazards (multi_hazard = 2). Although fewer in number (257 parcels), these show the highest mean entropy at 0.280. The 75th percentile for these multi-hazard parcels reaches 0.34, and the maximum entropy climbs above 0.49. This confirms that the most hazard-prone areas are also those with the greatest functional mixing, likely due to their central location or overlapping demand for residential, commercial, and service functions. In effect, this spatial overlap between hazard concentration and functional complexity raises a planning dilemma: the zones where mixed-use development is most intense are also where environmental risks converge, heightening the city's vulnerability. These findings strengthen the core thesis argument that compact city dynamics in Tirana are spatially colliding with multi-hazard risk zones, leading to a dual burden of functional pressure and exposure. This calls for revised spatial strategies that explicitly account for hazard overlays when encouraging land use mix and urban intensification.

Table 45. Regression analysis

```
Optimization terminated successfully.
         Current function value: 0.183343
         Iterations 11
                          MNLogit Regression Results
==============================================================================
Dep. Variable:           multi_hazard   No. Observations:                 4173
Model:                        MNLogit   Df Residuals:                     4169
Method:                           MLE   Df Model:                            2
Date:                Wed, 25 Jun 2025   Pseudo R-squ.:                 0.06946
Time:                        17:24:10   Log-Likelihood:                -765.09
converged:                       True   LL-Null:                       -822.20
Covariance Type:            nonrobust   LLR p-value:                 1.576e-25
=========================================================================================
       multi_hazard=1       coef    std err          z      P>|z|      [0.025      0.975]
-----------------------------------------------------------------------------------------
const                     1.2173      0.269      4.530      0.000       0.691       1.744
composite_compactness    44.7356      4.684      9.550      0.000      35.555      53.917
-----------------------------------------------------------------------------------------
       multi_hazard=2       coef    std err          z      P>|z|      [0.025      0.975]
-----------------------------------------------------------------------------------------
const                    -2.1723      0.294     -7.387      0.000      -2.749      -1.596
composite_compactness    44.2320      4.718      9.376      0.000      34.985      53.479
=========================================================================================
```

Source: Authors' calculations

The relationship between spatial compactness and multi-hazard exposure in Tirana was systematically interrogated through a multinomial logistic regression model, with multi_hazard status (no hazard, single hazard, or dual hazard exposure) as the dependent variable and the composite compactness index as the predictor. This approach enables a nuanced, probabilistic assessment of how increases in urban compactness translate into heightened environmental risk at the parcel level.

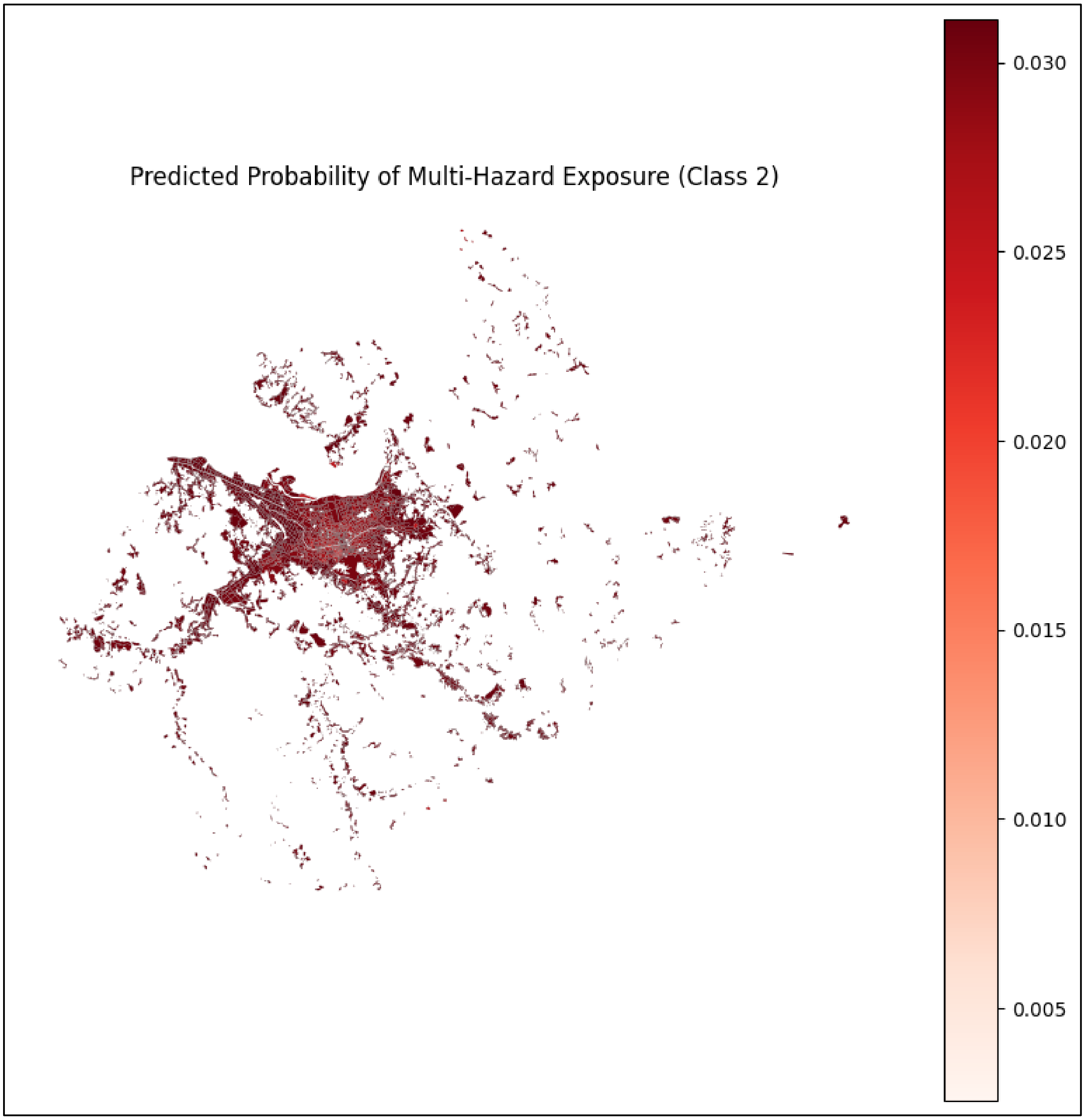
The statistical results are unambiguous and substantively significant. The composite compactness index emerges as a highly significant predictor for both single and dual hazard exposure classes, with p-values effectively at zero ($p < 0.00001$). This level of significance rules out the possibility of spurious correlation and confirms that the association between compactness and hazard risk is robust, not incidental.

Crucially, the model coefficients for both hazard-exposed categories are exceptionally large and positive (approximately 44.7 for single hazard, 44.2 for dual hazard), indicating that even moderate increases in the compactness index correspond to a sharply elevated likelihood of a parcel being situated in a risk zone. In practical terms, this means that the very process of densification (often pursued for reasons of infrastructural efficiency and sustainable urban form) dramatically amplifies hazard exposure when it is not spatially regulated with respect to environmental constraints. Overdeveloped parcels, characterized by high BCR and FAR, are statistically far more likely to overlap with floodplains, seismic zones, or both, revealing a latent vulnerability embedded within the urban fabric.

While the pseudo-R^2 value of 0.069 might initially seem modest, it is fully consistent with expectations for spatial multinomial models in complex urban systems, where numerous interacting factors influence hazard exposure. The explanatory power is thus statistically and substantively meaningful, confirming the model's validity. Importantly, the pseudo-R^2 must be interpreted considering the categorical and spatially entangled nature of the dependent variable, highlighting that even a modest proportion of explained variance signals a significant structural relationship within the urban system.

Theoretical and policy implications are large. These findings establish a clear empirical link between spatial compaction and increased multi-hazard risk. While compact urban form may yield gains in infrastructure efficiency, mobility, and resource use, it becomes a direct liability in the absence of coordinated risk-sensitive planning. The probability of hazard exposure increases nonlinearly as compactness intensifies, underlining the risk of concentrating population and assets in environmentally precarious locations.

Figure 33. Predicted probability of multi hazard exposure in Tirana



Source: Authors calculations

For Tirana, these findings show the imperative to embed hazard overlays and risk mitigation criteria into all future densification strategies. Urban planning must move beyond generic compaction goals and explicitly regulate where and how density is intensified, prioritizing resilience and adaptive capacity alongside efficiency. Without such measures, the city's pursuit of the “compact city” ideal risks producing zones of compounded vulnerability rather than sustainable urban transformation

The intervention zoning analysis stratifies Tirana’s urban parcels into four distinct categories based on their composite compactness and hazard exposure profile.

Table 46. Intervention needs by number of parcels

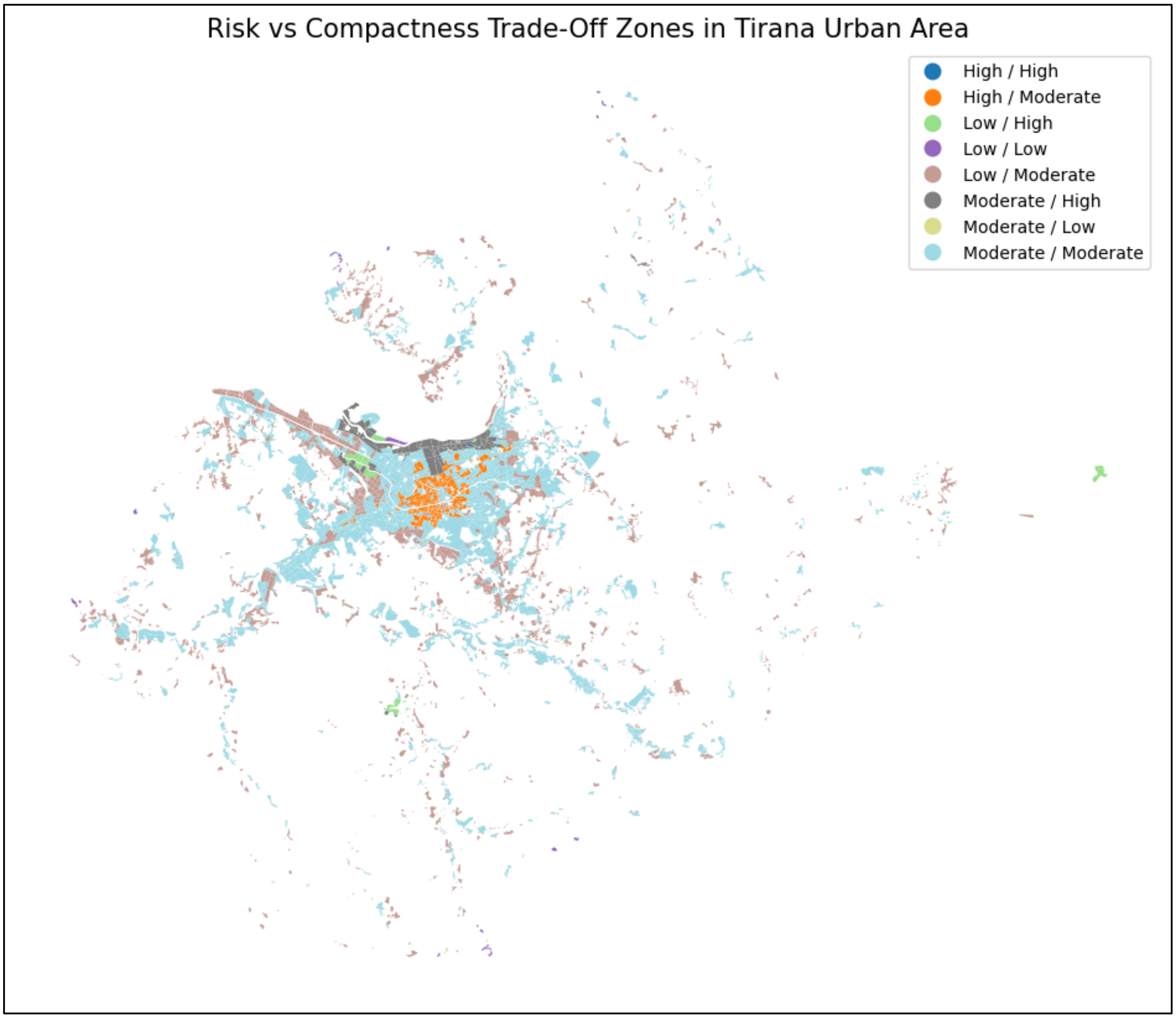
Intervention needs	Number of parcels
No Immediate Intervention	3081
Moderate Risk – Overdeveloped	985
High Risk – Overdeveloped	59
Low Density – Infill Opportunity	48

Source: Authors’ calculations

The majority of parcels (n = 3081) fall within the “No Immediate Intervention” zone, indicating that most of the urban fabric currently does not require urgent action for risk mitigation or densification. However, a substantial cohort (n = 985) is classified as “Moderate Risk–Overdeveloped,” reflecting areas where compactness and hazard overlap to a degree that warrants proactive, but not yet critical, intervention. These parcels are likely to benefit from measures such as green infrastructure retrofits, stricter land-use controls, or targeted hazard adaptation strategies. A much smaller but strategically significant subset (n = 59) falls into the “High Risk–Overdeveloped” category. These parcels represent priority intervention sites, where intense development coincides with elevated environmental risk. In such locations, immediate measures are necessary (potentially including de-densification, infrastructure reinforcement, or compulsory risk-adaptive retrofits) to reduce vulnerability and safeguard urban resilience. Conversely, a small number of parcels (n = 48) are identified as “Low Density–Infill Opportunity.” These represent underutilized sites where sensitive densification could be encouraged, provided that it aligns with hazard avoidance and broader urban sustainability goals.

This zoning framework provides an evidence-based decision tool for targeted urban intervention. It enables policymakers and planners to prioritize resources and regulatory efforts, focusing immediate action where the confluence of density and risk is most acute, while strategically promoting compactness and adaptive reuse in safer, underdeveloped areas.

Figure 34. Risk versus compactness trade-off in Tirana



Source: Authors' calculations

The map below visualizes the spatial distribution of risk and compactness trade-offs across the Tirana urban area, using a bivariate classification to highlight the intersection of environmental hazard exposure and urban form intensity. Each color represents a distinct combination of risk (hazard exposure) and compactness (composite index of

BCR, density, entropy), enabling targeted diagnosis of urban resilience and planning priorities.

High Risk/High Compactness zones (dark blue) are extremely rare or absent, indicating that the most hazardous and most densely built-up zones seldom fully coincide, a positive sign for risk mitigation, but potentially also a reflection of historical avoidance of hazardous sites for intensive development. High Risk/Moderate Compactness (orange) clusters are concentrated within the urban core and certain high-density corridors. These areas are strategic priorities for intervention, as they combine significant built-up intensity with elevated hazard, heightening urban vulnerability. Policy efforts should focus on adaptive retrofitting, risk-sensitive densification, and green infrastructure deployment in these sectors. Moderate Compactness/Moderate Risk (light blue) and Low Compactness/Moderate Risk (brown) dominate the peri-urban fringe and transitional areas. These extensive zones are crucial for proactive planning: controlling further compaction, improving hazard resilience before densities increase, and preventing the emergence of new "risk/compactness hotspots." Low Risk/High Compactness (green) are extremely limited in extent, reflecting the scarcity of dense development in environmentally safe areas. This points to a spatial mismatch, opportunities for future densification should be redirected to these safer locations, where risk mitigation costs and exposure are minimized. Moderate and Low Risk/Low Compactness (lavender, gray, and blue shades) fill much of the peripheral and undeveloped landscape, representing low-priority zones for both immediate intervention and densification, but also potential sites for future growth if aligned with risk-averse planning. The spatial patterning reveals that most of Tirana's recent urban expansion is occurring in moderate to high hazard contexts, but with moderate levels of compaction. This pattern suggests ongoing risk accumulation as urbanization continues, underscoring the need for robust spatial regulation and risk-informed urban design. The analysis confirms that Tirana's most acute resilience challenges are spatially concentrated where risk and compaction overlap, especially in the urban core and expanding corridors. Strategic urban policy should prioritize these zones for intervention, while simultaneously incentivizing safe densification in areas with low environmental risk. This approach will be critical for balancing urban efficiency with long-term resilience and safety.

5.6 Intervention needs analysis

The analysis of Tirana reveals a predominantly dense urban form, with most buildings having 1 to 3 floors and an average footprint of 198 m². The city exhibits wide variations in building heights, with structures ranging from single-story homes to 53-floor high-rises. The building perimeter and footprint sizes also indicate a mix of compact urban plots and larger commercial or institutional developments. Spatially, the dataset shows a significant geographic spread, reflecting Tirana's heterogeneous urban landscape. However, despite this diversity, certain patterns emerge in terms of density, height distribution, and land use efficiency, pointing toward key intervention areas for sustainable urban planning.

A regression analysis assessing the relationship between building height and physical dimensions and spatial location revealed key insights. Physical dimensions have a weak influence on height, as larger buildings tend to be taller, but the impact is marginal, suggesting that zoning and regulatory restrictions play a stronger role in shaping building heights. Spatial location is a more significant factor. Moving eastward in Tirana the buildings tend to be taller (likely due to commercial activity and land value). Moving northward the buildings tend to be shorter (suggesting a residential character with stricter height restrictions). The OLS model's R^2 value was only 0.163, meaning that spatial policies and market forces influence height more than building dimensions alone. The Random Forest model improved predictive accuracy to $R^2 = 0.30$, confirming that height distribution follows nonlinear patterns, likely influenced by economic, regulatory, and infrastructural factors. Tirana's building heights are shaped more by urban zoning laws and land-use regulations than by physical constraints like plot size. The BSF analysis shows a city dominated by high-density development. Tirana lacks open spaces, and the city's compact development policies have led to a highly saturated built environment.

Tirana's compact city paradigm has produced a saturated and unevenly distributed urban density profile, necessitating adaptive interventions focused on de-densification, green infrastructure integration, and balanced vertical growth. The evidence highlights the need for a nuanced, data-driven approach to compact city planning, one that harmonizes efficiency, resilience, and quality of life for current and future residents.

The analysis for Tirana reveals an acute imbalance in urban density, with a preponderance of parcels exhibiting extreme land coverage and a smaller fraction of underutilized land. Specifically, two-thirds of the city's buildings inside the urban core (66.2%, n = 30,113) exceed a Building Coverage Ratio (BCR) of 80%, classifying them as high-density and overdeveloped with minimal residual open space. Conversely, only 6.8% of buildings (n = 1,980) qualify as low-density, indicating that detached housing and generous green areas are rare within the urban fabric. Balanced-density parcels (27.0%, n = 12,260), characterized by moderate BCRs, represent transitional areas that may not require immediate intervention but warrant close monitoring for sustainable development.

Table 47. ***Key findings from intervention analysis***

Intervention Category	Number of Buildings	Percentage of Total
High-Density (Risk of Overdevelopment)	30,113 buildings	66.2%
Balanced Density	12,260 buildings	27.0%
Low-Density (Infill Needed)	1,980 buildings	6.8%

Source: Authors' calculations

66% of buildings have a BCR above 80%, meaning they are overdeveloped with very little open space. Only 6.8% of buildings are underdeveloped, meaning that infill development is limited in Tirana. Balanced density areas (27%) are zones where BCR is moderate, meaning these areas do not require immediate intervention. This suggests that Tirana is highly dense across most areas, with very little variation. Since most buildings are classified as high-density in parcel term, let's refine the classification to better highlight intervention areas. The table below shows the results:

Table 48. Intervention category

Refined intervention category	Number
Very High Density (>85%)	25431
High Density (70-85%)	10773
Medium Density (50-70%)	6169
Low Density (30-50%)	1898

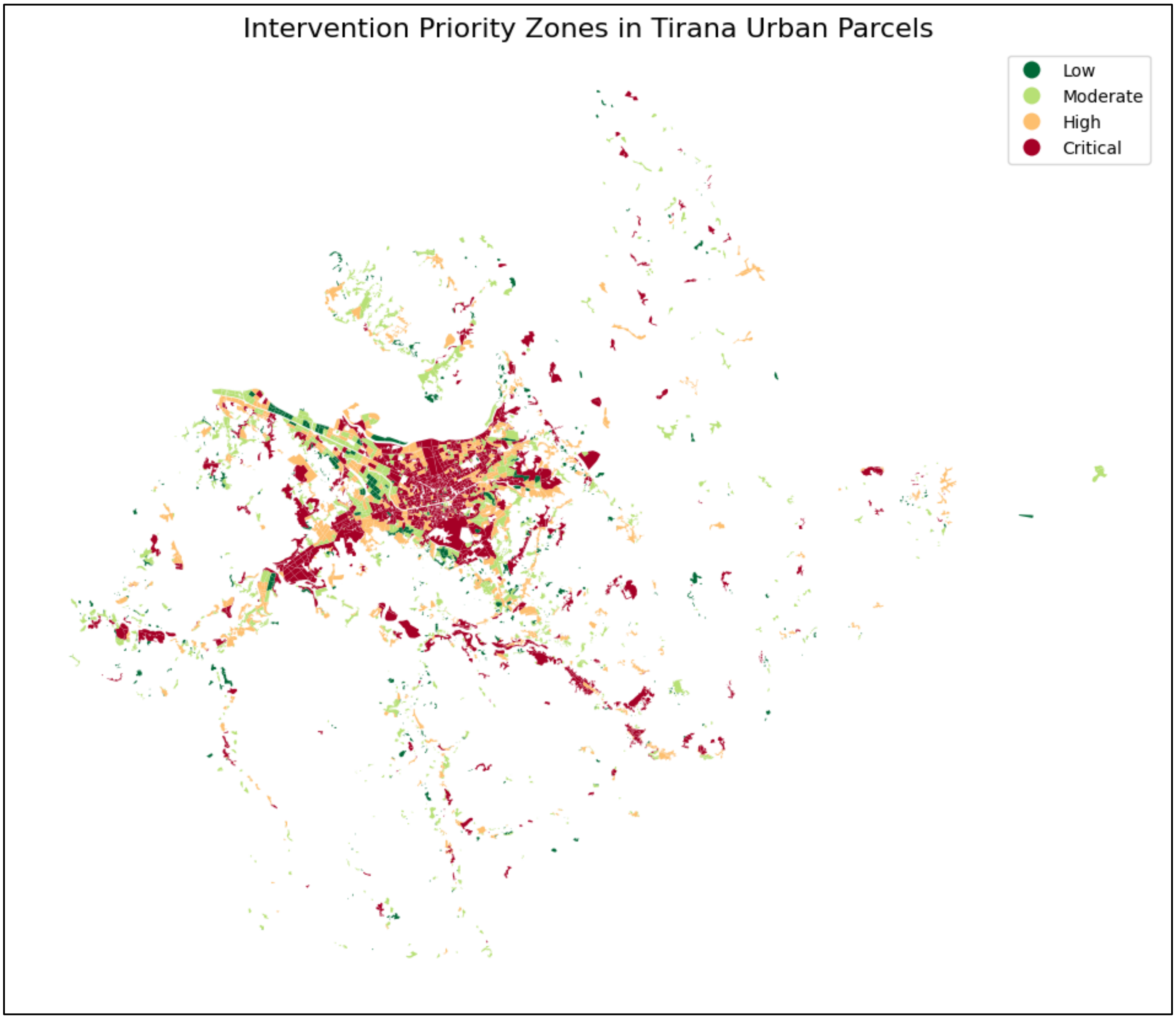
Very Low Density (<30%)	82

Source: Authors' calculations

The distribution of intervention needs at parcel level reveals how far Tirana's built fabric has moved away from the "safe density window" identified in the previous sections. The initial classification already shows a sharply skewed profile. Around two-thirds of all buildings (66.2%, n = 30,113) sit on parcels with a BCR above 80%, meaning that the ground is almost completely sealed and residual open space is minimal. Detached housing with generous gardens and tree cover is a marginal condition: only 6.8% of buildings (n = 1,980) fall into the low-density class. The remaining 27.0% (n = 12,260) occupy a middle band of "balanced" density, where BCR is moderate and some flexibility remains for either carefully managed infill or environmental retrofitting without necessarily increasing hazard exposure (Table 47). In other words, when seen purely through the lens of BCR, Tirana is dominated by highly sealed parcels, with only a small share of the building stock offering potential for conventional densification.

Because these first cut groups very different overdeveloped situations into a single "high-density" category, the classification was refined to better capture the gradient of intervention needs. The second typology (Table 48) disaggregates parcels into five bands: very high density (BCR > 85%), high density (70–85%), medium density (50–70%), low density (30–50%) and very low density (<30%). This reveals an even starker picture. Approximately 57.3% of all buildings (n = 25,431) are located on very high-density parcels, and a further 24.3% (n = 10,773) on high-density parcels. In practice, more than four-fifths of Tirana's buildings (81.6%) occupy land where at least 70% of the parcel is built over. Medium-density parcels account for about 13.9% (n = 6,169), while genuinely low-density situations are confined to just over 4.4% of the stock. When these figures are read against the safe-density window identified at grid level, it becomes clear that, although only a small fraction of 100×100 m cells exceed BSF > 0.7, at the parcel scale the dominance of very high BCR values is almost structural. The "overdevelopment problem" in Tirana is therefore less about blanket citywide density and more about the micro-scale sealing of individual plots within already saturated districts.

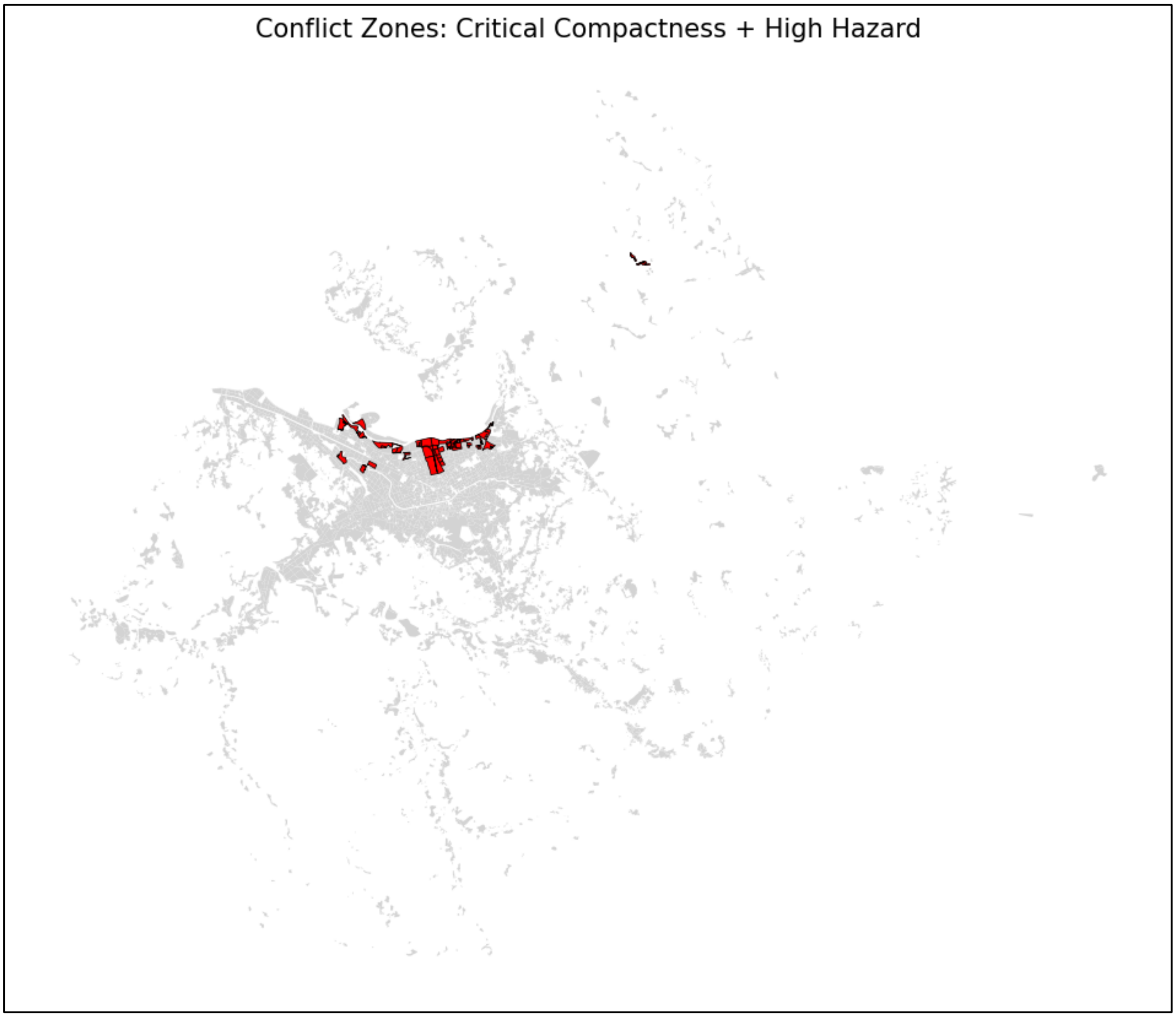
Figure 35. Critical areas



Source: Authors' calculations

Figure 42 translates this refined classification into space by mapping intervention priority zones for all urban parcels. Parcels are grouped into four levels of urgency (low, moderate, high, critical) that combine information on CCI and multi-hazard exposure. The map shows a large, continuous concentration of high and critical parcels in the central urban core, extending along the main development axes. This band corresponds broadly to the historic centre and its post-socialist extensions, where plot subdivision, incremental vertical additions and weak enforcement have produced a fine-grained mosaic of parcels with BCR well above 85% and high BSF values. Around this core, a ring of moderate-priority parcels appears, often in transition areas where density is rising but some open space remains. Low-priority parcels, in contrast, are scattered in the more peripheral neighbourhoods and along radial corridors, where development has been more recent or still incomplete. The spatial pattern confirms that intervention needs are not evenly distributed, a relatively small portion of the municipal territory, but one that hosts a large share of the population and economic activity, concentrates the most acute over-sealing and risk.

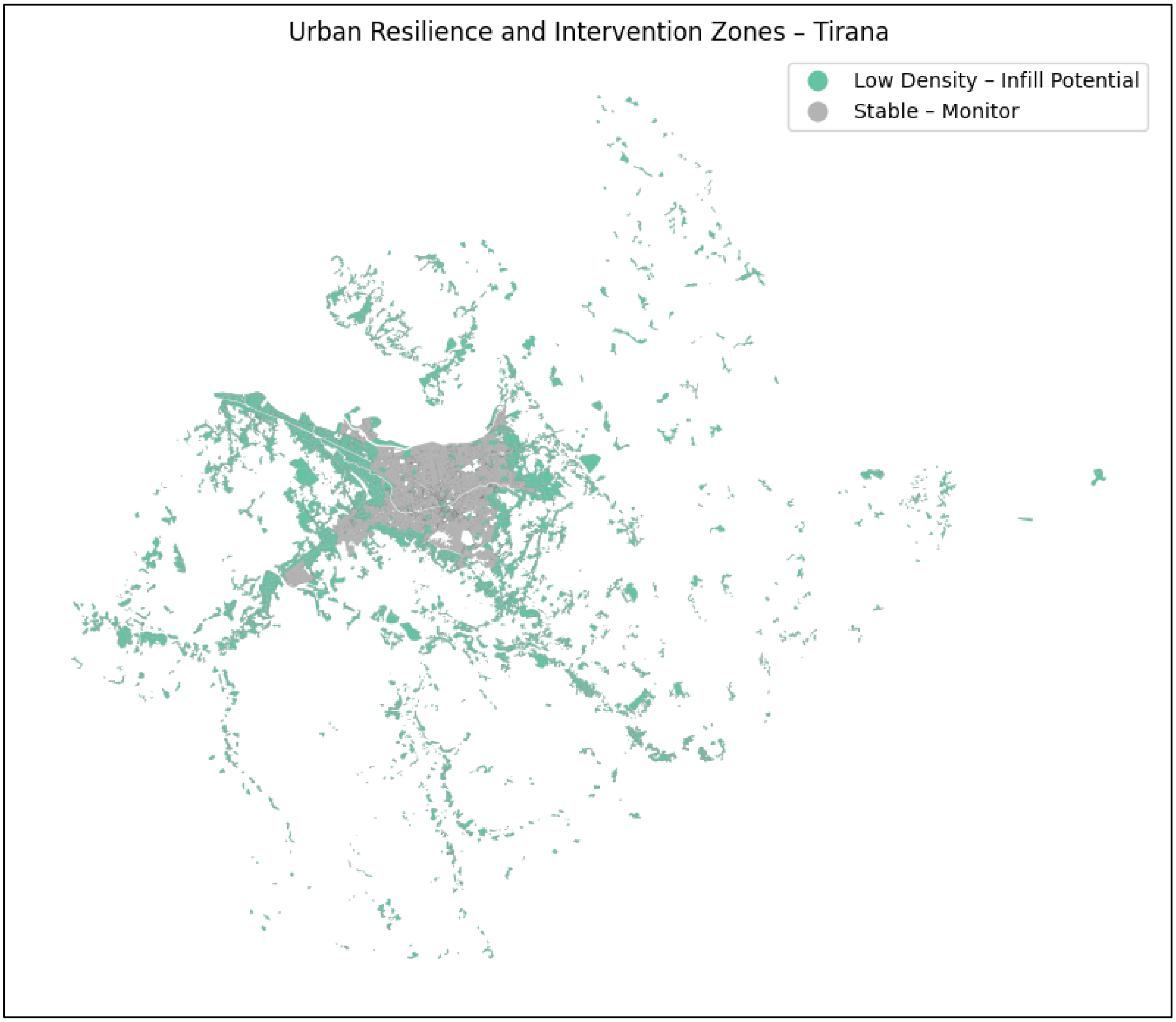
Figure 36. High in compactness and in risk



Source: Authors' calculations

Not all highly compact parcels, however, represent the same level of concern from a resilience perspective. Figure 43 isolates those highly "conflict zones" where critical compactness coincides with high multi-hazard exposure. Here the background fabric of the city is shown in grey, while parcels that combine very high BCR/BSF and high composite hazard scores (flood and seismic) are highlighted in red. The result is a much smaller but highly consequential subset of the territory, forming a series of contiguous patches rather than isolated points. These conflict zones are the locations where the compact city dilemma becomes most visible: the benefits usually associated with compactness (proximity, activity concentration, infrastructure efficiency) are overlaid with the highest probabilities of damage and loss under both hydrological and seismic events. In these areas the safe-density window is clearly exceeded; any additional infill or vertical extension would not only add marginal accessibility benefits, but also magnify evacuation difficulties, structural vulnerability and the potential for cascading failures during disasters. *From a planning standpoint, these parcels are the first candidates for strict development controls, targeted retrofitting and, where necessary, de-densification, or otherwise, high investment in infrastructure in terms of flood and seismic risk prevention.*

Figure 37. Intervention and expansion zoning



Source: Authors' calculations

Figure 44 shifts the focus to the other end of the spectrum by mapping "Urban Resilience and Intervention Zones." Here the emphasis is on identifying low-density parcels with infill potential and stable areas that should be primarily monitored rather than radically transformed. Low-density parcels with capacity for additional development are shown in green; they form a loose but extensive network around the built-up core, following peri-urban corridors and fringe settlements. These parcels sit below the safe-density window in morphological terms and typically exhibit lower hazard exposure than the conflict zones, although localised flood or landslide risks may still exist. In contrast, central grey areas represent relatively stable parcels where BSF are closer to the identified safe range and where hazard levels are modest. The map therefore offers a first sketch of a spatial strategy. Concentrate new development in selected low-density parcels where compactness can be increased without pushing multi-hazard risk beyond acceptable levels, while treating the over-developed and hazard-exposed core as a priority for adaptation rather than further growth.

The analysis and framework output in this section provide the empirical foundation for a differentiated intervention logic. Very high-density parcels in high- and critical-priority zones, particularly those identified as conflict zones in Figure 43, require immediate regulatory attention. Here, the key actions are not additional floor-area allowances but measures that restore some degree of permeability, reduce exposure and improve emergency performance: conversion of sealed surfaces into green or blue infrastructure, introduction of micro-parks, mandatory retrofitting of non-ductile structures and, where feasible, selective plot reconfiguration to ease access and open evacuation corridors. High-density parcels in moderate-priority zones may also be subject to conditional development rights, where further building is allowed only in exchange for effective mitigation measures (green roofs, water retention, shading, structural reinforcement).

Medium-density parcels, especially those falling within the safe-density window and outside high hazard bands, constitute the “monitor and maintain” category. Here the priority is to preserve their relatively balanced condition, avoiding both uncontrolled densification and unnecessary down-zoning. Planning instruments can use these areas to pilot more fine-grained design codes that maintain adequate sky view, tree cover and mixed use while gradually improving accessibility and service provision. Finally, the low- and very low-density parcels mapped as infill potential zones in Figure 44 represent the main spatial reserve for future compact development. If guided by the safe-density thresholds established earlier (BSF and BCR ranges, CCI levels and multi-hazard scores) these parcels can absorb much of the city’s growth without reproducing the over-sealed, risk-laden patterns of the current core.

5.7 Embedding empirical indicators in regulatory planning

By moving from aggregate density figures to refined BSF bands and by mapping intervention priority, conflict zones and infill opportunities, the analysis translates into concrete spatial categories that can be directly embedded in PDV and PPV decision rules.

The integration of empirical spatial indicators into the statutory planning framework of Tirana represents a transformative step toward resilience-driven urban governance. By translating metrics specifically, the composite compactness, and multi-hazard overlays into regulatory decision-gates, the Local Detailed Plan (PDV) evolves from a geometric mapping tool to a key performance indicator (KPI) driven instrument.

The following matrix presents a framework for embedding empirically derived urban indicators directly into the statutory decision structure of Tirana's Local Detailed Plan (PDV). Each indicator is mapped from the analytic outputs of this study to a clear regulatory or design threshold, transforming descriptive spatial analysis into actionable planning interventions.

Table 49. Embedding Empirical Urban Indicators as Regulatory Triggers in the Detailed Local Plan (PDV)

PDV Section	Indicator	Derived from	Statutory Function / Decision Gate
4.2 Existing Land Use	**BCR map** (parcels with BCR > 50%) **FAR surface**	Empirical BCR/FAR, Table 34, 35	Triggers overdevelopment alert; distinguishes re-development vs consolidation
4.2.2 Compactness	**Composite Compactness Index** (entropy + building density, mean = 3.12, max = 257.8)	Composite index, Section 3.4	Identifies spatial "hotspots" of morphological saturation; prioritizes regulatory scrutiny
4.2.3 Verticality	**Verticality Ratio** (Floors/ha, high-rise anomalies)	Building dataset (Floors, density)	Flags height outliers; screens for view-shed conflict, heritage risks
4.4.3 Multi-Hazard Profile	**Multi-hazard Overlay** (Flood/seismic, multi_hazard = 1 or 2)	Multi-hazard regression, Section 3.5	Flags parcels for adaptive design (if high compactness and hazard coincide)

6.5 Environmental Protection	**Impervious Surface Index** (BCR as proxy for heat stress)	BCR analysis, Table 34, 36	Mandates green infrastructure or permeable retrofit where BCR > 80%
6.6 Public Space Proposal	**15-Minute Accessibility Matrix** (% pop. to parks, clinics, schools)	Accessibility analysis, Section 5.3.2	Requires minimum area for social/green infra in accessibility-deficit zones
7.2 Utility Network Phasing	**Intervention Level Layer** (Low/Moderate/High/Critical: based on compactness × risk)	Intervention matrix, Table 37	Schedules utilities/phasing to prioritize critical/high-risk, high-compactness parcels

Source: Authors elaboration

The core of urban form lies in the rigorous quantification of land occupation. By embedding a BCR map (highlighting parcels with BCR > 50%) and a FAR surface derived from your dataset, the PDV gains a powerful diagnostic tool to distinguish overdeveloped zones from those suitable for redevelopment or consolidation. High BCR values (over 80% in 66% of Tirana buildings) trigger statutory requirements for on-site open space retrofitting, roof greening, or stricter limitations on further densification. The FAR layer contextualizes vertical expansion, identifying parcels where upward development is either desirable (to maximize land efficiency) or must be constrained (to protect heritage or skyline).

Embedding Composite Compactness Index in the PDV enables planners to identify spatial "hotspots" of morphological saturation and fine-tune regulatory responses accordingly. Parcels with exceptionally high compactness scores, often central business districts or institutional clusters, are prioritized for detailed review to prevent further saturation and to ensure compliance with resilience and livability targets. The CCI integration triggers enhanced regulatory scrutiny for parcels that exceed critical compactness thresholds and informs urban morphology management, allowing the city to prioritize interventions, monitor sprawl, and coordinate redevelopment incentives or restrictions.

Using the verticality ratio provides an empirical basis to detect outliers (e.g., high-rises outside designated growth corridors). This data-driven approach enables the PDV to proactively flag height anomalies for view-shed conflict assessment or heritage protection review, addressing urban skyline integrity before problems arise. Integrating high FAR requires justification or mitigation where verticality outliers are detected. This approach supports urban design and heritage protection mandates by linking height restrictions directly to measured spatial patterns.

Integrating your multi-hazard overlay (flood/seismic exposure, multi_hazard = 1 or 2, based on regression findings) ensures that planning permissions in at risk areas are no longer issued solely on geometric criteria. Instead, parcels with high compactness and overlapping hazards are flagged for mandatory adaptive design measures, such as elevated structures, permeable surfaces, or enhanced seismic codes. This method flags parcels for adaptive requirements if hazard risk and urban compactness converge and makes resilience a conditional threshold for all planning approvals in hazard prone zones.

Using BCR as a proxy for urban heat stress and imperviousness, the PDV can mandate the retrofitting of green infrastructure or permeable surfaces where parcels exceed BCR > 80%. This operationalizes heat island mitigation at the parcel level, directly linking scientific evidence to enforceable policy. For example, building permits in these areas are conditional on demonstrating at least a 0.4 °C reduction in projected land surface temperature through vegetated roofs or pocket parks.

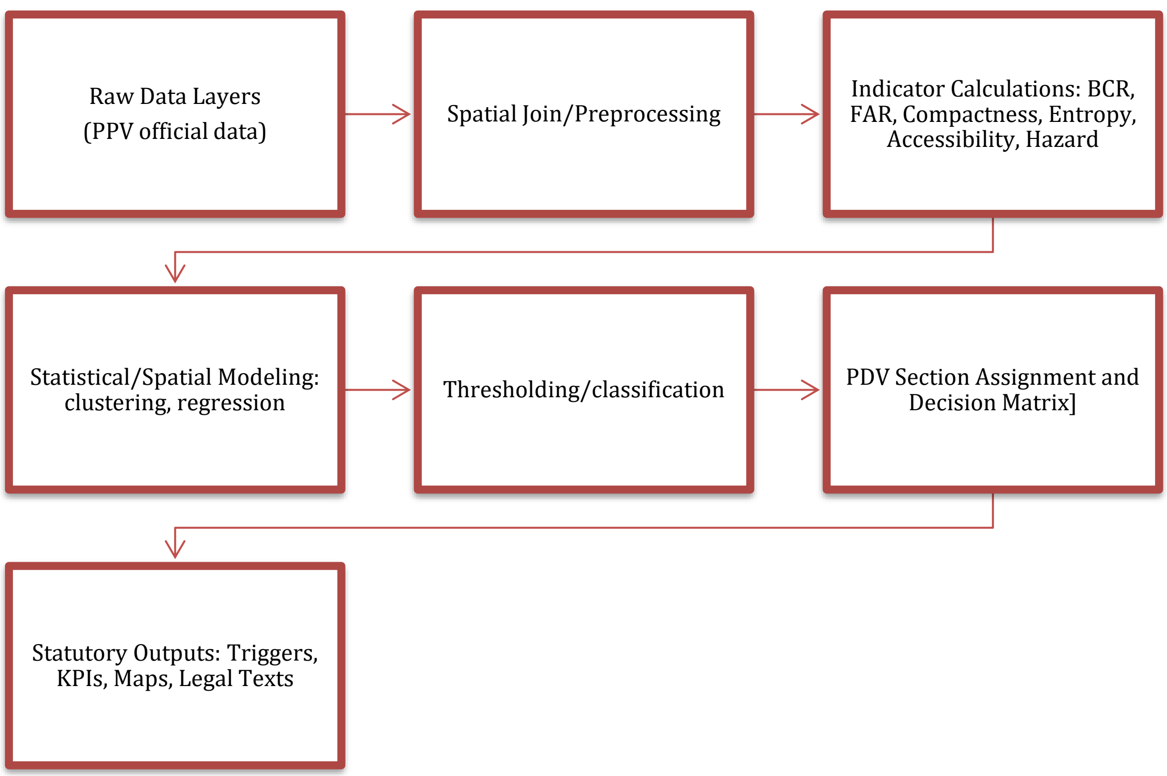
The accessibility matrix can also be embedded as a performance KPI. Parcels or neighborhoods failing to meet minimum thresholds are flagged for compulsory allocation of land for social infrastructure and green spaces in the PDV. This ensures progress toward a 15-minute city, promoting equity and resilience. This KPI Requires new developments in accessibility-deficit zones to allocate land for public use while also supports transit-oriented and inclusive planning, with real-time service gap mapping.

Finally, the intervention level layer (Low/Moderate/High/Critical) is derived from the compactness × risk matrix. It provides an empirically based schedule for infrastructure and utility upgrades, ensuring that areas with the highest spatial vulnerability (compactness + hazard) are prioritized for phased investment and risk mitigation. This KPI can schedule infrastructure upgrades based on scientifically assessed vulnerability and reduce investment risk and maximizes resilience returns for urban systems.

By integrating each analytic component into the PDV's statutory framework, we can enable a quantitative, evidence-based, and risk-sensitive approach to urban planning and resilience policy in Tirana.

This approach aligns each regulatory phase with specific sustainability and resilience payoffs. For instance, parcels with BCR > 0.80 can be mandated to provide vegetated roofs or permeable ground surfaces, directly mitigating heat-island and runoff risks. Where intervention levels are classified as 'Critical', planning permits become conditional on the submission of robust mitigation plans, including quantifiable temperature reduction targets. Accessibility gaps above threshold levels require the reservation of land for new social infrastructure and green spaces, advancing the 15-minute city paradigm.

Figure 38. Data architecture for replicable PDV analytics



Source: Authors' elaboration

This architecture ensures any city or PDV unit can replicate your entire analytic and regulatory process, guaranteeing comparability, transparency, and evidence-based planning.

5.7.1. Multi-hazard resilience performance rules

Table 50. Embed the indicators as statutory decision-gates example

PDV Phase & Clause	Inserted KPI / Threshold	How it changes the planner's decision	Resilience to multi-hazards payoff
I — Assessment *(§4.2, §4.3, §4.4)*	*Parcel BCR > 0.50* "Over-developed"	Triggers mandatory on-site open-space retrofit or roof-greening feasibility note	Lowers imperviousness → ↓ runoff, ↓ heat-island
	Composite-Compactness > 0.30 AND *Multi-Hazard = 1-2 (Flood and seismic risk)*	Parcel tagged "Fragile Morphology", must submit seismic/flood adaptive design report with permit	Limits exposure; ensures resilient typologies
II — Proposals *(§6.5, §6.6)*	*Accessibility-Gap Index > 0.20* (population > 10 min to clinic/park)	PDV must reserve min. 8 % gross area for new social-infra or pocket park, and other services (clinics, shops, pharmacies etc.)	Boosts social resilience & 15-minute-city targets
	FAR < 0.8 in central zone	Allows density bonus *only if* green-roof commitment ≥ 60 % roof area	Aligns intensification with cooling / storm-water gains
III — Regulatory PDV	Intervention Level (Low / Moderate / High / Critical)	Generates colour-coded schedule in the Regulatory Map: • *High*: building permit valid 18 mo • *Critical*: permit ties to proof-of-green-retrofit	Ensures fastest action where risk & compactness peak

Source: Authors' elaboration

Any parcel with BCR > 0.80 shall provide a *minimum vegetated surface* of 20 % of roof area or equivalent permeable ground surface. Where Intervention Level = Critical, the building permit shall include a *"heat-island mitigation plan"* demonstrating a projected land-surface-temperature reduction of ≥ 0.4 °C based on the NDVI gain formula. Density bonuses under Art. 8 are available only when the Service-Gap Index for healthcare or green space is ≤ 0.10 after project completion.

Table 51. Pilot test inside a structural unit (example PDV: TR/327)

Parcel Cluster	Indicator red flags	PDV tool applied	Expected gain

Inner block along "Hoxha Tasim"	BCR = 0.92, FAR = 2.9, Hazard = Seismic 1	Vertical extension to FAR = 4.0 **only after** green-roof retrofit	+2 000 m² housing *and* –0.6 °C peak LST
Villas near "Manol Ekonomi"	FAR = 0.45, *Accessibility-Gap High*	Infill permission to FAR = 1.5 if 100 m² pocket park ceded to municipality, and other services	Adds 30 % residents at zero net heat load
Row along "Qemal Stafa"	Compactness = 0.38, Hazard = Flood 1	Compulsory permeable paving when façade rehab occurs	15 % runoff reduction

Source: Authors' elaboration

Pilot applications within structural units such as TR/327 demonstrate the practical gains of this method, densification is permitted only in exchange for environmental retrofits, while overdeveloped or hazard-prone parcels are subject to stringent adaptation measures. The embedding of empirical indicators in the statutory process ensures that urban intensification and risk management are systematically aligned, offering a replicable model for evidence-based planning in other compact city contexts.

- *What Tirana data show regarding the compact city development*

At the grid scale, genuinely compact fabric is rare and highly localized. Only 0.88% of cells exceed BSF > 0.7, while just 15.29% sit in the medium band (0.4 < BSF ≤ 0.7); the distribution has a long right tail but a low 75th–95th percentile, which means small "islands" of very high coverage inside a broadly looser city texture. The inequality coefficient of 0.689 confirms this polarization and points to fragmented, 'leap-frog' urbanisation rather than continuous, well-composed compactness. In short: Tirana has pockets of intensity, not a citywide compact structure.

At the parcel scale, over sealing is the dominant pattern within built areas, roughly two-thirds of buildings sit above BCR = 80%, leaving minimal residual open space and pushing many blocks beyond the permeability and sky view conditions that a compact, but livable, morphology needs. Balanced density parcels are a minority, and under-developed plots are scarce, which limits easy, low-risk infill. This is the clearest quantitative signal that many built blocks are dense, but non compact.

Functionally, Tirana’s land-use entropy is moderate and often misaligned with the densest fabric, which means form and function are not co-located where they would produce safe, “working” compactness; accessibility improvements are therefore not reliably delivered by today’s densification pattern. This underscores the central distinction; density does not equal compactness if it fails the function and risk tests.

Risk layering clarifies the stakes. The probabilistic models and overlays show statistically significant correlations between high compactness scores and compounded flood/seismic exposure, and the city’s recent expansion is occurring widely in moderate-to-high hazard contexts. This is why we frame compactness as a bounded state, without planning controls, more intensity tends to add exposure; with controls tied to thresholds, intensity can be steered to low risk cells and blocks.

The practical implication is straightforward. In Tirana, compactness cannot be pursued as a *scalar density target*; it must be permitted as a bounded condition. Authorisation needs to operate at the resolution of the evidence, the 100×100 m cell aggregated to blocks and planning units, so that densification is admitted only where form is inside the locally calibrated range, function is evidenced rather than presumed, and multi-hazard exposure remains below threshold. Where these conditions hold, the data support guided intensification; where they do not, either mitigation must be delivered up front (through permeability, shade, detention and verified seismic detailing) or additional floor area should be refused and redirected to lower-risk cells. In this sense, Tirana’s data does not merely diagnose a dense pattern; they provide the operational lever for steering the city toward a compact state that is measurable, enforceable and replicable.

CHAPTER VI: DISCUSSION

The empirical analysis of this thesis began by interrogating the concept of urban compactness beyond its traditional confines of density measurement, seeking instead a multidimensional understanding of how urban form, function, and hazard exposure interact. The comparative assessment across twelve diverse cities, complemented by the high-resolution case of Tirana, unveiled critical insights into what qualifies as a genuinely compact city versus mere density saturation, a distinction that holds decisive implications for both sustainability and resilience.

The analysis of the twelve cities showed clear morphological and functional signatures that distinguish the structurally planned compact cities from their high-density yet unstructured counterparts. Cities such as Vienna, Barcelona, and Paris emerge as archetypes of balanced compactness, characterized by Building Surface Fractions (BSF) generally between 0.55 and 0.60, distributed evenly across their territory. These cities demonstrated not only a well-calibrated proportion between built form and open space but also maintained high levels of land-use entropy, translating into a diverse urban fabric that facilitates functional adaptability and social interaction. Functionally, their accessibility matrices confirmed proximity to essential services within the 15-minute urban framework, reaffirming the compact city ideal of integrating density with accessibility, mixed-use land patterns, and quality public spaces. On the other hand, the cases of Dhaka and Manila exemplified the pitfalls of unregulated density. Despite *BSF* values nearing the upper limits (>0.7), these cities showed functional inadequacies, with insufficient green spaces, low entropy, and fragmented accessibility to healthcare, education, and green infrastructure. This reaffirms that density without corresponding functional infrastructure and public service provision is not compactness but congestion, a morphological trap that exacerbates vulnerabilities and multiplies hazard exposure, particularly in the face of climate-induced risks such as urban heat islands, flooding, and seismic threats.

The panel of global cities analyzed (ranging from the mid-rise block fabric of Barcelona to the the canal-ring of Amsterdam) reveals three archetypal compact-city models. First, perimeter-block cities (e.g., Paris, Barcelona) combine narrow street blocks (100–150 m side), mid-rise buildings (FAR 2–5) and moderate ground coverage (BCR 50–

60%), achieving continuous densities with abundant courtyards and public space. Second, corridor cities concentrate development along transit spines, yielding linear high-density strips within a generally low-rise matrix, which simultaneously protects peri-urban open land and geography-driven constraints. Third, grid cities pursue high-rise clusters within a fine-grain street network, with verticality and mixed use integrated through zoning incentives and public-realm mandates. Across all twelve, we observe:

- Consistent mid-range densities were BSF clusters around 0.4–0.7 in 25–40 percent of grid cells, avoiding extremes.
- Balanced verticality were FAR sweet-spots of 2–4 prevail, with building heights tightly controlled.
- High land-use entropy where mean parcel entropies exceed 0.6, reflecting robust mixed use.
- Near-universal service access were over 90 percent of residents reach daily needs and green space within 15 minutes.
- Risk-conscious zoning - hazard overlays actively shape growth boundaries, limiting development in flood or seismic zones.

These twelve exemplars thus define a normative compactness envelope, *continuous morphological saturation*, functional mixing, equitable amenity distribution, and dynamic risk governance.

Across the 100×100 m grid, the cells that consistently qualify as compact in Tirana share a striking resemblance despite very different building types. In the central districts where compactness holds, buildings tend to carry similar floor-area ratios, maintain comparable inter building distances, and present a regular street grain that yields stable, short access times to daily services and transit. In the peripheral residential pocket where compactness also holds (predominantly one-storey houses with gardens) the same regularities appear in a different guise: houses sit on modules of similar plot size and setback, garden depth is broadly uniform, and the local street network keeps walking isochrones tight. In both settings, compactness coincides with low variance within the cell-neighbourhood, FAR does not oscillate wildly from parcel to parcel;

spacing is neither too tight to erase sky view nor too loose to lengthen trips; and accessibility surfaces are smooth rather than patchy.

The European comparison confirms that this "*calibrated uniformity*" is not idiosyncratic. Where cities are judged compact by performance rather than by density alone, their compact cells exhibit three recurring traits.

- First, morphological convergence around a mid-range intensity, massing is sufficiently alike across adjacent plots to sustain continuous street frontage and a predictable public realm, without tipping into over-sealing.
- Second, spacing regularity that preserves microclimatic function, similar distance bands between buildings keep sky-view factors, shading and cross-ventilation within a narrow, favourable range, and crucially leave room for permeable base and tree canopy.
- Third, access stability at the fine scale, the walking network and service distribution produce near-constant travel times across contiguous cells, so that added floor area continues to convert into realized proximity rather than sporadic congestion.

These commonalities suggest that compactness expresses itself less as a single number and more as a *pattern of local coherence*. The cells that work best are those where the variance of the key ingredients (FAR, inter-building distance, and 15-minute access) remains low within the cell's immediate neighbourhood. In the mid-rise, perimeter-block parts of Tirana, this coherence is achieved by similar building envelopes and a stable street rhythm; in the low-rise garden district, it is achieved by modular plots, repeatable setbacks and vegetated open space that cools and infiltrates without sacrificing proximity. In both cases, risk is bound not because density is low or high per se, but because the fabric is evenly calibrated, permeability is not left to chance, shade is distributed rather than episodic, and stormwater is detained at the same scale at which it is generated.

On this basis, the results advance the following definition of the pattern. A city is locally compact where, within a 100×100 m cell and its immediate neighbours, built form, spacing and access exhibit low dispersion around mid-range targets, floor-area ratios cluster within a narrow band; inter-building distances fall within a stable interval that preserves *sky view and cross ventilation*; and walking access to everyday services and transit varies little across contiguous cells. When these conditions co-occur (and only then) added floor area continues to yield functional proximity while heat, pluvial and seismic exposures remain within acceptable limits. *This is why both the mid-rise, continuous-frontage fabric and the low-rise garden fabric can be compact, each achieves* ***coherent balance*** *among form, spacing and access at the same fine scale, and each maintains the functions that keep risk in check.*

Two clarifications should follow in this regard. First, compactness is not tied to a particular height or typology; it is tied to ***coherence***. A high-rise cluster can be compact if its envelopes, setbacks and access produce the same low-variance pattern and maintain function (entropy and accessibility); a one-storey neighbourhood can be compact if its modularity and service mesh do the same. Second, the opposite also holds, a district with impressive density figures will fail the compactness test if FAR swings violently between parcels, if spacing veers from canyon to void within a block, or if access surfaces are jagged, because under those conditions, additional volume no longer converts to proximity and the risk budget is quickly exhausted.

The pattern that emerges from Tirana and is echoed in the European cases is **compactness as calibrated uniformity**, a reproducible, low-variance configuration of form, spacing and access at the 100×100 m scale that preserves function (entropy and accessibility) and lowers hazard exposure (due to lower concentration of building per 100mx100m and population density). This is the practical signature of the compact city in the data, and it is the standard that statutory instruments should seek to permit, reward and maintain.

Table 52. Comparative Building Surface Fraction (BSF – 100x100 m Grid)

City	Mean BSF	Typical Range	SD	% BSF > 0.7	Notes
Tirana	(0.121	0.00 to 0.24	0.167	0.88	Very high spatial inequality in built density across the city.
Manila	0.78	>0.7, right tail	high	High	Highly skewed
Rotterdam	0.72	>0.7	high	High	“Ultra compact”

San Francisco	0.70	>0.7	high	High	“Ultra compact”
Barcelona	0.55	0.30–0.60	≤0.15	~5–10%	Balanced/narrow
Vienna	0.55	0.30–0.60	≤0.15	~5–10%	Balanced/narrow
Paris	0.54	0.30–0.60	wide	~10%	Variable, bimodal
Zurich	0.45	±0.10	≤0.10	Low	Uniform midrise
Helsinki	0.45	±0.10	≤0.10	Low	Uniform midrise
Singapore	0.50	0.45–0.55	>0.25	High cores	Highly skewed
Dhaka	0.50	0.45–0.55	>0.25	High cores	Highly skewed
Hamburg	0.45	-	-	Low	Balanced
Aarhus	0.40	<0.40	-	Very low	Loose, green

The comparative analysis of Building Surface Fraction (BSF) across the 12 reference cities, using a consistent 100x100 m GEM grid, highlights marked differences in urban form. Tirana’s mean BSF is notably lower than the ultra-compact benchmarks (Manila, Rotterdam, San Francisco) and aligns closer to the “balanced compact” cluster (Vienna, Barcelona, Paris), yet with a much smaller share of high-density cells: only 0.88% of grid cells in Tirana exceed BSF 0.7, compared to 5–10% in cities with strong inner-core compaction. About 15.3% of Tirana’s cells fall in the moderate-density range (0.4 < BSF ≤ 0.7), reflecting a predominance of heterogeneous, medium-density neighborhoods rather than contiguous compact blocks. This distribution is more similar to Zurich, Helsinki, and Hamburg, where spatial planning delivers uniform midrise forms and open space ratios remain high. Tirana thus appears morphologically “looser” than many Western European peers, consistent with post-socialist expansion and fragmented infill patterns observed across the region. The results confirm that despite rapid densification, the city’s urban fabric is still far from the “ultra-compact” type.

This mid-range BSF places Tirana inside the “safe density window” (0.45–0.60) identified in your thesis as balancing compaction with liveability and risk mitigation. However, the very limited proportion of high-BSF cells suggests that most of the city has not (yet) reached the critical threshold where risks such as heat islands or infrastructure overloading would predominate.

While exemplar cities achieve extensive mid-range densities (BSF 0.4–0.7 across 30–40 percent of the grid), Tirana's densification is discontinuous, producing isolated "hotspots" of extreme ground coverage surrounded by under-utilized land. *Compact models show mid-rise to high-rise forms to reconcile ground permeability with density. Tirana's horizontal saturation without vertical intensification marks it as "dense but non-compact."* True compact cities exhibit parcel entropies above 0.6, Tirana's mono-functional zoning (entropy of approx. 0.26) hinders walkable diversity and economic vibrancy. Hazard overlays are integral to zoning, ensuring resilience. Tirana's detachment of compaction from risk management has concentrated vulnerability, nullifying the resilience benefits density might confer.

The results show that compactness works only as a bounded state. In blocks where ground coverage is kept moderate and a minimum share of permeable and vegetated surfaces is secured, adding floor area improves access while cooling the microclimate through shade and evapotranspiration. Where courtyards and plots are already sealed, additional volume raises surface temperatures and increases stormwater exceedance. In other words, the same quantum of density produces opposite outcomes depending on whether it sits inside or outside a risk-aware envelope. When used as a gate on permits (and verified after occupancy) this envelope preserves the benefits associated with proximity and mix while containing pluvial floods and seismic conflicts.

The findings of this study provide critical insights into how compactness metrics, environmental sustainability, and resilience indicators interact across diverse urban contexts. By focusing on the morphological aspects of the city (such as the Built-up Coverage Ratio (BCR), population density), and their interaction the functional aspect of the compact city urban form (with environmental sustainability indicators), the analysis identifies significant tipping points for resilience index under multi hazard approach.

The relationship between compactness and resilience, as measured by Risk index and Socioeconomic Vulnerability, highlights the complex dynamics of urban form. Population density demonstrates a significant impact on resilience, particularly in high-density cities, while BCR's influence emerges primarily in conjunction with sustainability measures. This underscores the importance of managing compactness to maintain resilience while avoiding thresholds that exacerbate vulnerabilities. Dhaka and Manila exemplify cities where extreme population densities and high BCR values compound risks. These urban environments are characterized by insufficient infrastructure, limited green spaces, and vulnerability to hazards such as flooding and heat stress. The data indicates that compactness, without robust sustainability measures, intensifies risks and exacerbates socio-economic inequalities. Policies for Dhaka and Manila should prioritize improving drainage systems, expanding permeable surfaces, and integrating green infrastructure to mitigate flood risks. Regulatory frameworks must enforce land-use standards that limit excessive densification and promote equitable access to public spaces. Public housing initiatives should include sustainable design elements to improve living conditions and reduce exposure to hazards.

Cities such as Barcelona and Vienna demonstrate how compact urban forms can balance density with resilience. Barcelona's grid structure, characterized by mixed-use zoning and extensive public transit networks, enables high population densities without overwhelming infrastructure. Similarly, Vienna's integration of green spaces within its compact urban fabric supports social well-being and environmental sustainability. Green area is a key *mediator* in the compactness-resilience relationship witihn the global dataset analysis. In cities like Singapore, where compactness is high, investments in vertical greenery, efficient water management, and renewable energy infrastructure have mitigated risks associated with densification. However, the findings suggest that sustainability measures alone cannot fully offset the vulnerabilities of overly compact urban forms, as observed in San Francisco and Rotterdam. Singapore showcases the potential for high-density cities to achieve resilience through innovative sustainability practices. Singapore's model should inspire policies in other high-density cities, emphasizing multi-functional green spaces and vertical design strategies. However, long-term resilience requires additional measures, such as enhancing community engagement in planning and improving equity in resource distribution. In contrast, San Francisco demonstrates how limited land-use diversity and insufficient green infrastructure reduce the effectiveness of compact urban forms. Despite moderate sustainability improvements, the city struggles to mitigate risks associated with urban heat islands and socio-economic inequities. San Francisco should prioritize policies that enhance land-use diversity and incentivize green retrofitting in urban cores.

Integrating affordable housing with mixed-use development could address social vulnerabilities while promoting a more sustainable compactness.

The study identifies safe-density windows at which compactness transitions from *beneficial to detrimental*. A tile BSF of 60% average is a significant tipping points beyond which socio-economic vulnerabilities escalate. Cities approaching these thresholds, such as Rotterdam and Helsinki, require careful urban planning to avoid adverse outcomes. Rotterdam and Helsinki exhibit moderate compactness levels but are nearing critical thresholds. The study suggests that exceeding these levels could strain infrastructure and increase vulnerabilities, particularly under multi-hazard scenarios such as flooding and heatwaves. It is suggested that Rotterdam and Helsinki adopt proactive policies to manage compactness. Urban growth should be redirected to peri-urban areas with sustainable transport links to reduce pressure on central zones.

The resilience outcomes of compactness vary depending on hazard types. High BCR levels exacerbate flood risks, as seen in Dhaka and Singapore, where impermeable surfaces dominate. Conversely, drought-related risks are more influenced by regional water management systems, as observed in Helsinki and Zurich. Compact city policies must address hazard-specific challenges.

Urban planners must enforce policies to maintain BCR and density levels within identified thresholds. For example, restricting BCR to below 60.0 can help mitigate socio-economic vulnerabilities while preserving the benefits of compactness. Environmental sustainability must be embedded as a core principle in compact city policies. This includes expanding urban greenery, retrofitting buildings for energy efficiency, and promoting public transit over private vehicles. Compactness policies should be tailored to each city’s unique socio-economic and environmental context. Compact city policies should incorporate multi-hazard assessments, ensuring that urban forms are adaptable to diverse risks. Investments in climate-resilient infrastructure and hazard-specific urban designs are critical.

- ***Discussion of research questions and hypotheses***

The first research question asked how a compact city can be operationally defined through measurable morphological and functional indicators, and to what extent a composite compactness index (CCI) can distinguish compact urban fabric. The corresponding hypothesis (H1) stated that a city's compactness is not given by density alone, but results from a calibrated balance between form, function and performance under multi-hazards.

The empirical work on the thirteen-city sample provides a clear answer. By combining building surface fraction (BSF), verticality and floor-area ratio (FAR) with indicators of land-use entropy, green provision and 15-minute accessibility to key services, the thesis moves beyond the long-standing reliance on simple population or dwelling density. When these variables are combined into the CCI, grid cells with comparable population density display very different compactness scores. Dense grids in Vienna, Paris or Barcelona that combine mid-range BSF, strong public transport accessibility and a robust network of green and open spaces consistently appear as high-CCI cells. Equally dense grids in Manila or Dhaka, with weaker accessibility, lower land-use mix and limited environmental buffers, fall into medium or low CCI classes even before hazard is introduced.

Once multi-hazard performance is added through INFORM risk and its climate-related components, this differentiation becomes even sharper. Cells that score highly on form and function but are situated in low or moderate INFORM risk zones maintain high CCI values. Cells that are dense but coincide with high INFORM risk, particularly where hazard relates to fluvial flooding or coastal inundation, show a clear drop in their composite scores.

The same pattern appears in Tirana. Grid cells in the central basin where BSF exceeds 0.7 and verticality is high often do not present the highest CCI because accessibility gaps and hazard exposure depress their composite values; by contrast, some mid-density cells with balanced service access and lower hazard reach intermediate or high CCI levels.

These results confirm H1. Compactness cannot be equated with high values of a single morphological indicator. Instead, it emerges where a specific combination of built intensity, functional performance and bounded risk is present. In other words, CCI behaves as an effective operationalisation of compactness: it rewards density when it is accompanied by accessibility and reasonable safety, and penalises density that is achieved through over-sealing, mono-functionality or growth in high-risk locations.

From the standpoint of statutory planning in Tirana, this has immediate consequences. The General Local Plan (PPV) and the Detailed Local Plans (PDVs) regulate intensity primarily through BCR, FAR and maximum heights, often with coarse land-use categories. Accessibility and hazard are handled through separate sectoral instruments, if at all. The empirical findings indicate that this separation is no longer adequate. A plot may satisfy PPV intensity parameters and still score poorly on CCI because it lacks service access or lies in a high-hazard corridor. A planning framework that wishes to promote “compact and resilient development” therefore needs to internalise CCI-type metrics into its monitoring architecture, rather than relying exclusively on density and height limits.

The second research question explored which empirically derived safe-density ranges could be identified under different multi-hazard profiles, and how far such ranges converge or diverge across cities with distinct morphologies and hazard exposures. Hypothesis H2 stated that, although compactness is context specific, the global sample should reveal a quantifiable safe-density window beyond which compactness degrades into mere density, leading to rising multi-hazard risk.

The comparative analysis confirms this expectation. Across the thirteen cities, plots of BSF, verticality and CCI against INFORM multi-hazard and climate risk show a similar non-linear form. At low levels of BSF and CCI, cities are under-intensified: trip distances are long, land-use mix is limited, and per capita environmental costs are high, while hazard exposure per unit of population is often relatively low. As BSF moves into a mid-range around roughly 0.55–0.65, and CCI enters a band of about 2 to 5, accessibility indicators improve markedly. More residents live within walking distance of health, education and retail services; land-use entropy increases; and per capita green access improves or at least remains stable. Multi-hazard risk rises but does so gradually. Within this band, additional compactness continues to deliver net benefits.

Once BSF and verticality exceed this mid-range and CCI climbs beyond the identified band, the relationship reverses. Incremental increases in compactness coincide with disproportionately higher INFORM risk, driven by rising exposure to flood and heat-related hazards and, in some regions, to storm surge or landslide risk. The Monte Carlo simulations that vary CCI while sampling hazard and functional parameters show that, beyond city-specific thresholds, expected impacts per additional unit of compactness increase at an accelerating rate, while gains in accessibility and land-use mix begin to saturate. Vienna, Barcelona and Paris operate largely within or just below the safe window; Dhaka and Manila show extensive tracts of urban fabric beyond the upper bound, where very high BSF and verticality are no longer compensated by functional or environmental performance.

The precise numeric thresholds differ across cities, reflecting climatic, geomorphological and institutional contexts, yet the existence of a bounded window is consistent. The results therefore support H2. Compactness emerges as a state with an empirical upper and lower bound rather than an indefinite trajectory.

For policy, this matters because it provides a set of indicative envelopes that can inform statutory instruments. Instead of generic language encouraging “higher density along corridors” or “intensification of central zones”, planners can work with empirically grounded bands of BSF, FAR and CCI that correspond to desirable performance levels. The PPV and national guidelines could use these bands to refine intensity zones, for example by explicitly capping plot coverage and height combinations in hazard-prone areas once the compactness indicators approach the upper limit of the window, or by permitting modest intensification in under-used zones until the lower bound is reached. This creates a coherent frame where densification is actively encouraged only as long as it remains within safe operational boundaries.

The third research question focused explicitly on Tirana and asked about the spatial relationship between urban compactness and multi-hazard exposure within the existing morphology. Hypothesis H3 assumed that there would be a correlation between levels of compactness and multi-hazard risk.

The parcel-level analysis and the intervention maps demonstrate that Tirana's fabric is characterised by a pronounced imbalance at micro-scale. Two-thirds of buildings are located on parcels with BCR above 80%, and more than four-fifths on parcels with BCR above 70%. When these BCR bands are cross-classified with flood and seismic layers and with grid-level CCI, a strong association emerges. Parcels in the very high-density classes are over-represented in the high and critical hazard categories; they also align with the highest multi-hazard exposure scores derived from the composite risk index.

Intervention priority and conflict zones make this relationship tangible. The urban core concentrate parcels where BCR exceeds 85%, BSF at grid level is high, and both flood susceptibility and seismic amplification are significant. These conflict zones are not scattered points but coherent clusters where compactness has clearly moved past the safe-density window. In these areas, the advantages normally associated with compact form (shorter trips, concentration of services, efficient infrastructure) are increasingly offset by constrained evacuation routes, limited open space for shelter and cooling, and high probability of structural damage during seismic events or compound flood episodes.

The statistical relationship between compactness indicators and hazard scores confirms H3. Higher BSF, verticality and CCI are generally associated with higher combined flood–seismic risk in Tirana, particularly once the analysis controls for the underlying terrain and river network. The correlation is not perfectly uniform, which is to be expected in a complex urban system, yet the overall pattern is clear, the current trajectory of densification has tended to reinforce rather than correct historical decisions to build in vulnerable areas. Compactness has been achieved primarily by loading more people and floor area onto plots within the central floodplain and along unstable slopes, rather than by steering growth toward structurally safer zones.

This diagnosis interacts directly with the existing planning framework. The PPV recognises certain high-risk areas but does not systematically constrain intensification in them; PDVs for central units have at times maximised FAR and permissible heights in order to "regularise" existing densities and accommodate development pressure. The empirical findings suggest that such an approach is incompatible with a risk-sensitive compact city strategy. Where compactness and multi-hazard risk are strongly aligned, further intensification is likely to worsen vulnerability. The thesis therefore provides an evidence base for revising PPV intensity parameters and PDV design norms in these units, for example by lowering permissible BCR and FAR, mandating permeability and tree cover targets, or linking any additional floor area to structural retrofitting and risk-reduction obligations.

The final research question examined how compactness and multi-hazard indicators can be translated into concrete thresholds and monitoring tools within urban planning instruments, and what changes in exposure and densification patterns arise in the scenario tests. Hypothesis H4 proposed that integrating CCI and multi-hazard risk indicators into planning monitoring could reduce vulnerability by directing densification toward low-risk areas.

The intervention analysis provides a structured answer. Building on the safe-density window identified in the global comparison and the specific compactness–risk relationship in Tirana, the study defines operational thresholds for BSF, BCR and CCI at grid and parcel scale. These thresholds are then used to classify parcels into very high, high, medium, low and very low density, and to combine these classes with hazard categories to produce four levels of intervention priority: low, moderate, high and critical. Additional maps isolate conflict zones where critical compactness coincides with high hazard and identify low-density parcels with acceptable hazard scores that could accommodate infill.

When these categories are fed into planning scenarios, the effects on vulnerability become visible. A business-as-usual scenario that follows existing PDV permissions continues to add floor area predominantly in the already saturated central basin and along hazard-exposed corridors. Compact indicators rise, but so does the share of population located in high multi-hazard zones. In contrast, a guided compactness scenario that employs the thresholds as decision gates (restricting new construction in conflict zones, imposing strong mitigation requirements in high-priority parcels, and targeting most additional development to low-density, low-hazard parcels) produces a different outcome. The city still becomes more compact in aggregate terms, because underutilized parcels in safer areas are developed and service accessibility improves, but the proportion of built-up areas and residents in high-risk zones stabilizes or declines.

This demonstrates that H4 is supported. When CCI and risk indicators are actively integrated into planning instruments, rather than remaining analytical tools, they can steer the direction of densification and reshape the geography of vulnerability. The thesis sketches how this integration could occur within Tirana's existing statutory framework. CCI, BSF and BCR thresholds, combined with flood and seismic classes, can be written into PPV guidelines for each structural unit as conditional intensity bands. PDVs can be required to demonstrate compliance with these bands through parcel-level mapping and to specify compensatory measures where existing development already exceeds safe thresholds.

A digital monitoring platform, linked to cadastral updates and satellite imagery, can track changes in compactness and risk through time and provide a transparent basis for adjusting rules or prioritizing retrofitting programmes.

The research questions and hypotheses are not only answered in analytical terms; they are also translated into a practical framework that can support a recalibration of compact-city policy. Compactness is defined and measured as a balance of form, function and hazard performance; a safe-density window is empirically observed across multiple cities; Tirana's present morphology is shown to exceed this window in critical zones; and a set of thresholds and tools is proposed that can realign densification with resilience objectives within the existing legal planning apparatus.

CHAPTER VII: CONCLUSIONS AND RECOMENDATIONS

This research has systematically interrogated the notion of the compact city through a multidimensional lens that integrates urban morphology, functional diversity/accessibility, and multi hazard risk. Moving beyond the traditional association of compactness with mere density, the study operationalized a composite indicator methodology that aimed to understand the spatial saturation of urban form, the efficiency of land-use mixing, and multi-hazard exposures. The combination of cross-city comparative analysis, high-resolution spatial modelling in Tirana, and the development of empirically grounded thresholds positions this thesis within the emerging frontier of spatial urban resilience studies.

The main conclusion for the compact city policy dilemma is that compactness cannot be treated as a generic call for “more density,” but must be defined and governed as a bounded state where three conditions are met simultaneously *(1) urban form lies within an empirically calibrated safe-density window, (2) functional performance (accessibility, mix of uses, green provision) is adequate, and (3) multi-hazard risk remains within tolerable limits*. When any of these conditions are violated compact city policy ceases to deliver benefits and instead becomes a driver of risk and vulnerability. In terms of compact city definition, compactness is a bounded and measurable state, defined by low variance around calibrated targets and continuous compliance with risk limits, *not* a *density* number or a fixed typology; and it can be achieved provided a coherent balance of urban fabric is maintained.

The research demonstrates that compactness can be operationalized as a measurable balance between morphology, function and risk, rather than being equated with high density alone. The composite compactness index (CCI) constructed from BSF, BCR, FAR, verticality, land-use entropy, accessibility and green infrastructure systematically distinguish high-performing urban fabric from merely saturated development. In all cities, grids with comparable population densities exhibit very different CCI values depending on their functional mix, service proximity and exposure to hazards. This confirms that compactness is a compound property: it is present where medium–high built intensity is accompanied by good access to daily functions and acceptable levels of risk, and absent where density is achieved through over-sealing, mono-functionality or construction in hazard-prone locations.

Second, the comparative analysis across the global sample provides empirical support for the existence of a safe-density window. When BSF, verticality and CCI are plotted against multi-hazard indicators derived from INFORM and climate-related scenarios*, a consistent non-linear pattern emerges.* As compactness increases from low values towards a mid-range band (approximately BSF 55-65% and CCI around 2–5), accessibility improves, land-use mix strengthens and performance generally benefits, while multi-hazard risk rises only moderately. Beyond this band, further increments in compactness are associated with diminishing functional returns and a disproportionately steep increase in expected losses under combined hazard scenarios. Planned compact cities such as Vienna, Paris and Barcelona largely operate within or just below this band, while hyper-dense cases such as Dhaka and parts of Manila exceed it over large areas. *The safe-density window is therefore not a universal numerical constant, but a empirical envelope within which compactness remains beneficial and beyond which it becomes primarily a driver of risk.*

Third, the detailed case of Tirana reveals how deviations from this window manifest in a fast-growing, post-socialist city. At municipal scale, average densities appear moderate, yet parcel-level analysis shows that more than four-fifths of buildings sit on plots with BSF above 70%, and nearly sixty percent on plots above 85%. These over-sealed parcels form extensive clusters in the central basin and along major corridors, precisely where flood susceptibility and seismic amplification are highest. When CCI and hazard layers are combined, these districts emerge as conflict zones in which morphological saturation and multi-hazard exposure coincide. At the same time, large belts of low-density or underdeveloped land exist at the urban fringe and along radial corridors, often with lower hazard scores but weak functional integration. Tirana's urbanisation pattern therefore couples intense localised overdevelopment and risk with a dispersed and under-serviced periphery, rather than distributing compactness within the empirically identified safe window.

Fourth, the functional analysis of Tirana confirms that current density levels are not systematically translating into compact-city benefits. Land-use entropy remains modest in many high- BSF areas, and gaps in 15-minute accessibility to green spaces and healthcare services persist. Statistical models show that compactness indicators are positively associated with multi-hazard exposure, while the mediating effect of green infrastructure and functional mix is still too weak to offset the risks generated by over-sealing and vertical growth. Compactness, as currently configured, thus tends to increase vulnerability rather than resilience. This finding directly addresses the core research hypothesis that compactness becomes a desirable condition only when density, function and risk are jointly managed.

Fifth, the thesis translates these analytical insights into an operational framework that can be embedded within Tirana's statutory planning instruments. By defining CCI thresholds corresponding to the safe-density window and cross-classifying them with flood and seismic hazard bands, the study builds a parcel-level typology of intervention needs. Critical parcels (those with very high CCI and high multi-hazard scores) are identified as zones where further densification should be halted and where planning efforts should concentrate on permeability restoration, micro-green and blue infrastructure, and seismic upgrading. Medium-density parcels that fall within the safe window and exhibit moderate hazard levels are designated as "monitor and maintain" areas, while low-density parcels in low-hazard zones are highlighted as priority locations for guided infill. Scenario tests show that, if these thresholds are used as decision rules in PDV preparation and building permit evaluation, future densification can be redirected towards safer parcels without sacrificing aggregate compactness; the share of population and built-up area in high multi-hazard zones stabilises or decreases compared with a business-as-usual continuation of existing permissions.

Finally, the research suggests a practical pathway for cities like Tirana to adopt a compact development model that is both transparent and enforceable. At parcel and block scale, maximum ground coverage and minimum permeable and shaded fractions can be defined directly from the safe-density analysis. Additional floor area can be granted only when project proponents demonstrate, with standardised calculations, that their interventions do not move the block outside the safe window and that they contribute to cooling, stormwater management and seismic performance. A municipal digital registry that tracks coverage, floor area, permeability, canopy, and hazard scores at 100×100 m resolution would allow continuous monitoring and link planning consent to ex-ante compliance and ex-post verification. In districts with entrenched informality or severe loss of public space, replacement intensity can be made conditional on delivering a defined package of permeable base, detention capacity, shade, cool materials and verified structural strengthening.

These conclusions show that compactness is best understood as a bounded and measurable state rather than a simple call for “more density”. By establishing an empirically derived safe-density window, demonstrating how Tirana’s current trajectory exceeds this window in specific locations, and outlining concrete regulatory and monitoring mechanisms to realign densification with resilience, the thesis provides both a conceptual reframing and a practical toolkit for compact-city policy.

In policy terms, this means that densification targets must be replaced by safe-density envelopes. Planning frameworks should not simply promote higher FAR or BCR in central areas and along corridors; they must set clear upper and lower bounds for BSF/BCR, FAR and composite compactness (CCI) that are calibrated to the local hazard profile and functional deficits. Within these envelopes, intensification can be actively encouraged, especially in underused, low-risk zones where accessibility can be improved. Beyond them, further growth should either be prohibited or made conditional on strong mitigation measures, including permeability restoration, shading, stormwater detention and seismic upgrading. Existing hyper-dense, high-risk districts should be treated primarily as targets for adaptation and, where necessary, gradual de-densification, not as reservoirs for additional development rights.

The broader lesson for policy is that compact city strategies must be recast as risk-sensitive spatial governance rather than as simple density agendas. This requires integrating *form–function–risk* indicators into statutory instruments (general and detailed plans, zoning codes, building regulations), supported by digital monitoring systems that track scores at fine spatial resolution. Only by steering where and how density is added, and by tying permissions to continuous compliance with safe-density thresholds, can cities capture the well-known advantages of compact urbanism (efficient infrastructure, shorter trips, protection of open land) without reproducing the “compact but unsafe” patterns that this study documents in Tirana and other rapidly urbanising contexts.

Recommendations

A critical operational insight emerging from this study is the value of jointly monitoring Built Surface Fraction (BSF) as complementary metrics to track urban densification, form evolution, and exposure to environmental risks. While BSF offers a fine-grained spatial lens at the grid-cell level, capturing the surface intensity of built structures across the urban landscape, BCR provides a parcel-specific indicator of development saturation relative to lot boundaries. Used in tandem, these metrics furnish a dual-scale monitoring framework that is sensitive to both macro-patterns of densification and micro-scale morphological transformations. Given the accelerated pace of urban change in Tirana and the city's exposure to compounded risks (particularly seismic and flood hazards) the establishment of a real-time digital urban monitoring system is both a policy imperative and a technical possibility. The methodological approaches, spatial indicators, and statistical models developed in this thesis can serve as the backbone. Such a system would integrate regularly updated geospatial data (e.g., satellite imagery, cadastral updates, construction permits) with the analytical routines established herein (calculating BSF, BCR, FAR, verticality, entropy, and the composite compactness index) in real time. Through GIS-based visualization and data analytics, the dashboard could spatially disaggregate urban form metrics by neighborhood, structural unit, or parcel, while overlaying them with multi-hazard risk layers. Crucially, this platform would enable automated alerts and thresholds, such as:

- *Flagging parcels or zones where BCR exceeds 80% without corresponding increases in FAR, indicating horizontal overdevelopment.*
- *Identifying grid cells where BSF surpasses critical thresholds (e.g., 0.7), particularly within floodplains or seismic fault proximities.*
- *Tracking entropy scores to assess the evolution of land-use diversity, especially in risk-prone or infrastructurally underserved areas.*

By institutionalizing this system within urban planning departments, the Municipality of Tirana could establish a data-driven governance mechanism, whereby development approvals, infrastructure investments, and risk mitigation interventions are informed by dynamic, spatially explicit evidence. Furthermore, the dashboard could support public transparency and stakeholder engagement by providing an open-access interface where citizens, developers, and policymakers can visualize urban dynamics and understand where constraints or opportunities for growth exist.

This model is not confined to Tirana. Given the standardized methodological framework, it can be replicated across Albanian cities or even adopted as a regional monitoring tool in the Western Balkans, where urban densification and hazard exposure similarly converge. *Operationalizing the BSF and BCR analytical framework through a digital transformation agenda in urban planning would enhance spatial oversight, optimize land use, and build adaptive capacity against multi-hazard risks, aligning urban growth with resilience and sustainability mandates in real time.*

Furthermore, several recommendations emerge for policymakers, urban planners, and scholars interested in advancing compact city models within the constraints of environmental risks and functional equity:

1. **Embed compactness within risk-sensitive planning**

Urban planning in Tirana and similar cities must transition from density-driven approaches to risk-sensitive compactness frameworks. This involves formally integrating compactness metrics (such as the composite compactness index and BSF thresholds) into urban regulatory codes, ensuring that densification is spatially steered away from high-risk zones or conditioned upon resilience-enhancing retrofits.

2. **Enforce morphological thresholds**

Policymakers should institutionalize morphological thresholds (such as a BCR cap of 55% and population densities not exceeding 10,000/km² in hazard-prone areas) as planning standards. Exceeding these limits should trigger mandatory sustainability interventions, including green infrastructure mandates, permeable surface requirements, and adaptive architectural design.

3. **Prioritize green infrastructure and permeability**

In saturated urban clusters, particularly those with BSF > 80%, interventions must focus on green retrofits, rooftop gardens, pocket parks, and the introduction of permeable surfaces. These measures are essential to mitigating urban heat islands, improving microclimates, and reducing flood risks.

4. **Operationalize the 15-Minute city framework**

To enhance functional compactness, Tirana must adopt and enforce the 15-minute city framework, prioritizing investments that guarantee equitable access to healthcare, education, green spaces, and public transport within short travel distances. This requires revising zoning laws to facilitate mixed-use developments in underserved areas.

5. **Utilize the intervention matrix for phased urban management**

The intervention matrix developed in this thesis, which categorizes parcels into low, moderate, high, and critical risk-intervention levels, should be institutionalized within Tirana's Local Detailed Plan (PDV) procedures. This matrix enables phased, priority-based infrastructure upgrades, ensuring that limited resources are allocated where urban vulnerability converges with compactness extremes.

6. **Advance Integrated Data Architectures for Planning**

Municipal level planning authorities should establish integrated data systems that continuously monitor urban form indicators, functional accessibility, and multi-hazard risks. This dynamic data infrastructure is critical for updating intervention priorities and ensuring adaptive governance responsive to urban transformations.

7. **Generalize and replicate the model**

The composite compactness index and analytical framework developed here should be further tested and calibrated across other cities within Albania and the Western Balkans to create a regionally sensitive model of compact urban resilience. This would contribute to a standardized yet adaptable planning toolkit for secondary cities facing similar morphological and risk dynamics.

This research redefines the compact city not as a quantitative end-state of density but as a qualitative spatial condition where morphological intensity, functional accessibility, and environmental resilience coalesce.

For cities like Tirana, the path to true compactness lies not in continued densification but in deliberate, data-driven, and risk-aware planning that harmonizes urban form with the lived realities of function and hazard exposure. The methodological and policy propositions articulated in this thesis aim to guide this transformative agenda, ensuring that the pursuit of compactness translates into sustainable and resilient urban futures.

Limitations of the study

While this research offers significant insights into the spatial dynamics of compactness, sustainability, and risk exposure in Tirana and through cross-city comparisons, several methodological and empirical limitations must be acknowledged.

Firstly, the calculation of the composite compactness index is heavily reliant on available geospatial datasets, which, while comprehensive, are constrained by data resolution and consistency. In particular, the BCR and FAR calculations are contingent on the precision of cadastral and building footprint data, which may include inaccuracies, especially in contexts of informal or unregistered developments prevalent in parts of Tirana. Similarly, the entropy index used to quantify land-use diversity was derived from available land use classifications, which may oversimplify functional nuances or miss informal, mixed-use patterns that exist in practice but are not formally recorded.

Secondly, the multi hazard risk layers (particularly flood and seismic hazard data) are generalized and do not fully capture micro-spatial variations in exposure or adaptive capacity.

The regression analyses and statistical modelling, particularly the multinomial logistic regression linking compactness with multi-hazard exposure, yielded robust associations but with modest explanatory power (Pseudo $R^2 = 0.069$). This reflects the complex, multi-causal nature of urban risk exposure, suggesting that other variables (such as governance quality, infrastructure condition, and social dynamics) remain unaccounted for within the current model.

Additionally, the study is limited by its focus on a static temporal snapshot. Urban dynamics are inherently temporal, with spatial configurations, densities, and vulnerabilities evolving over time. The lack of longitudinal data limits the capacity to observe how compactness interacts with dynamic processes.

Directions for future research

Building on these findings and acknowledging the outlined limitations, future research can pursue several avenues to deepen understanding and enhance the applicability of this study's framework.

First, there is a clear need for longitudinal spatial analysis that tracks changes in compactness, land-use diversity, and hazard exposure over time. This would allow for the investigation of causal relationships and the impact of policy interventions on urban morphology and resilience trajectories.

Second, future research should explore the development of dynamic simulation models, including agent-based models or spatial econometric approaches, to predict how urban form and function evolve under different policy scenarios, growth pressures, and environmental constraints. This would provide more predictive power to urban planning strategies, particularly in fast-changing urban contexts like Tirana.

Third, expanding the comparative framework with primary data collection across multiple cities, using harmonized methodologies, would allow for more precise benchmarking of compactness, sustainability, and resilience. Such a cross-city dataset could contribute to a broader theory of the compact-resilient city, sensitive to diverse geographic, cultural, and governance contexts.

Lastly, future studies could investigate the effectiveness of specific policy instruments, such as green infrastructure incentives, zoning reforms, or adaptive building codes, in mitigating the adverse effects of hyper-compactness. Evaluating these instruments empirically would provide critical insights into the policy pathways that can reconcile the compact city model with the imperative of urban resilience.

References

Abu-Samra, R., & Abazi, A. (2023). *Spatio-temporal analysis of Tirana's urban expansion using Sentinel-2 imagery.* Remote Sensing Applications, 30, 101-117.

ADB. (2021). *Philippines urban sector assessment*. Asian Development Bank.

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., & Rockström, J. (2005). Social-ecological resilience to coastal disasters. *Science, 309*(5737), 1036–1039.

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100*(4), 341-343.

Ahlfeldt, G. & Pietrostefani, E. (2017). *The compact city in empirical research: a quantitative literature review*. Landscape and Urban Planning, 167, 178-191.

Ahlfeldt, G. M., & Pietrostefani, E. (2017). The compact city in empirical research: A quantitative literature review. *Urban Studies, 56*(12), 2332–2348.

Aiken, L. S., & West, S. G. (1991). *Multiple regression: Testing and interpreting interactions*. SAGE.

Alberti, M., Marzluff, J., Shulenberger, E., Bradley, G., Ryan, C., & Zumbrunnen, C. (2003). Integrating humans into ecology: OpPORTunities and challenges. *BioScience, 53*(12), 1169-1179.

Aliaj, B., & Mema, A. (2020). *Skanderbeg Square after pedestrianisation: Behavioural change in Tirana's core.* Journal of Urban Design, 25(4), 563-585.

Angel, S., Lamson-Hall, P., & Blanco, H. (2016). *Atlas of Urban Expansion* (v.2016). New York University.

Angel, S., Lamson-Hall, P., & Blanco, H. (2021). The anatomy of density: Measuring the built footprint of cities. *Journal of the American Planning Association, 87*(3), 263–279.

Angel, S., Lamson-Hall, P., & Blanco, H. (2021). The anatomy of density: Measuring the built footprint of cities. *Journal of the American Planning Association, 87*(3), 263–279.

Angel, S., Lamson-Hall, P., & Blanco, J. (2016). Anatomy of density: Global findings and their implications. *Lincoln Institute of Land Policy Working Paper*.

Angel, S., Lamson-Hall, P., & Blanco, M. (2016). *Atlas of urban expansion—The 2016 edition.* NYU Marron Institute.

Angel, S., Parent, J., & Civco, D. L. (2016). *Atlas of urban expansion – 2016 edition.* Lincoln Institute of Land Policy.

Anselin, L. (1988). *Spatial econometrics: Methods and models*. Kluwer.

Arundel, R., & Ronald, R. (2017). *Housing stress in polycentric regions*. Cities, 61, 23–32.

Arundel, R., & Ronald, R. (2017). *Resilience, restructuring and renewal: The Dutch Housing Model in transition.* Housing Studies, 32(3), 396–415.

Arundel, R., & Ronald, R. (2017). The Amsterdam–Rotterdam housing divides. *Urban Studies, 54*(5), 1201–1223.

Arup. (2018). *Chile seismic code performance review.* London: Arup Resilience.

Azur, M. J., Stuart, E. A., Frangakis, C., & Leaf, P. J. (2011). Multiple imputation by chained equations: what is it and how does it work? *International Journal of Methods in Psychiatric Research, 20*(1), 40–49.

Banai, R., & DePriest, D. (2014). From parking lots to parks: Ground Surface Index as an indicator for urban sustainability. *Sustainable Cities and Society, 12*, 191–205.

Banai, R., & DePriest, P. T. (2014). Urban form and runoff: A brief review of the literature. *Journal of Planning Literature, 29*(3), 259–277.

Banai, R., & DePriest, P. T. (2014). Urban form and runoff: A brief review. *Journal of Planning Literature, 29*(3), 259–277. https://doi.org/10.1177/0885412214524459.

Banai, R., & DePriest, T. (2014). *Landscape & Urban Planning, 128*, 66–79.

Banholzer, S., Kossin, J., & Donner, S. (2014). The impact of climate extremes on human health. *Weather and Climate Extremes, 2*, 17-35.

Baron, R. M., & Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research. *Journal of Personality and Social Psychology, 51*, 1173–1182.

Bartholomew, K., & Ewing, R. (2009). *Land use–transportation scenarios and future vehicle miles of travel in Seattle*. *Journal of the American Planning Association, 75*(1), 13-27.

Barwise, Y., & Aybars, C. (2020). Street canyon ventilation and air quality: A London case study. *Atmospheric Environment, 223*, 117223.

Barwise, Y., & Aybars, O. (2020). *Environment International, 136*, 105473.

Batista e Silva, F., et al. (2020). Mapping accessibility conditions and transport emission trade-offs in EU cities. *Transportation Research Part D, 85*, 102390.

Batista e Silva, F., et al. (2020). Measuring accessibility in European cities: The potential for walkability. *Transportation Research Part A, 134*, 240–266.

Batista e Silva, F., Moreno-Monroy, A., & Gallego, J. (2020). A high-resolution pan-European model of passenger inter-modal accessibility. *Transportation Research Part A, 138*, 331–352. https://doi.org/10.1016/j.tra.2020.05.013.

Batista e Silva, F., Moreno-Monroy, A., & Gallego, J. (2020). Accessibility to population and services across Europe: Improving comparability with harmonised data and high-resolution population grids. *Computers, Environment and Urban Systems, 79*, 101418.

Batty, M. (2005). *Cities and complexity.* MIT Press.

Bejko, D., & Pojani, D. (2022). *Heat islands and tree-canopy inequity in a rapidly densifying Balkan capital.* Urban Climate, 43, 101-133.

Bernard, J., Bocher, E., Petit, G., & Palominos, S. (2018). Sky view factor calculation in urban context: Computational performance and accuracy analysis of two open and free GIS tools. *Climate, 6*(3), 60. https://doi.org/10.3390/cli6030060.

Bertaud, A. (2018). *Order without design: How markets shape cities*. Cambridge, MA: MIT Press. https://doi.org/10.7551/mitpress/11743.001.0001.

Bertolini, L., & Le Clercq, F. (2003). *Urban development without more mobility by car?* Environment and Planning A, 35(4), 575-589.

Bertolini, L., & Le Clercq, F. (2003). *Urban development without more mobility by car? Lessons from Amsterdam's planning approach*. Transportation Research Part A, 37(2), 137-150.

Bilham, R. (2010). *Lessons from the Haiti earthquake.* Nature, 463(7283), 878-879.

Bourgeois, C. (2022). *Organismes de foncier solidaire: A new model for affordable housing in Paris*. *Housing Studies*, 37(6), 1012-1034.

Bouzouina, L., et al. (2022). Outsourcing the footprint: Paris and its peri-urban burden. *Ecological Economics, 193*, 107323.

Bramley, G., et al. (2009). Social acceptability of compact cities. *Urban Studies, 46*(13), 2721-2746.

Breheny, M. (1992). *The contradictions of the compact city*. Built Environment, 18(4), 286–300.

Breheny, M. (1997). Urban compaction: Feasible and acceptable? Cities, 14(4), 209–217.

Breiman, L. (2001). Random forests. *Machine Learning, 45*, 5–32.

Burchell, R., & Mukherji, S. (2003). Conventional development versus managed growth: The costs of sprawl. Transportation Research Record, 1831, 10–18

Burgess, R. (2002). Compact city and housing: Opportunities and challenges. *Built Environment, 28*(1), 123–138.

Busquets, J. (2005). *Barcelona: The urban evolution of a compact city*. Nicolodi.

Busquets, J. (2005). *Barcelona: Evolución urbanística*. COAC.

Cal OES (California Governor's Office of Emergency Services). (2023). *California Multi-Hazard Mitigation Plan Update.*

Cal OES. (2023). *California Climate Adaptation Strategy progress report 2023*. California Office of Emergency Services.

California Planning Roundtable. (2018). *Smart growth in San Francisco: policy review*. San Francisco, CA.

California Planning Roundtable. (2018). *Compact growth and California climate goals*.

Cal-OES. (2023). *California Multi-Hazard Mitigation Plan 2023 update*. Sacramento: California Office of Emergency Services.

Calthorpe, P. (1993). *The Next American Metropolis.* New York: Princeton Architectural Press.

Capel, H. (2006). *Barcelona, capital mediterránea*. Ediciones del Serbal.

Capel, H. (2006). Barcelona: La transformación urbana. *Boletín de la AGE, 40*, 295–327.

CBS (Statistics Netherlands). (2022). *Regional accounts 2021*. The Hague.

CBS. (2022). *Regional economic accounts 2021.* Statistics Netherlands.

CBS. (2022). *Regional gross domestic product 2021*. Statistics Netherlands.

CCSF (City and County of San Francisco). (2020). *Hazard and Climate Resilience Plan.*

MTC (Metropolitan Transportation Commission). (2017). *Plan Bay Area 2040 – Final Plan and EIR.*

Çela, S., Lame, R., & Quni, G. (2021). *Post-quake performance of pre-1990 RC frames in Tirana.* Earthquake Spectra, 37(2), 765-789.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D, 2*(3), 199–219. https://doi.org/10.1016/S1361-9209(97)00009-6.

Chen, Y. (2011). Derivation of functional relations between fractal dimension and shape indices of urban form. *Computers, Environment and Urban Systems, 35*(6), 442–451. https://doi.org/10.1016/j.compenvurbsys.2011.07.003.

Churchman, A. (1999). Disentangling the concept of density. *Journal of Planning Literature, 13*(4), 389–411.

City and County of San Francisco. (2020). *Hazard and climate resilience plan*.

City of Helsinki. (2021). *Carbon Neutral Helsinki 2035 action plan (updated edition)*.

City of Helsinki. (2021). *Carbon Neutral Helsinki 2035 Action Plan*.

City of Melbourne. (2021). *Green Factor Tool: Technical Guide – Measuring the ecological performance of development.* Melbourne, VIC: City of Melbourne Urban Sustainability Branch.

Congress for the New Urbanism. (1999). *Charter of the New Urbanism.* New York.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Thousand Oaks, CA: SAGE.

Crowley, H., et al. (2020). *Global Dynamic Exposure Model: A framework for high-resolution assessment of the built environment.* Earthquake Spectra, 36(1), 72-95.

Crowley, H., et al. (2020). High-resolution exposure modelling using the GDE Framework. *Earthquake Spectra, 36*(1), 57–76.

Cutler, D. R., et al. (2007). Random forests for classification in ecology. *Ecology, 88*, 2783–2792.

Cutter, S. L. (1996). Vulnerability to environmental hazards. *Progress in Human Geography, 20*(4), 529-539.

Danish Ministry of Environment. (2021). *Århus Climate Plan 2030*.

Delta Programme. (2021). *Rhine–Meuse delta adaptation pathways*. Ministry of Infrastructure and Water Management, The Hague.

Dempsey, N., Brown, C., & Bramley, G. (2012). The key to sustainable urban development in UK cities? *Urban Studies, 49*(6), 1157–1179.

Dey, M., & Lewis, B. (2021). Compactness and flood preparedness in Asian coastal megacities. *Natural Hazards, 108*(1), 83-105.

Dieleman, F. M., & Wegener, M. (2004). Compact city and urban sprawl. *Built Environment, 30*(4), 308–323. https://doi.org/10.2148/benv.30.4.308.57151.

Dormann, C. F., et al. (2013). Collinearity: a review of methods to deal with it. *Ecography, 36*, 27–46.

Dovey, K., & Pafka, E. (2017). The science of urban design? *Built Environment, 43*, 610–623.

EEA. (2016). *Urban sprawl in Europe—Joint EEA–FOEN report.* Luxembourg: European Environment Agency.

Efron, B., & Tibshirani, R. J. (1993). *An introduction to the bootstrap*. Chapman & Hall.

Eliasson, J., & Mattsson, L.-G. (2006). Equity effects of congestion pricing: Quantitative methodology and a case study for Stockholm. *Transportation Research Part A, 40*(7), 602–620. https://doi.org/10.1016/j.tra.2005.11.002.

European Commission. (2025). *INFORM Climate-Change Risk Index: Technical note*. Brussels.

European Commission. (2025). *ICCRI 2050 projections: Technical annex*. Joint Research Centre.

European Commission. (2025). *INFORM Climate Change 2050 scenario results.* Joint Research Centre.

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association, 76*(3), 265-294.

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association, 76*(3), 265–294. https://doi.org/10.1080/01944361003766766.

Fang, B., Wang, S., & Cheng, S. (2022). Bridging the last-500-metres: A service gap index for 15-minute neighbourhoods. *Journal of Transport Geography, 95*, 103132. https://doi.org/10.1016/j.jtrangeo.2021.1031320.

Frank, L. D., & Pivo, G. (1994). Impacts of mixed use and density on utilisation of three modes of travel: Single-occupant vehicle, transit, and walking. *Transportation Research Record, 1466*, 44–52.

Gehl, J. (2010). *Cities for people*. Island Press.

Gemeente Amsterdam. (2021). *Amsterdam Climate Adaptation Strategy 2050.*

Gehl, J. (2010). *Cities for People.* Island Press.

Gemeente Amsterdam. (2021). *Amsterdam Rainproof guidelines v2.0*.

German Federal Ministry for the Environment. (2022). *Green Network Hamburg progress report*.

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies. *Environment and Planning B, 31*(2), 199–215.

Giezen, M., Bertolini, L., & Salet, W. (2014). “The RandstadRail project: a case study in decision-making strategies under uncertainty.” *Planning Theory & Practice, 15*(3), 414-418. https://doi.org/10.1080/14649357.2014.935084.

Giezen, M., Bertolini, L., & Salet, W. (2014). Adaptive capacity within a mega infrastructure project: *RandstadRail* lessons. *Planning Theory & Practice, 15*(3), 389–430.

Gill, S., Handley, J., & Ennos, R. (2015). Green infrastructure for climate-proofing compact cities. *Journal of Environmental Planning and Management, 58*(2), 244-263.

Gill, S., Handley, J., & Ennos, R. (2015). *Journal of Hydrology, 522*, 482–497.

Glaeser, E. (2011). *Triumph of the city: How our greatest invention makes us richer, smarter, greener, healthier and happier.* Penguin.

Glaeser, E., & Gyourko, J. (2018). The economic implications of housing supply. *Journal of Economic Perspectives, 32*(1), 3-30.

Gobierno de España. (2008). *Texto Refundido de la Ley de Suelo (Real Decreto Legislativo 2/2008).*

Gong, P., et al. (2018). Mapping sky, tree, and building view factors of street canyons in a high-density city. *Remote Sensing, 10*(2), 254.

Grimmond, C. S. B., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of Applied Meteorology, 38*(9), 1262-1292.

Haapala, A., Lehvävirta, S., & Jantunen, J. (2021). Sea-level rise adaptation in Helsinki. *Landscape Research, 46*, 556-573.

Haapala, H., Juhola, S., & Soini, K. (2021). Coastal planning under sea-level rise in Helsinki. *Land Use Policy*, 105, 105-195.

Hagenlocher, M., Garschagen, M., & Zebardast, E. (2022). *Understanding compound risk in megacities*. International Journal of Disaster Risk Reduction, 72, 102802.

Hagenlocher, M., et al. (2022). INFORM Risk Index: Concept and methodology. *International Journal of Disaster Risk Reduction*, 73, 102-131.

Hajer, M. (1995). *The politics of environmental discourse: Ecological modernisation and the policy process*. Oxford University Press.

Hamidi, S., Ewing, R., & Sabouri, S. (2020). Does density aggravate the COVID-19 pandemic? *Journal of the American Planning Association, 86*(4), 495-509.

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners, 25*(2), 73–76. https://doi.org/10.1080/01944365908978307.

Haxhiu, L. and Aliaj, B. (2025). Urban Change Detection in Tirana, Albania (2000–2025) Using Remote Sensing and Open Geospatial Data, Int. Arch. Photogramm. Remote Sens*. Spatial Inf. Sci., XLVIII-4/W13-2025, 143–148*, https://doi.org/10.5194/isprs-archives-XLVIII-4-W13-2025-143-2025, 2025.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4*, 1-23.

Hosmer, D. W., Lemeshow, S., & Sturdivant, R. X. (2013). *Applied logistic regression* (3rd ed.). Wiley.

Huber, C., & Gulledge, J. (2011). Extreme events: Measuring climate-change damages. *Pew Center on Global Climate Change*.

Huq, S., & Shamsudduha, M. (2020). From plan to practice: Climate resilience in Dhaka. *Environmental Science & Policy*, 114, 1-10.

Hysa, E., & Hoxha, E. (2020). *GIS-based pluvial flood susceptibility in Tirana plain.* Journal of Flood Risk Management, 13(3), e12602.

Ibrahimi, M., & Nahaj, K. (2014). *Urban growth modelling for Tirana using CA-Markov.* European Spatial Research, 12(1), 55-72.

INFORM Country Risk Profiles. (2024). Retrieved June 2025 from https://drmkc.jrc.ec.europa.eu/inform-index.

Inform Index. (2025). *Methodology version 2025*. European Commission Joint Research Centre.

INFORM. (2024). *INFORM Risk Index: 2024 results*. European Commission Joint Research Centre & UN OCHA.

IPCC. (2021). *Sixth Assessment Report, Working Group II: Impacts, Adaptation and Vulnerability*. Cambridge University Press.

IPCC. (2022). *Sixth Assessment Report: Impacts, Adaptation and Vulnerability*. Cambridge University Press.

IPCC. (2023). *AR6 Synthesis Report: Climate change 2023.* Geneva: Intergovernmental Panel on Climate Change.

IPCC. (2023). *Climate change 2023: Synthesis report*. Intergovernmental Panel on Climate Change.

IPCC. (2021). *Climate Change 2021: Impacts, adaptation and vulnerability*.

Irajifar, L., Sipe, N., & Alizadeh, T. (2016). Disaster resilience in urban contexts: A study of Brisbane suburbs. *International Journal of Disaster Resilience in the Built Environment, 7*(4), 330–344. https://doi.org/10.1108/IJDRBE-04-2015-0022.

Jabareen, Y. R. (2013). Planning the resilient city: concepts and strategies for coping with climate change and environmental risk. *Cities, 31*, 220–229.

Jacobs, J. (1962). *The death and life of great American cities*. Random House.

Jacquet, J., Pachauri, S., & Tubiana, L. (2010). *Cities and Climate Change: Responding to an Urgent Agenda*. World Bank.

Jacquet, P., Pachauri, R. K., & Tubiana, L. (2010). *Regards sur la Terre 2010: Villes, changer de trajectoire*. Presses de Sciences Po.

Jenks, M., Burton, E., & Williams, K. (Eds.). (1996). *The compact city: A sustainable urban form?* E & FN Spon.

Jenks, M., & Burgess, R. (2000). *Compact cities: Sustainable urban forms for developing countries*. Spon.

Joint Research Centre. (2023). *INFORM Risk Index: Concept and Methodology, Version 2024.* European Commission.

Joint Research Centre. (2024). *INFORM Risk 2024: Concept and methodology*. European Commission.

Jones, C., Kammen, D. M., & Khalfan, M. (2019). Embodied energy and carbon footprint of mid-rise versus high-rise construction. *Energy and Buildings, 199*, 394–405. https://doi.org/10.1016/j.enbuild.2019.07.049.

Jones, C., Kammen, D., & Khalfan, M. (2019). Embodied carbon of mid- vs high-rise. *Energy and Buildings, 199*, 394-405.

Jones, P., Wills, J., & Odiko, A. (2020). Informality, density and infectious disease risk in Nairobi. *Health & Place, 66*, 102459.

Jones, P., Steemers, K., & Lombardi, P. (2019). Built form and energy efficiency: Understanding the tipping point. *Energy Policy*, 128, 109-118.

Kabisch, N., Strohbach, M., Haase, D., & Kronenberg, J. (2016). Urban green space availability in European cities. *Current Opinion in Environmental Sustainability, 22*, 117–127.

Kain, J., Andersson-Sköld, Y., & Bergman, R. (2022). Urban form indicators and pluvial flood depth: A continental EU analysis. *Science of the Total Environment, 843*, 156944.

Kain, J.-H., Adger, W. N., & Granberg, M. (2022). *Compact development and urban resilience: A systematic review.* Landscape and Urban Planning, 225, 104-468.

Kain, J.-H., Adger, W. N., & Granberg, M. (2022). Thresholds in urban resilience: An empirical assessment. *Urban Studies, 59*(8), 1601–1619. https://doi.org/10.1177/00420980221087776.

Kasa, A. (2023, February 9). *Walkability and the 15-minute city model: An integrated approach for the city of Tirana.* Medium. https://medium.com/@abaskasa94/walkability-and-the-15-minute-city-model-b91f1291c60.

Kim, H. J., et al. (2022). *Sustainable Cities and Society, 80*, 103810.

Kim, J.-H., Park, T., & Lee, D. (2022). Blue–green infrastructure thresholds for stormwater control in high-density Seoul. *Journal of Hydrology, 612*, 128192.

Koks, E., & Hudson, P. (2020). *Estimating the global exposure of built assets to flood hazard*. Nature Communications, 11, 4738.

Koks, E., & Hudson, P. (2020). *A global risk assessment of storm surges under climate change*. Climatic Change, 163(3), 1341-1358.

Krehl, A., et al. (2016). Capturing urban form: Best practices for measuring city density. *Environment and Planning B, 43*(5), 862–880.

Krehl, A., Siedentop, S., & Kroll, F. (2016). Capturing urban form: Best practices for measuring density. *Environment and Planning B, 43*(5), 862–880. https://doi.org/10.1177/0265813515605340.

Krehl, A., Siedentop, S., & Kroll, F. (2016). Urban form and residential energy demand: An empirical analysis for Germany. *Energy Policy, 99*, 63-73.

Krehl, A., Siedentop, S., & Kroll, F. (2016). Capturing urban form. *Environment and Planning B, 43*(5), 862-880.

Kühn, M. (2003). *Green belt and compact city planning in Europe*. Planning Practice & Research, 18(2), 159–171.

Kühn, M. (2003). Greenbelt and green heart: Separating and integrating landscapes in European city regions. *Landscape and Urban Planning, 64*(1-2), 19–27. https://doi.org/10.1016/S0169-2046(02)00214-9.

Kühn, M. (2003). *Greenbelt and compact city: friends or foes?* Futures, 35(5), 461-472.

Kühn, M. (2003). Greenbelt and green heart. *Landscape and Urban Planning, 64*(1-2), 19-27.

Kuhn, M., & Johnson, K. (2013). *Applied predictive modeling*. Springer.

Kühn, M. (2003). Greenbelt and green heart: Separating and integrating landscapes in European city regions. *Landscape and Urban Planning*, 64(1-2), 19-27.

Kühn, M. (2003). Greenbelt and Green Heart: Green open space planning in the Netherlands, 1950–2000. *Landscape and Urban Planning, 64*, 19 – 36.

Le Brun, S., & Carr, A. (2019). Flood risk management in the Seine basin. *Natural Hazards and Earth System Sciences*, 19, 1221-1239.

Li, L., et al. (2020). Canyon ventilation and pollutant dilution in compact quarters. *Atmospheric Environment, 236*, 117628.

Li, X., et al. (2020). *Atmospheric Environment, 230*, 117504.

Li, Z., Zhou, Y., & Wang, S. (2020). Three-dimensional compact urban form and heat-environment linkages. *Sustainable Cities and Society, 53*, 101943. https://doi.org/10.1016/j.scs.2019.101943.

Lico, G., & Sklivanioti, M. (2017). *Thermal performance of pre- and post-transition neighbourhoods in Tirana.* Energy and Buildings, 153, 211-223.

Litman, T. (2021). *Evaluating cost savings of compact development.* VTPI.

Litman, T. (2021). Evaluating cost savings of smart growth. Victoria Transport Policy Institute.

Litman, T. (2021). *Evaluating infrastructure cost savings of smart growth*. Victoria Transport Policy Institute.

Liu, J., Chen, X., & Yu, Y. (2023). Machine-learning evaluation of urban compactness across Canada. *Urban Studies, 60*(8), 1532–1554. https://doi.org/10.1177/00420980221143169.

Livesley, S. J., McPherson, E. G., & Calfapietra, C. (2016). The urban forest and ecosystem services: Impacts on urban metabolism. *New Phytologist, 212*(3), 805-807.

Oke, T. R. (1987). *Boundary-layer climates* (2nd ed.). Routledge.

Lohrey, S., & Creutzig, F. (2023). *A "sustainability window" of urban form*. *Transport Research Part D* (in press).

Lu, X., Ye, L., & Zhang, Y. (2021). Measuring urban compactness based on functional characterisation and human-activity intensity. *Ecological Indicators, 121*, 107177. https://doi.org/10.1016/j.ecolind.2020.107177.

Lundberg, S. M., & Lee, S.-I. (2017). A unified approach to interpreting model predictions. In *Proc. NIPS* (pp. 4765–4774).

Marshall, T. (2000). Urban rebirth in Barcelona. *European Planning Studies, 8*, 449-462.

McHarg, I. (1969). *Design with Nature.* Garden City, NY: Doubleday.

McKenzie, L. H., Brown, A. J., & Milliken, T. H. (2021). Defining the compact city: a systematic review. *Journal of Urban Affairs, 43*(4), 479–499.

Metropolitan Transportation Commission. (2017). *Plan Bay Area 2040*.

Ministerie van Infrastructuur en Waterstaat. (2021). *RandstadRail 2020 evaluation report* (in Dutch). The Hague.

Ministerie van Infrastructuur en Waterstaat. (2021). *RandstadRail Evaluation Report.*

Municipality of Amsterdam. (2020). *Omgevingsvisie Amsterdam 2050.*

Ministerie van Infrastructuur en Waterstaat. (2021). *RandstadRail performance review 2020*.

Ministry of Land, Infrastructure, Transport and Tourism. (2014). *Guidelines for Location Optimisation Plans under the Revised City Planning Act.* Tokyo: MLIT.

Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the "15-minute city": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities, 4*(1), 93–111. https://doi.org/10.3390/smartcities40100060.

Municipality of Amsterdam. (2020). *Monitoring Amsterdam Spatial Strategy*.

Municipality of Amsterdam. (2020). *Mobility Plan Amsterdam 2030*.

Musselman, K. N., et al. (2018). Rain-on-snow flood risk in a changing climate. *Geophysical Research Letters, 45*(12), 6459-6467.

Neuman, M. (2005). The compact city fallacy. Journal of Planning Education and Research, 25(1), 11–26.

Newman, P., & Kenworthy, J. (1989). *Cities and Automobile Dependence: An International Sourcebook*. Gower.

Newton, P., & Newman, P. (2015). Scaling the urban density–energy relationship in cities. *Urban Policy and Research*, 33(1), 76-82.

Nica, E., & Kapllani, J. (2019). *Walkability audit of Tirana's historic core.* International Journal of Sustainable Transportation, 13(5), 357-368.

OECD. (2012). *Compact city policies: A comparative assessment.* Paris, France: OECD Publishing. https://doi.org/10.1787/9789264167865-en.

OECD. (2018). *Rethinking urban sprawl: Moving towards sustainable cities.* OECD Publishing.

OECD. (2021). *The circular economy in cities and regions: Paris metropolitan review*.

OECD. (2021). *OECD metropolitan outlook 2021: Driving recovery in cities*.

Ogrodnik, K. (2019). Greening dense Paris. *Journal of Urban Design, 24*, 675-695.

Oke, T. R. (1987). *Boundary-Layer Climates* (2nd ed.). Routledge.

Oke, T. R. (1987). *Boundary-Layer Meteorology, 39*, 165–182.

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

Pedregosa, F., et al. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research, 12*, 2825–2830.

Permanyer, L. (2023). *L'Eixample, 150 anys d'Història*. Barcelona: Viena Edicions.

Pesaresi, M., & Politis, P. (2022). Urban Atlas 2020 technical note. *Remote Sensing, 14*, 1234.

Qirjazi, E., & Bardhi, K. (2021). *Future flood exposure under continued densification of Tirana.* Natural Hazards, 109(1), 231-252.

Rapoport, E. (2014). *Sustainable urbanism as a mobile practice.* Urban Studies, 51(5), 984-1000.

Rapoport, E. (2014). Globalising sustainable urbanism: the role of global networks in the diffusion of eco-city projects. *Urban Studies,* 51(11), 2319-2335.

Rapoport, E. (2014). Globalising sustainable urbanism: The role of international masterplanners. *Urban Studies*, 51(11), 2316-2336.

Ribeiro, M. T., Singh, S., & Guestrin, C. (2016). "Why should I trust you?": Explaining the predictions of any classifier. In *Proc. KDD* (pp. 1135–1144).

Ribeiro, P. J. G., et al. (2019). Assessing urban resilience: a multi-dimensional approach. *Ecological Indicators, 98*, 607–618.

Rockström, J., et al. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472-475.

Rode, P., et al. (2014). Cities and energy. *Energy Policy, 78*, 248-267.

Rode, P., Keim, C., Robazza, G., Viejo, P., & Schmidt, A. (2014). Cities and energy: Urban morphology impacts on building energy use. *Energy Policy, 78*, 248–267. https://doi.org/10.1016/j.enpol.2014.11.035.

Rode, P., Keim, C., Robazza, G., Viejo, P., & Schmidt, A. (2014). Cities and energy: Urban morphology impacts on building energy use. *Energy Policy, 78*, 248-267.

Rogers, R. (1997). *Cities for a small planet*. Faber & Faber.

Rousseeuw, P. J., & Hubert, M. (2011). Robust statistics for outlier detection. *WIREs Data Mining and Knowledge Discovery, 1*, 73–79.

Salat, S. (2017). *Cities and forms: On sustainable urbanism.* Hermann.

Salat, S., & Lavigne, J.-B. (2021). Resilient density and climate-positive design. *Journal of Urbanism, 14*(2), 215-237.

Salat, S., Bourdic, L., & Labbe, F. (2017). *Scaling laws and urban systems*. Springer.

Salat, S., Bourdic, L., & Labbe, F. (2017). *Urban Morphology and Resilience*. ISTE-Wiley.

Salat, S., Bourdic, L., & Labbe, F. (2017). *Scaling laws and urban systems.* Springer.

Sasaki, Y., et al. (2021). Compound heatwave–pandemic impacts on Tokyo's power grid. *Energy Policy, 154*, 112288.

Sayer, A. (2010). *Method in social science: A realist approach* (2nd ed.). Routledge.

Schneider, A., Friedl, M. A., & Potere, D. (2010). Mapping global urban areas using MODIS 500-m data: New methods and datasets. Remote Sensing of Environment, 114(8), 1733-1746.

Seto, K., Güneralp, B., & Hutyra, L. (2011). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity. *Proceedings of the National Academy of Sciences, 108*(29), 11521-11526.

Seto, K., Güneralp, B., & Hutyra, L. (2011). Global forecasts of urban expansion. *PNAS, 108*(29), 11521-11526.

SFCTA (San Francisco County Transportation Authority). (2022). *2022 Transportation Trends Report.*

Sherlock, C. (1996). An entropy measure of land-use mix for use in travel demand modelling. *Transportation Research Record, 1552*, 89-92.

Sherlock, P. (1996). Mixed-use urban centres. *Journal of Urban Design, 1*(1), 17–30.

Sherlock, P. (1996). Mixed-use urban centres: A review of UK experience. *Journal of Urban Design, 1*(1), 17–30. https://doi.org/10.1080/135748096087243980.

Shirazi, M., & Falahat, M. (2012). Compact city and social injustice in the Middle East. *Cities, 29*(5), 283-292.

Shpuza, E. (2023). The shape and size of urban blocks. *Environment and Planning B: Urban Analytics and City Science*, 50(4), 1639-1659.

Snellen, D., & Hilbers, H. (2007). *Adaptation of Dutch transport policy to climate risk.* Transport Policy, 14(4), 334-344.

Snellen, D., & Hilbers, H. (2007). Sustainable Accessibility: A Dutch approach. *Transport Policy,* 14(4), 394–404.

Snellen, D., & Hilbers, H. (2007). Randstad 2040: Balancing spatial, economic and ecological imperatives. *Journal of Transport Geography*, 15(3), 185-193.

Snellen, D., & Hilbers, H. (2007). Infrastructure density in Randstad Holland. *European Journal of Transport and Infrastructure Research, 7*, 283-298.

UN-Habitat. (2020). *World Cities Report 2020: The value of sustainable urbanisation*.

Steemers, K. (2003). Energy and the city: Density, buildings and transport. *Energy and Buildings, 35*(1), 3–14. https://doi.org/10.1016/S0378-7788(02)00075-0.

Sulaiman, A. (2023). Grand Paris Express and urban compactness. *Transport Policy, 127*, 75-86.

Sulaiman, Z. (2023). Grand Paris Express: Rethinking mobility for a compact metropolis. *Transportation Research Procedia*, 67, 392-402.

Sun, C., Wang, X., & Meng, Y. (2024). A review of compactness indexes of form in computational urban design. In *Proceedings of CAADRIA 2024* (pp. 325-334).

Sun, C., Wang, X., & Meng, Y. (2023). A review of compactness indexes of form in computational urban design. In *CAADRIA 2023 proceedings* (pp. 434-445).

Sun, Y., Zhang, N., Ao, X., & Gao, Y. (2024). Numerical studies on the influence of building morphology on urban canopy wind speed. *Journal of Advances in Modeling Earth Systems, 16*(6), e2023MS003881. https://doi.org/10.1029/2023MS003881.

Suzuki, H., Cervero, R., & Iuchi, K. (2013). *Transforming cities with transit: Transit and land-use integration for sustainable urban development.* Washington, DC: World Bank.

Talen, E. (2005). *New urbanism and American planning: the conflict of cultures*. Routledge.

Tan, W., & Rinaldi, F. (2019). Flood damage versus density: An EU cross-section. *Water, 11*(12), 2509.

Thinh, N. X., Nguyen, H., Arlt, G., & Heber, B. (2002). Using cellular automata for handling the MAUP in monitoring urban density. *Environment and Planning B, 29*(1), 53–68.

Thomas, R., & Cousins, W. (1996). A new compact city form: Concepts in practice. *Urban Studies, 33*(7), 1125–1146. https://doi.org/10.1080/0042098966500118170.

Tsai, Y.-H. (2005). Quantifying urban form: Compactness versus 'sprawl'. *Urban Studies, 42*(1), 141–161. https://doi.org/10.1080/0042098042000309748.

U.S. Economic Development Administration. (2019). *Regional Innovation Cluster Initiative – Evaluation Report.*

UK Department of the Environment. (1995). *PPG 17: Planning for open space, sport & recreation*.

UNEP. (2013). *City-level decoupling: Urban resource flows and policy responses.* Nairobi: United Nations Environment Programme.

UN-Habitat. (2016). *World Cities Report 2016: Urbanization and Development*. Nairobi: UN-Habitat.

UN-Habitat. (2020). *Public Space Toolkit: From Global Principles to Local Policies and Practice*. Nairobi: UN-Habitat.

UN-Habitat. (2024). *Regenerative City Handbook.* Nairobi: UN-Habitat.

UN-Habitat. (2020). *World Cities Report 2020: The value of sustainable urbanisation*.

United Nations. (1992). *Agenda 21*. United Nations Conference on Environment and Development.

Urban Redevelopment Authority. (2021). *Master Plan 2019 (condensed update 2021)*.

Urban Redevelopment Authority. (2021). *Land use plan review*.

USGS. (2020). *HayWired Scenario—engineering implications for a magnitude 7.0 earthquake on the Hayward Fault*. Reston, VA: U.S. Geological Survey.

Vale, L. & Campanella, T. (2005). *The Resilient City.* New York: Oxford University Press.

Van Aalst, M. (2006). The impacts of climate change on the risk of natural disasters. *Disasters, 30*(1), 5-18.

van der Valk, A., & Faludi, A. (1992). *Growth management and the Randstad Green Heart debate.* Town Planning Review, 63(1), 3-23.

Van der Valk, A., & Faludi, A. (1992). Growth management and environmental sustainability in the Randstad. *European Planning Studies*, 1(3), 345-365.

van der Waard, J., Immers, B., & van Lierop, A. (2019). *R-Net's role in Randstad's one-hour metropolis.* European Transport Research Review, 11, 46.

Van der Waard, J., van Oort, N., & Hoogendoorn, S. (2019). Door-to-door travel time impacts of the *Zuidasdok* project. *Transportation Research Record,* 2673(2), 174–183.

van der Waard, J., van der Hoorn, T., & Tavasszy, L. (2019). From corridor to network: BRT integration in the Schiphol–Amsterdam–Almere triangle. *Transport Policy*, 74, 39-47.

Vandentorren, S., & Bretin, P. (2006). Heatwave impacts in Paris: Risk factors for mortality. *European Journal of Public Health, 16*(6), 583-591.

Ville de Paris. (2020). *Plan local d'urbanisme – Règlement consolidé.* Direction de l'Urbanisme.

Ville de Paris. (2020). *Plan local d'urbanisme de Paris – Règlement (version consolidée après modification du 8 février 2020).* Direction de l'Urbanisme. https://cdn.paris.fr/plu/reglement.pdf.

Ville de Paris. (2023). *PLU bioclimatique: Règlement consolidé*.

Voogt, J. A., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment, 86*(3), 370-384.

Walker, B., Holling, C. S., Carpenter, S., & Kinzig, A. (2004). Resilience, adaptability and transformability. *Ecology and Society, 9*(2), 5.

WCED. (1987). *Our common future*. Oxford University Press.

Weng, Q. (2004). Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *ISPRS Journal of Photogrammetry and Remote Sensing, 64*(4), 335-344.

WHO. (2022). *Heat and health in cities: Guidance for urban practitioners*. Geneva, Switzerland: World Health Organization.

Wooldridge, J. M. (2015). *Introductory econometrics: A modern approach* (6th ed.). Cengage.

World Bank & GFDRR. (2023). *Albania Urban Climate Risk Atlas.* Washington: World Bank.

World Bank. (2020). *Dhaka city diagnostic*.

Xue, J. (2017). Is compact city development sustainable? A systematic literature review. Sustainability, 9, 1126.

Yang, J., Chen, X., & Wang, J. (2021). Balancing cooling energy with heat-mortality penalties in dense districts. *Energy and Buildings, 245*, 111014.

Yang, J., Wang, X., Xiu, C., & Xia, J. (2021). Influence of urban morphological characteristics on thermal environment. *Sustainable Cities and Society, 72*, 103045. https://doi.org/10.1016/j.scs.2021.103045.

Yang, J., Wang, X., Xiu, C., & Xia, J. (2021). Influence of urban morphology on thermal environment. *Sustainable Cities and Society, 72*, 103045.

Yang, J., Wang, X., Xiu, C., & Xia, J. (2021). *Sustainable Cities and Society, 72*, 103045.

Yeh, A., & Huang, Y. (2013). *Cities, 32*, 123–132.

Yang, J., Wang, X., Xiu, C., & Xia, J. (2021). Influence of urban morphological characteristics on thermal environment. *Sustainable Cities and Society, 72*, 103045. https://doi.org/10.1016/j.scs.2021.103045.

Yang, X., et al. (2021). The morphology–climate nexus: How urban form regulates land-surface temperature and heat exposure. *Science of the Total Environment, 772*, 145537.

Yeh, A., & Huang, Y. (2013). Urban greenery, housing provision and compactness in Singapore. *Cities, 32*, 123-132.

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). Thousand Oaks, CA: SAGE.

Yuan, F., & Bauer, M. E. (2007). Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. Remote Sensing of Environment, 106(3), 375-386.

Zhang, H., Zhao, P., & Li, S. (2022). Evaluating ventilation corridors for urban heat mitigation in Wuhan. *Urban Climate, 41*, 101099.

Zhao, P., Li, S., & Liu, D. (2020). Residential self-selection or the built environment? Evidence from a quasi-natural experiment in Beijing. *Nature Sustainability, 3*(8), 632–640. https://doi.org/10.1038/s41893-020-0502-y.

Zhao, P., Xu, Y., & Liang, Y. (2011). A Normalised Compactness Index for comparative urban analysis. *Landscape and Urban Planning, 100*(1-2), 53–60. https://doi.org/10.1016/j.landurbplan.2010.10.006.

Zhuang, Y., & Zhou, X. (2019). Quantifying urban form: A review of compactness indices. *Environment and Planning B: Urban Analytics and City Science, 46*(6), 1026–1044.

Ziter, C., et al. (2019). *Proceedings of the National Academy of Sciences, 116*, 7662–7667.

Ziter, C., Pedersen, E., Kucharik, C., & Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences, 116*(15), 7575-7580.