



POLITECNICO DI TORINO

Inter University Department of Regional and Urban Studies and Planning

Master of Science in Digital Skills for Sustainable Societal Transitions

Urban Geospatial Analytics as a Decision-Support System

Neighbourhood Sustainability Monitoring and Metro-Driven
Property Value Uplift in Turin

Master's Thesis

Candidate

Roderick William Tossato Silva

Student ID: s336217

s336217@studenti.polito.it

Supervisor

Prof. Piero Boccardo

Co-supervisor

Prof. Emere Arco

Academic Year 2025–2026

Turin, June 2026

Abstract

Urban planning decisions increasingly depend on spatially granular, multi-dimensional evidence that open-data environments now make possible but that accessible decision-support tools have not yet operationalized at the neighbourhood scale for Italian cities. This thesis develops a geospatial Decision-Support System (DSS) for Turin (Torino), Italy, integrating two analytically complementary use cases built from open data using a reproducible Python geoprocessing stack.

Use Case 1 operationalizes 24 indicators from the Sustainable Neighbourhood Tool for Mediterranean Cities (SNTTool MED) framework across Turin's 94 *zone statistiche*, applying Weighted Linear Combination (WLC) to produce a Composite Sustainability Index (CSI). Of the 24 indicators spanning five thematic domains (land use and biodiversity, transport and mobility, social equity, economy, and climate and energy), 18 meet the discriminatory power criterion for composite scoring. The spatial results confirm a statistically robust north-south inequality gradient, highlighting key differences in service accessibility, income and property values between the historical city centre, south and eastern areas and the disadvantaged northern zones.

In addition to operationalizing the SNTTool MED framework, use case 1 also conducts a city-wide acoustic noise assessment, derived from CNOSSOS-EU road noise buffers and GTT tram network geometry, revealing a strong positive correlation between the quietness score and the Composite Sustainability Indicator (CSI) calculated in the first step (Spearman's $\rho = 0.623$, $p < 0.001$).

The use case also links CSI performance with property values through a three-predictor multivariable OLS regression including the economy-prioritized CSI, the noise exposure score, and a log-transformed commercial establishment count ($R^2 = 0.383$, $n = 93$ *zone statistiche*): a one-unit increase in the economy-prioritized CSI is associated with an average price increase of approximately €480/m² based on data from the Osservatorio del Mercato Immobiliare (OMI). The commercial establishment count is not independently significant once noise is controlled for, indicating that the noise variable already proxies the commercial animation of central zones; Variance Inflation Factor and Breusch-Pagan diagnostics confirm the absence of multicollinearity and heteroscedasticity in the model.

Use Case 2 develops a raster-based net suitability model for the proposed Metro Line 2 Phase I corridor at 5 × 5 m resolution. A two-step normalization pipeline embeds road and tram acoustic disamenity as proportional post-normalization penalties, producing a Net Suitability Score that captures both the disamenity donut geometry immediately surrounding each station and the second-row premium band at 200-500 m.

Net Suitability Scores are translated into projected residential property value uplift, ranging from €0-84/m² in the northern Rebaudengo-Barriera di Milano corridor to €120-384/m² in the Porta Nuova and Crocetta environs. The distributional asymmetry of projected uplift carries direct implications for *Contributo Straordinario* design and land value capture (LVC) policy.

Both use cases are operationalized through an integrated DSS dashboard, intended to serve city planning officials, real estate development professionals, and citizens through a browser interface requiring no GIS or Python expertise.

Keywords: urban sustainability monitoring; composite sustainability index; transit-induced property value uplift; land value capture; geospatial decision-support system; SNTTool MED; Turin; open geospatial data

Contents

Abstract	i
Glossary of Terms	xi
1 Introduction	1
1.1 Context and Motivation	1
1.2 The Two Use Cases	2
1.2.1 Use Case 1 – PRG Sustainability Monitoring	2
1.2.2 Use Case 2 — Metro Line 2 Net Suitability and Property Value Uplift	3
1.3 Research Questions and Objectives	3
1.4 Study Area: Turin, Italy	5
1.5 Scope and Limitations	6
1.6 Thesis Structure	6
2 Literature Review	8
2.1 Review Methodology	8
2.2 Urban Sustainability: Frameworks and Measurement	9
2.2.1 The Sustainability Transition in Urban Policy	9
2.2.2 Multi-Criteria Decision Analysis in Urban Contexts	9
2.2.3 International Indicator Frameworks for Urban Sustainability	10
2.2.4 The 15-Minute City Concept and Walkability	11
2.2.5 Spatial Autocorrelation and Neighbourhood Effects	11
2.3 Transit Infrastructure and Land Value Theory	12
2.3.1 The Hedonic Pricing Model	12
2.3.2 The Inverted U-Curve: Nuisance versus Accessibility	12
2.3.3 Announcement and Anticipation Effects	13
2.3.4 Accessibility Measurement: From Buffers to Indices	13
2.3.5 Land Value Capture: Theory and Mechanisms	14
2.3.6 GIS-Based Multi-Criteria Evaluation for Real Estate Suitability	15
2.4 Acoustic Noise as a Real Estate Disamenity	15
2.4.1 Evidence on Transit and Road Noise Penalties	15
2.4.2 Legacy Tram Systems and Their Acoustic Profile	16
2.4.3 CNOSSOS-EU: The European Noise Modelling Standard	16
2.4.4 Integrating Noise into Suitability Models	17
2.5 Urban Decision-Support Systems and Dashboards	18
2.5.1 The Urban Dashboard: Genealogy and Critiques	18
2.5.2 Communicative Planning and Participatory GIS	18
2.5.3 Decision-Support Systems in Urban Planning	19

2.5.4	Positioning This Thesis in the Literature	20
3	International Indicator Frameworks, GIS Methodology, and Study Area	22
3.1	International Indicator Frameworks for Urban Sustainability Assessment	22
3.1.1	The Global Urban Monitoring Framework	22
3.1.2	The U4SSC Collection Methodology for Key Performance Indicators for Smart Sustainable Cities	23
3.1.3	The SNTTool MED Framework	23
3.1.4	Comparative Analysis of the Three Frameworks	23
3.1.5	Selection of the SNTTool MED Framework	25
3.2	The SNTTool MED Framework: Detailed Methodology	26
3.2.1	SNTTool MED — Sustainable Neighbourhood Tool for Mediterranean Cities	26
3.3	GIS Methodology: Use Case 1 — Composite Sustainability Index	27
3.3.1	Spatial Unit and Coordinate Reference System	27
3.3.2	Weighted Linear Combination for the Composite Index	28
3.3.3	Spatial Analysis Techniques for Use Case 1	28
3.4	GIS Methodology: Use Case 2 — Metro Line 2 Net Suitability Model	29
3.4.1	Model Architecture: The Two-Step Normalization Pipeline	29
3.4.2	Technical Implementation	30
3.4.3	School Buffer Differentiation	31
3.4.4	Economic Uplift Coefficient Model	32
3.5	Turin: Urban Context and Study Area Profile	33
3.5.1	Urban Structure and Post-Industrial Transformation	33
3.5.2	Public Transport Network and Metro Line 2	33
3.5.3	Turin’s Real Estate Market and Aree di Trasformazione	34
4	Indicator Selection	36
4.1	Selection Methodology	36
4.1.1	Guiding Principles	36
4.1.2	Framework Alignment and Indicator Mapping	37
4.1.3	Completion Status	37
4.2	Domain A: Use of Land and Biodiversity	37
4.3	Domain F: Transportation and Mobility	38
4.4	Domain G: Social Aspects	39
4.5	Domain H: Economy	40
4.6	Domain I: Climate Change	41
4.7	Complete Indicator Inventory	41
4.8	Discussion of Selection Approach	43
5	Data Sources, Geoprocessing, and Indicator Calculation	45
5.1	Data Sources and Acquisition	45
5.1.1	Geoportale della Città di Torino	45
5.1.2	ISTAT 2021 Census	46
5.1.3	GTT GTFS Feed (March 2026)	46
5.1.4	Regione Piemonte: TGM Traffic Data	46
5.1.5	Agenzia delle Entrate: OMI Data	47

5.1.6	Ministry of Economy and Finance: IRPEF Data	47
5.1.7	OpenStreetMap	47
5.1.8	Land Cover Piemonte 2023 (LCP2023)	47
5.2	Geoprocessing Environment and Technical Stack	47
5.3	Spatial Unit Definition and Population Attribution	48
5.3.1	Population Coefficient Methodology	48
5.3.2	PT Accessibility: GTT Stop Selection	49
5.4	Indicator Calculation: Domain A — Land Use and Biodiversity	49
5.4.1	A1.1 Population Density	49
5.4.2	A1.2 Urban Compactness	49
5.4.3	A2.1 Green Space Coverage	49
5.4.4	A2.2 Green Space per Capita	49
5.4.5	A2.3 Green Space Accessibility	50
5.4.6	A3.2 Biodiversity in Green Zones	50
5.5	Indicator Calculation: Domain F — Transport and Mobility	50
5.5.1	F1.1 PT System Performance	50
5.5.2	F2.2 EV Charging Infrastructure	50
5.5.3	F2.3 Bicycle Network Density	50
5.5.4	F3.3 Safety of Bicycle Lanes	50
5.5.5	F4.1–F4.2 Street Network Morphology	50
5.6	Indicator Calculation: Domain G — Social Aspects	51
5.6.1	G2.1 and G2.2: Housing Affordability	51
5.6.2	G2.3 Vacant Residential Units	51
5.6.3	G3.1–G3.4: Service and Facility Proximity	51
5.7	Indicator Calculation: Domains H and I	52
5.7.1	H1.1 Per-Capita Income	52
5.7.2	H2.1 Employment Rate (25–64)	52
5.7.3	H2.2 Youth NEET Rate (15–29)	52
5.7.4	G3.5 Outdoor Public Spaces	52
5.7.5	I3.3 Permeability of Land (KPI)	52
5.8	CNOSSOS-EU Road Noise Buffer Calculation	52
5.9	UC2 Geoprocessing: Raster Pipeline	53
5.10	INSPIRE Metadata Compliance	54
5.10.1	SN Tool Indicator Datasets (24 GeoPackages)	54
5.10.2	Ancillary and Supporting Datasets (18 GeoPackages)	55
5.11	Data Limitations and Uncertainty	56
6	Use Case 1 — PRG Sustainability Monitoring and Acoustic Noise Assessment	59
6.1	Overview and Stakeholder Context	59
6.2	Domain-by-Domain Spatial Results	59
6.2.1	Domain A: Land Use and Biodiversity	59
6.2.2	Domain F: Transport and Mobility	62
6.2.3	Domain G: Social Equity	66
6.2.4	Domain H: Economy	70
6.2.5	Domain I: Climate and Energy	72

6.3	Composite Sustainability Index	73
6.3.1	Baseline Composite Score	73
6.3.2	Scenario Analysis: Weight Sensitivity Testing	75
6.4	Correlation with Property Values	78
6.5	Vulnerability Mapping and PRG Priority Zones	80
6.5.1	Cross-Linkage: Noise, Sustainability, and Property Values	81
7	Use Case 2 — Metro Line 2: Net Suitability and Property Value Uplift	86
7.1	Turin Public Transport Baseline and Equity Case	86
7.2	Metro Line 2 Project Context	87
7.2.1	Alignment and Station Programme	87
7.2.2	Urban Regeneration Context	88
7.2.3	Policy and Planning Framework	88
7.3	Net Suitability Model — Phase I Results	89
7.3.1	Model Configuration and Inputs	89
7.3.2	Spatial Pattern of Phase I Net Suitability	89
7.4	Net Suitability Model — All Phases Results	91
7.4.1	Corridor Extension and Coverage	91
7.4.2	Comparative Phase Differencing	92
7.4.3	Priority Uplift Zones - All Phases	92
7.5	Economic Uplift Model	93
7.5.1	Theoretical Grounding	93
7.5.2	Uplift Coefficient Specification	94
7.5.3	Uplift Surface Results	94
7.5.4	Aggregate Uplift Estimation	95
7.5.5	Sensitivity of Uplift Estimates to Capitalization Ceiling Assumptions	95
7.6	Compound Disamenity and Acoustic Shadow Analysis	96
7.6.1	Conceptual Framework	96
7.6.2	The “Movida” Externality	97
7.6.3	Spatial Pattern of Compound Disamenity	97
7.6.4	Sensitivity Analysis: Tram Network Retirement Scenario	98
7.7	Land Value Capture Implications	98
7.7.1	The Italian LVC Framework	98
7.7.2	Aree di Trasformazione as Primary LVC Targets	98
7.7.3	LVC Calculation Methodology	99
7.7.4	Aggregate LVC Potential — Phase I	100
7.7.5	Policy Recommendations	100
7.7.6	Relationship to the Dual Dividend Framework	100
8	The Dashboard: A Unified Decision-Support System	102
8.1	From Analysis to Action: The DSS Rationale	102
8.2	Design Philosophy and Target Architecture	103
8.2.1	Guiding Principles	103
8.2.2	Target Three-Audience Architecture	103
8.3	Phase I Implementation: The Urban Spatial Analysis Dashboard	104

8.3.1	Technical Architecture	104
8.3.2	Spatial Layer Management and Analysis Module	105
8.3.3	Use Case 1: Indicator Framework Management and Visualization	106
8.3.4	Use Case 2: Raster Map Integration	110
8.4	Scoring Methodology	111
8.5	Towards Three-Audience Architecture: Design Target and Implementation Gap	111
8.6	Phase II: Planned Enhancements	112
8.7	Dashboard as DSS: Capabilities and Limitations	113
8.7.1	What the Phase I Prototype Enables	113
8.7.2	Current Limitations	113
9	Discussion	115
9.1	Revisiting the Research Questions	115
9.1.1	RQ1: Operationalizing Sustainability Indicators for Turin	115
9.1.2	RQ2: Spatial Patterns, PRG Monitoring, and Residential Market Conditions	122
9.1.3	RQ3: Net Suitability, Property Value Uplift, and Land Value Capture	125
9.2	Methodological Contributions	127
9.2.1	SNTool MED Indicator Operationalization at the Neighbourhood Scale	127
9.2.2	Two-Step Normalization Pipeline with Proportional Acoustic Penalty	127
9.2.3	Integrated Multi-User DSS Dashboard	128
9.3	Limitations and Boundary Conditions	128
9.3.1	Data Vintage and Coverage	129
9.3.2	Model Structure and Analytical Assumptions	129
9.3.3	Acoustic Modelling Simplifications	130
9.3.4	Scope Restrictions: Residential Focus and Static Analysis	131
9.3.5	Planning Law and LVC Feasibility	131
9.4	Implications for Practice	131
9.4.1	For Municipal Planners: PRG Monitoring and Priority Allocation	132
9.4.2	For Real Estate Professionals: Investment Screening and Due Diligence	132
9.4.3	For Land Value Capture Policy	133
9.5	Comparison with Comparable European Studies	133
9.5.1	Rome Metro C: Cascarano and Mocetti (2022)	133
9.5.2	Milan M4 and M5: Errera (2020) and Related Literature	134
9.5.3	Grand Paris Express: LVC Benchmark	134
9.5.4	Smart City and DSS Positioning	134
10	Conclusions	136
10.1	Summary of Findings	136
10.2	Contribution to Knowledge	138
10.3	Future Research Directions	139
10.3.1	Model Extensions	139
10.3.2	Governance and Scaling	140
10.4	Closing Reflection	141
	Disclosure on the Use of LLMs and Artificial Intelligence Tools	142

Appendices	150
A INSPIRE-Compliant Metadata Catalogue	151
B Python Scripts and Reproducibility	153

List of Figures

1.1	Research Framework Overview	4
1.2	Thesis structure and chapter dependencies. Chapters 1–5 establish the analytical foundation; Chapters 6 and 7 present the two use cases, which feed into the integrated dashboard (Chapter 8), the cross-cutting Discussion (Chapter 9), and the Conclusion (Chapter 10).	7
3.1	The two-step normalization pipeline for the Use Case 2 net suitability model. Positive accessibility scores (Steps A and B) are computed and normalized before acoustic disamenity penalties are subtracted (Step C). A second normalization pass (Step D) ensures the final Net Suitability Score spans the full 0–100 range. The pipeline ensures that noise penalties are proportional to each location’s own accessibility quality.	29
3.2	Study area overview: City of Turin with Metro Line 1, Metro Line 2, and Aree di Trasformazione (ZUT).	35
4.1	Radar chart of Turin city-average domain scores (A, F, G, H, I) on the -20–100 normalized scale, shown against the SNTTool MED minimum acceptable threshold (score 0) and ideal threshold (score 100), population-weighted	44
5.1	Spatial coverage and resolution comparison of primary data sources. ISTAT census sections provide the finest resolution. OMI zones and IRPEF CAP zones represent coarser administrative units used for economic indicators. All boundaries are shown within the Turin administrative boundary in EPSG:3003.	58
6.1	Domain A - Land Use and Biodiversity: Indicator score maps.	61
6.2	Domain A (Land Use and Biodiversity) composite score by statistical zone, with major green spaces overlaid.	62
6.3	Performance of the public transport system, classified by the frequency of daily trips.	63
6.4	Domain F - Transport and Mobility: Indicator Score Maps	65
6.5	Domain F - Transport - Composite Score	66
6.6	Domain G - Social Aspects: Indicator Score Maps (set A)	68
6.7	Domain G - Social Aspects: Indicator Score Maps (set B)	69
6.8	Social Aspects Composite Scores	70
6.9	Domain H - Economy: Indicator Score Maps	71
6.10	Domain H - Economy - Composite Scores	72
6.11	Permeability of Land	73
6.12	Composite Index - equal weights	74
6.13	Transport-prioritized	76
6.14	Social-Equity-prioritized	77
6.15	Economy-prioritized Composite Sustainability Index (CSI) scores.	78

6.16	Equal-weight CSI vs Price scatter plot	79
6.17	Economy-prioritized CSI vs Price scatter plot	79
6.18	Composite CSI scores and proposed Metro Line 2, showing potential "dual dividend" areas.	80
6.19	Correlation between CSI and Noise Exposure Score (higher score = quieter environment). The strong positive trend illustrates the synergistic relationship between sustainability and acoustic quality.	82
6.20	Correlation between Noise Exposure Score and Mean Property Value. The negative trend highlights the market premium placed on noisier, highly accessible central locations over quieter peripheral zones.	83
6.21	Partial regression plots isolating the independent effects of the economy-prioritized CSI score (left), noise exposure score (centre), and log-transformed commercial establishment count (right) on average OMI property values. All plots are based on the three-predictor OLS model ($n = 93$ <i>zone statistiche</i>). The non-significant slope of the commercial vitality panel ($p = 0.287$) indicates that once noise exposure and economic sustainability are controlled for, commercial establishment count does not contribute independent explanatory power.	84
7.1	Performance of the public transport system - planned metro line 2, base map shows the number of daily PT trip stops.	87
7.2	Net Suitability - Residential Properties - Line 2 Phase I	90
7.3	Price Uplift - Residential Properties - Line 2 Phase I	91
7.4	Economic Uplift - Residential Properties - Line 2 all phases	93
7.5	Transformation Areas within Line 2 - Phase I catchment area	99
8.1	Dashboard layer management interface	105
8.2	Dashboard spatial analysis interface	106
8.3	Dashboard indicator configuration interface	107
8.4	Dashboard visualize indicators	108
8.5	Visualize Spatial Units	109
8.6	Neighbourhood Profile View	110
9.1	Comparison of equal-weight composite sustainability scores across the 94 <i>zone statistiche</i> under the 24-indicator (left) and 18-indicator (right) configurations. The redistribution of upper-tier scores from peri-urban hill zones to compact inner-urban neighbourhoods is visible in the colour shift across the eastern fringe.	118
9.2	Scatter plot of 24-indicator versus 18-indicator equal-weight CSI scores for the 94 <i>zone statistiche</i> of Turin.	119
9.3	18-indicator equal-weight Composite Sustainability Index across Turin's 94 <i>zone statistiche</i>	121
9.4	Net Residential Suitability around metro line 2 proposed stations, overlaid on OMI zones categorized by mean property value (thousand €).	125

List of Tables

1	List of Acronyms and Abbreviations	xi
2.1	Research streams, coverage, primary sources, and residual gaps addressed by this thesis.	21
3.1	Comparison of the three international indicator frameworks reviewed for this thesis. KPI counts are approximate and refer to core or mandatory indicators; total indicator inventories (including optional or advanced items) are substantially larger for all three frameworks.	24
3.2	Piecewise linear distance-decay parameters for Use Case 2 amenity layers. Detractor buffers create a nuisance zone adjacent to the feature where score rises from 0 (at the feature) to 100 (at the detractor boundary); booster zones reverse this, with score declining from 100 (at the inner booster boundary) to 0 (at the outer booster boundary). Pure detractors impose a score of 0 within the nuisance zone and 100 beyond it.	30
4.1	Complete indicator inventory for the Turin neighbourhood sustainability framework (24 SNTTool MED indicators).	41
4.2	SN Tool domain average scores for Turin	43
5.1	INSPIRE-documented SN Tool indicator GeoPackages (all in EPSG:3003).	55
5.2	INSPIRE-documented ancillary GeoPackages (all in EPSG:3003). Geoportale-derived datasets are licensed under CC BY 3.0 IT.	56
6.1	Statistical areas with the highest composite scores	74
6.2	Statistical areas with the lowest composite scores	75
7.1	Expected uplift coefficient and price increment ranges for Phase I, by station proximity band. OMI reference values are approximate medians for the relevant microzones (source: Agenzia delle Entrate OMI 2024–25).	95
7.2	Qualitative sensitivity of Phase I uplift estimates to capitalization ceiling assumption. Directional magnitudes relative to the central case (12% ceiling).	96
9.1	Indicators excluded after post-calculation discrimination test	116
9.2	Impact of the six-indicator exclusion on equal-weight CSI scores for the five zones most positively affected (compact inner-urban) and the five zones marginally negatively affected (peri-urban hill zones). Scores are on the WLC scale (−1 to 5); the normalized 0–100 value is given by $(s + 1)/6 \times 100$	117
9.3	Final set of 18 indicators used in the Composite Sustainability Index	120
9.4	Top 15 highest-scoring statistical areas under the 18-indicator equal-weight CSI	122
9.5	Bottom 15 lowest-scoring statistical areas under the 18-indicator equal-weight CSI	122
B.1	List of Python scripts created for this thesis.	153

Glossary of Terms

Table 1: List of Acronyms and Abbreviations

Acronym	Definition
ASC	Area sub-comunale
BIM	Building Information Modelling
CAP	Codice di Avviamento Postale
CDN	Content Delivery Network
CI	Competitiveness Index
CNOSSOS-EU	Common Noise Assessment Methods in Europe
CSI	Composite Sustainability Index
DID	Difference-in-Differences
DSS	Decision Support System
ESDA	Exploratory Spatial Data Analys
GIS	Geographic Information System
GTFS	General Transit Feed Specification
GTT	Gruppo Torinese Trasporti
GWR	Geographically Weighted Regression
HDI	Human Development Index
HPM	Hedonic Price Modeling
IDISE	Indice di Disagio Socio-Economico
KPI	Key Performance Indicator
LISA	Local Indicators of Spatial Association
LRT	Light Rail Transit
LVC	Land Value Capture
MCDA	Multi-Criteria Decision Analysis
MCE	Multi-Criteria Evaluation
NSDI	Noise Sensitivity Depreciation Index
OLS	Ordinary Least Squares
OMI	Osservatorio del Mercato Immobiliare
PGIS	Participatory GIS
PNRR	Piano Nazionale di Ripresa e Resilienza
PRG	Piano Regolatore Generale
PT	Public Transit
SDG	Sustainable Development Goal
SHAP	SHapley Additive exPlanations
TGM	Traffico Giornaliero Medio
TOD	Transit-Oriented Development
XGBoost	eXtreme Gradient Boosting
WHO	World Health Organization
WLC	Weighted Linear Combination
VLR	Voluntary Local Review
ZUT	Zona Urbana di Trasformazione

Chapter 1

Introduction

1.1 Context and Motivation

Cities worldwide are navigating a convergence of pressures that have no historical precedent in their simultaneity: climate change, demographic shifts, housing affordability crises, and the need to decarbonize both mobility and the built environment, all while preserving the social cohesion and economic vitality that make urban life viable. The international policy architectures that frame these challenges, from the United Nations 2030 Agenda for Sustainable Development ([United Nations, 2015](#)) to the New Urban Agenda ([United Nations, 2016](#)) and the European Green Deal ([European Commission, 2019](#)), place cities at the centre of the global sustainability transition. These frameworks are explicit in their ambitions: Sustainable Development Goal 11 calls for cities that are inclusive, safe, resilient, and sustainable; the New Urban Agenda envisions urbanization as a transformative force for equality; the Green Deal commits the European Union to climate neutrality by 2050.

What these frameworks share, alongside their ambition, is a dependence on evidence. Targets require measurement; measurement requires data; data requires methodologies capable of translating the richness of the urban environment into standardized indicators that planners, policymakers, and citizens can understand and act upon. In this context, the emergence of open geospatial data and reproducible digital analysis has been genuinely transformative. Municipalities across Europe now maintain detailed open data geoportals; census agencies publish granular population and housing data; public transport operators release standardized GTFS feeds; and remote sensing platforms provide open-access satellite imagery of unprecedented spatial and temporal resolution. The capacity for evidence-based urban analysis has expanded dramatically in recent years.

Yet a persistent gap separates this abundance of data from its translation into actionable intelligence. Decision-support tools for urban planning remain largely bespoke, expensive, and inaccessible to smaller municipalities and neighbourhood-level stakeholders who need them the most. Published composite sustainability assessments for Italian cities tend to operate at the regional or metropolitan scale, offering limited granularity for the neighbourhood-level decisions that determine where green space is invested, which transit corridors are prioritized, or how brownfield land is designated ([Dawodu et al., 2022](#)). The academic literature on transit-induced property value capitalization is substantial, but the methodologies employed are rarely operationalized in tools that planners or real estate professionals can apply to specific corridors in real time ([Higgins and Kanaroglou, 2016](#); [Mohammad et al., 2013](#)).

This thesis addresses these gaps directly. It develops a geospatial Decision-Support System (DSS) for Turin (Torino), Italy, built around two complementary and analytically integrated use cases. The first constructs a composite sustainability index for all of Turin's neighbourhoods, operationalizing indicators from an internationally-recognized framework, and primarily relying on open data. The second builds a raster-based net suitability model for the proposed Metro Line 2 corridor, embedding acoustic disamenity as a direct economic penalty within the suitability surface, and translating the resulting scores into projected residential property value uplift at 5x5 meter resolution. Both use cases are united through a shared technical platform, a common

spatial reference system, and a single integrated dashboard designed to serve three distinct professional user groups.

Turin provides an exceptionally well-suited laboratory for this research. As Italy's fourth-largest city and a former industrial powerhouse that has undergone profound post-Fordist transformation since the 1990s (Politecnico di Torino, 2016), it exhibits the full spectrum of urban sustainability challenges: stark neighbourhood inequality between its affluent southern and central districts and its post-industrial northern periphery, a complex transport network that combines a modern automated metro line with a legacy tram fleet operating on embedded tracks, an active Piano Regolatore Generale (PRG) revision process that requires precisely the kind of evidence-based neighbourhood benchmarking this thesis provides, and a planned Metro Line 2 whose property value and spatial equity implications are of immediate practical interest to planners, developers, and prospective residents alike. Turin was also a leading partner city in the development of the *SNTool MED framework*, ensuring that the indicators and benchmarks applied in this thesis have been validated for the local urban context (Moro et al., 2023).

The thesis situates itself at the intersection of four bodies of academic literature: urban sustainability monitoring and composite indicator theory; transit infrastructure and land value capitalization; acoustic noise as a real estate disamenity; and urban decision-support systems and dashboard design. Each of these is treated in depth in Chapter 2. The contribution of this work is not simply to apply existing methods to a new case study, but to propose three methodological advances, namely an indicator harmonization for Turin at the neighbourhood scale, a two-step normalization pipeline that treats acoustic disamenity as a post-normalization economic penalty rather than a weighted criterion, and a dashboard that integrates sustainability monitoring with transit suitability analysis for multiple user groups, each of which is described in detail in the chapters that follow.

1.2 The Two Use Cases

The analytical architecture of this thesis rests on two use cases, designed to be analytically distinct yet mutually reinforcing. They share a study area (the City of Turin), a coordinate reference system (EPSG:3003, Monte Mario / Italy zone 1), a Python-based geoprocessing stack, and the acoustic noise analysis that runs through both as a shared spatial dimension.

1.2.1 Use Case 1 – PRG Sustainability Monitoring

The first use case constructs a neighbourhood-level sustainability assessment framework for Turin using indicators drawn from the Sustainable Neighbourhood Tool for Mediterranean Cities (SNTool MED) (Moro et al., 2023), selected from among three leading international frameworks reviewed and compared in Chapter 3. The indicator set covers five thematic domains: land use and biodiversity (Domain A), transport and mobility (Domain F), social equity (Domain G), economy (Domain H), and climate and energy (Domain I).

The spatial unit of analysis is the ISTAT 2021 *zona statistica* (Statistical Zone), of which Turin has 94, with a mean area of roughly 1.4 km². This is the most suitable administrative subdivision, roughly corresponding to a neighbourhood with distinct characteristics and geographic boundaries that are relatable to a variety of stakeholders. The resulting composite Sustainability Index is produced through Weighted Linear Combination (WLC), with scenario analysis via weight sensitivity testing across five domain weights.

The analysis is extended by a dedicated city-wide acoustic noise impact assessment (Section 6.5.1), which maps road traffic noise buffers calculated using the CNOSSOS-EU methodology (European Parliament and Council, 2015) and GTT tram network noise buffers, linking exposure to the composite sustainability index and

to residential property values from the Agenzia delle Entrate's Osservatorio del Mercato Immobiliare (OMI).

The primary stakeholder for this use case is the urban planning professional or municipal policy analyst who needs a spatially granular, multi-dimensional neighbourhood baseline to support the PRG revision, identify Priority Intervention Zones, and produce evidence for EU-level sustainability reporting under the Urban Audit and the SDG Voluntary Local Review process.

1.2.2 Use Case 2 — Metro Line 2 Net Suitability and Property Value Uplift

The second use case develops a raster-based net suitability model for the proposed Turin Metro Line 2 corridor at $5\text{ m} \times 5\text{ m}$ resolution. Unlike a conventional multi-criteria evaluation (MCE) model, this approach embeds acoustic disamenity directly within the suitability calculation through a strict two-step normalization pipeline. In the first step, base amenity and metro accessibility scores, computed using piecewise distance-decay functions for metro stations, schools, markets, hospitals, and public safety facilities, are normalized to a 0-100 scale. In the second step, road traffic noise penalties (calculated using CNOSSOS-EU dynamic buffers from TGM traffic data) and tram network noise penalties (static 50 m and 100 m buffers from GTT GTFS geometry) are subtracted from the normalized surface before a final re-normalization pass, producing the Net Suitability Score.

This two-step design ensures that the noise discount is applied in percentage terms relative to each location's own accessibility quality, rather than as a flat absolute deduction, a design that reflects how real estate markets actually price the combination of transit accessibility and acoustic disamenity (Debrezion et al., 2007; Seo et al., 2014). The Net Suitability Score is then translated into an economic uplift coefficient and projected €/m² price changes via OMI zone values, with Aree di Trasformazione (ZUT - *Zone urbane di trasformazione*) as the primary land value capture (LVC) target.

The primary stakeholders for this use case are real estate development professionals interested in identifying Strategic Investment Zones within the Metro Line 2 corridor, municipal finance officers assessing the basis for Contributo Straordinario calculations on Aree di Trasformazione (Governo Italiano, 2001), and retail investors or citizens evaluating specific residential addresses for purchase or rental decisions.

1.3 Research Questions and Objectives

This thesis is structured around three research questions, each corresponding to a specific analytical objective and a distinct section of the empirical analysis.

RESEARCH FRAMEWORK

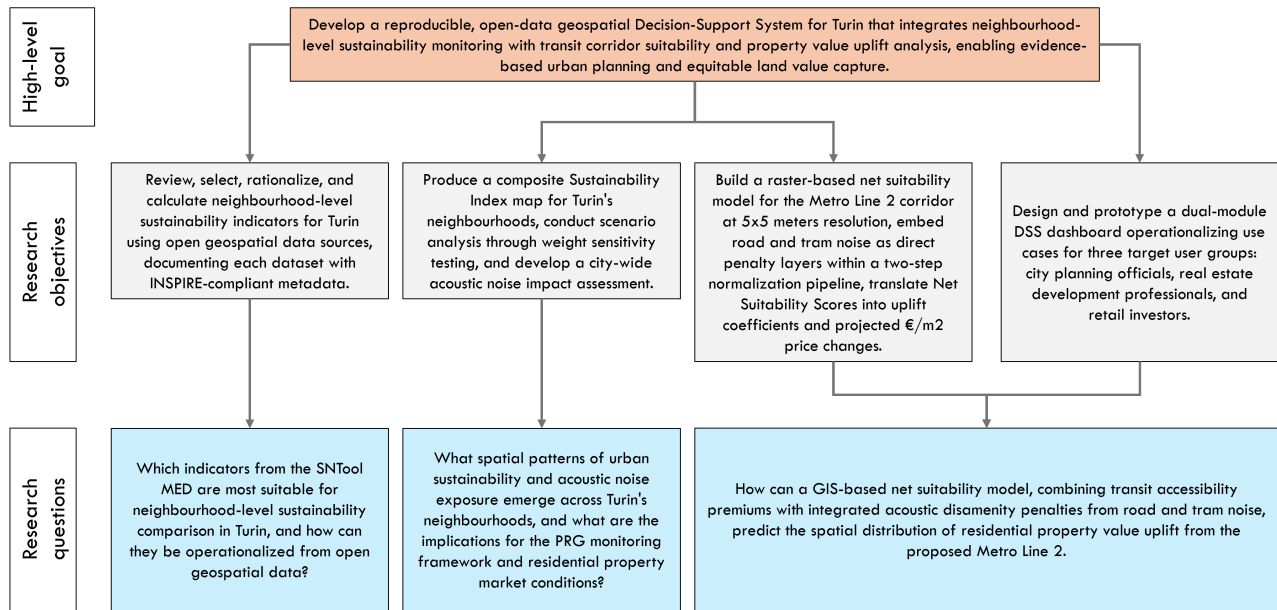


Figure 1.1: Research Framework Overview

Research Questions:

RQ1: Which indicators from the SNTTool MED are most suitable for neighbourhood-level sustainability comparison in Turin, and how can they be operationalized from open geospatial data?

RQ2: What spatial patterns of urban sustainability and acoustic noise exposure emerge across Turin's neighbourhoods, and what are the implications for the PRG monitoring framework and residential property market conditions?

RQ3: How can a GIS-based net suitability model, combining transit accessibility premiums with integrated acoustic disamenity penalties from road and tram noise, predict the spatial distribution of residential property value uplift from the proposed Metro Line 2, and what are the implications for land value capture policy and Contributo Straordinario calculations for Aree di Trasformazione?

Corresponding to these research questions, the thesis pursues four objectives:

- O1** Review, select, rationalize, and calculate neighbourhood-level sustainability indicators for Turin using open geospatial data sources, documenting each dataset with INSPIRE-compliant metadata.
- O2** Produce a composite Sustainability Index map for Turin's neighbourhoods, conduct scenario analysis through weight sensitivity testing, and develop a city-wide acoustic noise impact assessment combining TGM-based road noise buffers (CNOSSOS-EU) and tram network geometry, linking noise exposure to the sustainability index and OMI property values.
- O3** Build a raster-based net suitability model for the Metro Line 2 corridor at 5x5 meters resolution, embed road and tram noise as direct penalty layers within a two-step normalization pipeline, translate Net Suitability Scores into uplift coefficients and projected €/m² price changes, and quantify LVC potential for Aree di Trasformazione via Contributo Straordinario.
- O4** Design and prototype a dual-module DSS dashboard operationalizing both use cases for three target user groups: city planning officials, real estate development professionals, and retail investors and citizens

seeking granular residential suitability information.

1.4 Study Area: Turin, Italy

Turin (Torino) is the capital of the Piedmont region in north-western Italy and the country's fourth-largest city, with a resident population of approximately 840,000 within the municipality and roughly 1.7 million in the broader metropolitan area. The city occupies a position of particular significance in the Italian urban landscape: it was the original capital of unified Italy, the home of FIAT, and the epicentre of Italy's post-industrial transformation. The de-industrialization of the 1980s and 1990s left a profound spatial imprint, concentrating brownfield land, social deprivation, and housing dilapidation in the city's northern and western districts, particularly in the neighbourhoods of Barriera di Milano, Aurora, Falchera, and Rebaudengo, while the southern and eastern residential areas, such as Crocetta, Cit Turin, and Precollina, have retained and improved their property values and service accessibility (Bottero et al., 2023; Politecnico di Torino, 2016).

This north-south inequality gradient is a defining feature of Turin's urban structure and provides the critical context for both use cases in this thesis. The composite sustainability assessment is expected to reveal, and quantify, this gradient across five thematic domains. The Metro Line 2 Phase I alignment is designed to traverse precisely the northern corridor where sustainability deficits are most acute, providing the analytical motivation for the "Dual Dividend" hypothesis explored in Chapter 6: that transit investment in these areas could simultaneously address transport inequity and broader sustainability deficits Valenzuela-Levi and Abreu (2021), generating private-sector value uplift that could be partially recaptured through LVC mechanisms.

Turin's public transport network is operated by GTT (Gruppo Torinese Trasporti) and comprises 15 active tram lines, a bus network, and Metro Line 1, an automated, driver-less metro using VAL technology with 23 stations. The tram network is operated using a variety of vehicles, including the historic Series 2800 rolling stock on legacy embedded tracks, a fleet whose acoustic profile is substantially harsher than modern light rail transit (LRT) systems due to high-decibel flange squeal on curves, heavy pneumatic braking noise at stops, and low-frequency track vibrations (Beria et al., 2025). This acoustic characteristic is a material input to the noise assessment methodology and distinguishes Turin's tram noise profile from the parameters typically applied in European HPM studies based on modern tramway systems.

The Metro Line 2 project is one of Italy's most significant ongoing urban infrastructure investments. The planned alignment comprises 23 stations across three construction phases, with an overall length of approximately 22 kilometres. Phase I (Lotto 1) covers the northern corridor, connecting the Falchera and Rebaudengo districts to the city centre via Porta Nuova, passing through Barriera di Milano. Phase I of the project is expected to begin operations between the end of 2032 and early 2033 (Comune di Torino, 2024).

The project represents a substantial commitment to closing the public transport accessibility gap in Turin's most underserved neighbourhoods, and the capitalization effects observed for Metro Line 1, which generated announcement-phase residential price increases of 3-5% (Cascarano and Mocetti, 2022), provide a well-documented precedent for the property value analysis in Chapter 7.

Turin's real estate market is organized by the OMI zone system maintained by the Agenzia delle Entrate, which provides semi-annual median sale and rental prices per square metre for residential properties by zone, typology, and condition. The data used in this thesis covers the period 2024-2025, with "abitazioni civili" in "normale" condition as the baseline typology.

Median residential values vary substantially across the city: central Zone B areas achieve €2,200-3,500/m², semi-central Zone C areas €1,800-2,500/m², and peripheral Zone D areas €1,200-1,800/m². Aree di Trasformazione, the PRG-designated brownfield and redevelopment parcels within or adjacent to the Metro Line 2 corridor, are the primary targets for Contributo Straordinario and the principal beneficiaries of the uplift model

developed in Chapter 7.

The city’s participation as a leading partner in the SNTool MED development process under the *Sustainable MED Cities Interreg ENI CBC MED program* (Moro et al., 2023) means that the indicators and benchmarks applied in this thesis have been subject to local contextualization and validation, strengthening the transferability of the findings.

Turin’s Geoportale provides one of Italy’s richest open geospatial data repositories, covering buildings, land use, transport infrastructure, green spaces, public facilities, and administrative boundaries, making it an ideal study area for an open-data-driven analytical framework.

1.5 Scope and Limitations

Spatial scope. The sustainability assessment (UC1) covers the full City of Turin administrative boundary. The net suitability and uplift model (UC2) is restricted to the 800 m metro station catchment area, computed as the union of 800 m Euclidean buffers around all proposed Metro Line 2 stations (Phase I and All Phases scenarios). The acoustic noise assessment is conducted at city scale (UC1) and within the 800 m metro corridor (UC2), with the CNOSSOS-EU road noise model applied to the full Turin road network in both cases.

Temporal scope. The analysis uses a static baseline rather than a dynamic time-series. Population and housing data are sourced from the ISTAT 2021 Census. GTFS transit data is from the GTT March 2026 feed. TGM (Traffico Giornaliero Medio) road traffic count data was compiled in 2024 by Regione Piemonte. OMI real estate price data covers 2024-2025. Where data from different reference years is combined, this is noted in the indicator metadata (Chapter 5) and treated as a limitation in Chapter 9.

Out of scope. Dynamic real-time data feeds, social survey or participatory data collection, architectural or engineering design of the dashboard interface, full ISO 1996 acoustic measurement campaigns, and Building Information Modelling (BIM) integration are all outside the scope of this thesis.

The analysis produces projected uplift estimates, not econometrically causal valuations. The absence of a post-construction observation period for Metro Line 2 precludes a Difference-in-Differences (DID) approach (Marzolla et al., 2025); this limitation is discussed explicitly in Chapter 9.

Indicator completion. All 24 sustainability indicators included in the framework have been fully calculated and validated for Turin’s 94 *zone statistiche*. Of these, 18 meet the discriminatory power criterion for inclusion in the composite CSI; the remaining six are calculated and presented individually at indicator level but do not provide sufficient spatial differentiation across Turin’s neighbourhoods to contribute meaningfully to a composite score. The rationale for each exclusion is detailed in Chapter 9.

1.6 Thesis Structure

The remainder of this thesis is organized as follows. Chapter 2 reviews the four bodies of academic literature that underpin the analytical framework: I - urban sustainability monitoring and composite indicator construction; II - transit infrastructure and land value capitalization theory; III - acoustic noise as a real estate disamenity; and IV - urban decision-support systems and dashboard design. Chapter 3 reviews three leading international indicator frameworks — the Global Urban Monitoring Framework (UN-Habitat, 2022), the U4SSC Collection Methodology for Key Performance Indicators for Smart Sustainable Cities (International Telecommunication Union, 2017), and the SNTool MED (Moro et al., 2023) — compares them across key structural and methodological dimensions, and

justifies the selection of the SNTTool MED as the primary framework for this thesis. The chapter then details the GIS methodologies employed in both use cases, with particular attention to the two-step normalization pipeline of the net suitability model and the CNOSSOS-EU noise buffer calculation. Chapter 4 presents the indicator selection methodology and provides domain-by-domain justification for all indicators, supported by a complete indicator inventory table. Chapter 5 documents the data sources, geoprocessing environment, and calculation procedures for all spatial outputs, with INSPIRE-compliant metadata summaries. Chapter 6 presents the spatial results for Use Case 1, covering domain-by-domain sustainability scores, the composite index, scenario analysis, spatial autocorrelation, and the full city-wide acoustic noise assessment. Chapter 7 presents the results for Use Case 2, covering the net suitability model, phase comparison, economic uplift calculations, and land value capture implications for Aree di Trasformazione. Chapter 8 describes the design and architecture of the integrated DSS dashboard across its three user modules. Chapter 9 synthesizes findings across both use cases, answers the three research questions, situates results in the broader literature, and addresses methodological limitations. Chapter 10 summarizes the four principal contributions of the thesis, provides policy recommendations, and outlines future research directions.

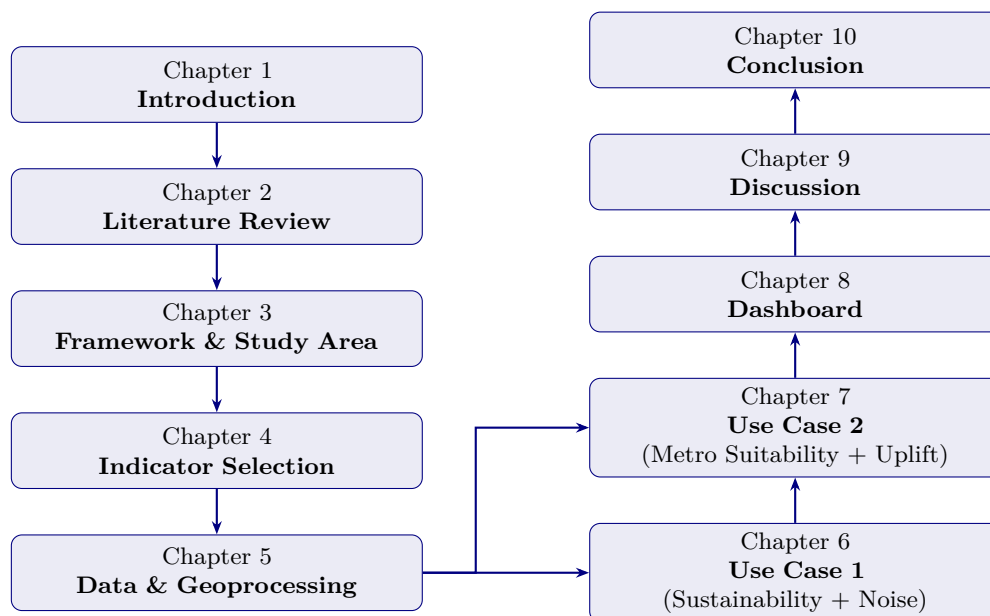


Figure 1.2: Thesis structure and chapter dependencies. Chapters 1–5 establish the analytical foundation; Chapters 6 and 7 present the two use cases, which feed into the integrated dashboard (Chapter 8), the cross-cutting Discussion (Chapter 9), and the Conclusion (Chapter 10).

Chapter 2

Literature Review

This chapter reviews four interconnected bodies of academic literature that together form the theoretical foundation of the thesis. Section 2.2 examines the evolution of urban sustainability monitoring and composite indicator construction. Section 2.3 surveys the theory and evidence on transit infrastructure and land value capitalization. Section 2.4 analyzes acoustic noise as a real estate "disamenity", with attention to Italian evidence and the CNOSSOS-EU modelling standard. Section 2.5 reviews the genealogy and critical literature on urban decision-support systems and dashboards. Together, these reviews position the thesis within existing scholarship and identify the three gaps that the analytical framework is designed to address.

2.1 Review Methodology

This literature review is a critical narrative review rather than a systematic review in the PRISMA sense. A systematic meta-analysis was not appropriate for this study: the research questions span four heterogeneous bodies of literature (urban sustainability measurement, transit hedonic pricing, acoustic modelling, and urban DSS design) whose empirical methods, units of analysis, and outcome metrics are too diverse for pooled quantitative synthesis. The review instead follows a scoping approach, mapping the key theoretical contributions, methodological precedents, and empirical findings relevant to each analytical component of the thesis.

Search strategy. Google Scholar was the primary search tool, supplemented by targeted bibliographic mining from high-relevance works identified in initial searches. For each thematic domain, searches were conducted using keyword strings including, but not limited to: *neighbourhood sustainability indicators composite index*; *SNTool MED Mediterranean sustainability*; *weighted linear combination urban sustainability*; *transit infrastructure property values hedonic pricing*; *metro line capitalization Italy*; *noise disamenity hedonic property prices*; *CNOSSOS-EU road noise model*; *urban decision support system GIS dashboard*; and *participatory GIS communicative planning*. Language was not formally restricted, but the review prioritized English and Italian sources, with French and Spanish sources included where directly relevant to the Mediterranean urban sustainability literature.

Inclusion criteria. Sources were selected on the basis of thematic relevance to one or more of the four review domains, methodological quality (peer-reviewed articles and books were prioritized over grey literature), and recency (works published since 2010 were prioritized, with earlier foundational texts included where they represent canonical contributions to the field). Technical reports, planning frameworks, and official guidance documents from recognized institutions (UN-Habitat, ITU, EU Commission, Italian government agencies) were included as primary regulatory and policy references. Grey literature sources (municipal websites, real estate data portals, project documentation) were used exclusively for factual data calibration or institutional context and are identified as such in the text. The bibliography distinguishes peer-reviewed sources from grey literature and institutional reports.

Limitations. As a critical narrative review, this chapter is not exhaustive: it does not claim to have

identified all published works on any of the four topics. Selection bias towards English-language and Italian scholarly output may underrepresent contributions from other Mediterranean countries directly relevant to the SNTool MED framework. The review should be read as a structured account of the literature that most directly informs the analytical choices made in this thesis, rather than as a comprehensive systematic mapping of the field.

2.2 Urban Sustainability: Frameworks and Measurement

2.2.1 The Sustainability Transition in Urban Policy

The intellectual foundations of urban sustainability policy can be traced to the Brundtland Commission's definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" ([World Commission on Environment and Development, 1987](#)). While this formulation is deliberately general, it established the canonical three-pillar structure of sustainability assessment: environmental, economic, and social, that continues to organize indicator frameworks four decades later. Its translation into the urban domain was accelerated through a series of landmark agreements: Agenda 21, adopted at the Rio Earth Summit in 1992, explicitly addressed local authorities as agents of sustainable development [United Nations \(1992\)](#); the Aalborg Charter of 1994 mobilized European cities around sustainability commitments [European Conference on Sustainable Cities & Towns \(1994\)](#); and the Leipzig Charter on Sustainable European Cities (2007, revised 2020) provided a comprehensive framework for integrated urban development in the European context [European Ministers responsible for Urban Development \(2007\)](#).

The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals represent the most ambitious iteration of this policy trajectory ([United Nations, 2015](#)). SDG 11, "Make cities and human settlements inclusive, safe, resilient and sustainable," is the most directly relevant to urban planning practice, and its 10 targets span housing, transport, disaster risk, environmental quality, cultural heritage, and urban governance. The New Urban Agenda, adopted at Habitat III in Quito in 2016, reinforced these commitments by calling for cities that are "planned and managed to optimize their spatial dimension and afford sustainable urbanization" ([United Nations, 2016](#)). At the European scale, the European Green Deal ([European Commission, 2019](#)) and the EU Urban Agenda provide the regulatory and investment framework within which Italian cities, including Turin, are expected to operationalize these global goals.

The Italian dimension is particularly relevant. The Piano Nazionale di Ripresa e Resilienza (PNRR), Italy's €191.5 billion National Recovery Plan funded through the NextGenerationEU instrument, allocates substantial resources to urban regeneration, green infrastructure, and sustainable mobility [Governo Italiano \(2021\)](#).

For cities like Turin, which combine significant post-industrial brownfield legacies with ambitious sustainability commitments, the PNRR represents both an opportunity and an accountability mechanism: funding is conditional on demonstrable progress against sustainability indicators that must, in principle, be measurable at the neighbourhood level. This context directly motivates the indicator framework utilized in this thesis.

2.2.2 Multi-Criteria Decision Analysis in Urban Contexts

Multi-Criteria Decision Analysis (MCDA) has been applied to urban planning problems since the late 1970s, but its integration with Geographic Information Systems (GIS) in the 1990s marked a qualitative shift in its practical utility ([Malczewski, 1999](#)). The combination of GIS's spatial data management and analytical capabilities with MCDA's ability to handle multiple, often incommensurable criteria opened new possibilities for evidence-based planning. The Weighted Linear Combination (WLC) method, in which normalized indicator scores are multiplied

by decision-maker-assigned weights and summed to produce a composite index, became the dominant approach in urban spatial analysis due to its transparency, interpretability, and computational accessibility (Eastman, 1999).

Methodologically, WLC requires three steps: standardization of criteria to a common scale (typically 0-100 or 0-1); assignment of weights reflecting the relative importance of each criterion; and aggregation into a composite score. Each step involves normative choices that affect the results. Standardization may be based on external benchmarks (such as WHO standards for green space), reference to the best-performing location in the dataset, or percentile-based internal normalization. Weight assignment may be objective (derived from statistical methods such as Principal Component Analysis), subjective (reflecting stakeholder priorities), or based on established frameworks. Aggregation by WLC is *compensatory*: a very high score on one criterion can offset a low score on another, which may or may not be analytically appropriate depending on the context (Dawodu et al., 2022).

The sensitivity of composite indices to weighting assumptions is a well-documented challenge. Neighbourhood rankings can shift substantially when weights are changed, undermining the apparent certainty of any single composite score (Taddeo et al., 2024). The appropriate methodological response is not to avoid composite indices, which offer irreplaceable communication value to non-expert audiences, but to routinely subject them to scenario analysis in which weight assumptions are varied systematically and results are reported for multiple scenarios. The sensitivity analysis implemented in this thesis (Section 6.3.2) follows this practice, identifying “robust under performers” that remain in the bottom quintile across all weighting scenarios and “sensitive switchers” whose ranking depends materially on weight choices.

A further issue in neighbourhood-level sustainability assessment is the selection of spatial units. The choice between administrative boundaries (circonsrizioni), census sections (sezioni di censimento) or statistical zones (zone statistiche), postal code zones (CAP), and real estate market zones (zone OMI) involves trade-offs between data availability, population representativeness, and spatial granularity (Fitzgerald and Lenhart, 2016).

This thesis uses the ISTAT 2021 *Zona Statistica* (Statistical Zone) as the primary spatial unit for sustainability indicators, supplemented by zone OMI for economic indicators, with explicit documentation of the join methodology where spatial units differ.

2.2.3 International Indicator Frameworks for Urban Sustainability

Alongside the general methodological literature on composite indices, a number of internationally endorsed indicator frameworks have been developed specifically to operationalize urban sustainability measurement at the city, neighbourhood, or metropolitan scale. These frameworks differ substantially in their institutional origins, thematic scope, spatial scale, and practical data requirements, and their comparison constitutes an important methodological choice for any study that adopts one of them as a primary reference.

Three frameworks are most relevant to the scope of this thesis. The Global Urban Monitoring Framework (GUMF), published by UN-Habitat in 2022, provides the most authoritative international reference for city-scale SDG and New Urban Agenda monitoring, structured around more than 50 core indicators aligned with Voluntary Local Review (VLR) reporting obligations (UN-Habitat, 2022). The U4SSC Collection Methodology for Key Performance Indicators for Smart Sustainable Cities, led by the ITU, assesses city-level sustainability with particular emphasis on ICT infrastructure, smart metering, and e-government provision (International Telecommunication Union, 2017). Both frameworks operate at the city or metropolitan scale and are not designed for sub-municipal spatial disaggregation. The Sustainable Neighbourhood Tool for Mediterranean Cities (SNTTool MED), developed by iiSBE Italia R&D within the EU ENI CBC MED-funded Sustainable MED Cities project, is distinguished by its explicit neighbourhood-scale design, its Mediterranean contextual specificity, and its mandatory KPI set enabling transnational comparisons (Moro et al., 2023).

A detailed comparative analysis of the three frameworks and the rationale for selecting SNTTool MED as the primary framework for this thesis are presented in Chapter 3 (Section 3.1).

2.2.4 The 15-Minute City Concept and Walkability

The “15-minute city” concept, articulated by [Moreno et al. \(2021\)](#) proposes that residents should be able to reach all essential daily destinations, work, education, healthcare, commerce, recreation, and green space, within a 15-minute walk or cycle ride from their home. The concept draws on a longer lineage of proximity-based urbanism theories, from Jane Jacobs’s celebration of urban density and mixed use [Jacobs \(1992\)](#) to the transit-oriented development (TOD) literature, but gives them a temporal and equity-focused framing that has proved persuasive in both academic and policy discourse.

Empirically, the 15-minute city has been operationalized in a variety of ways, ranging from network distance calculations to isochrone analysis and composite walkability indices ([Bornioli and Parkhurst, 2024](#); [Kissling et al., 2022](#)). Research applying these methods to Italian cities has documented significant spatial inequalities in proximity-based accessibility: central areas of Rome, Milan, and Turin score consistently higher on composite walkability metrics than peripheral areas, with the gap most pronounced for higher-order services such as hospitals and cultural venues ([Garau and Annunziata, 2024](#); [Venerandi et al., 2021](#)). These findings are directly relevant to the “Transportation and mobility” and “Social Aspects” domain indicators in this thesis, several of which do operationalize proximity-based accessibility to schools, health facilities, and key services.

The relationship between the 15-minute city concept and transit infrastructure is particularly important for Use Case 2. The 800 m pedestrian catchment used as the influence zone for Metro Line 2 stations corresponds approximately to a 10-minute walk at average urban walking speeds, situating the model within the broader proximity-based accessibility literature. The piecewise distance-decay functions applied in the net suitability model are consistent with empirical research demonstrating that transit accessibility premiums follow a non-linear spatial decay rather than a binary threshold ([Farhan and Murray, 2008](#); [Jiang et al., 2022](#)).

2.2.5 Spatial Autocorrelation and Neighbourhood Effects

Tobler’s First Law of Geography, the observation that “everything is related to everything else, but near things are more related than distant things” ([Tobler, 1970](#)), is the theoretical foundation for spatial autocorrelation analysis. In the context of urban sustainability indicators, spatial autocorrelation is both a diagnostic and an analytical tool. As a diagnostic, it reveals whether observed neighbourhood patterns are the result of genuine spatial clustering or random variation, informing how much confidence to place in apparent high-low contrasts. As an analytical tool, it enables the identification of statistically significant clusters through Local Indicators of Spatial Association (LISA) analysis ([Anselin, 1995](#)).

Moran’s I , the most widely used global measure of spatial autocorrelation, ranges from -1 (perfect dispersion) through 0 (randomness) to $+1$ (perfect clustering). A value of $I = 0.640$ for the public transport Competitiveness Index in Turin, as reported by [Zini et al. \(2024\)](#), indicates a high degree of spatial clustering in transit accessibility, suggesting that neighbourhoods with good transit service are adjacent to other well-served neighbourhoods, and poorly served areas cluster together.

The expected pattern for composite sustainability scores in Turin is broadly similar: the north-south inequality gradient implies significant positive spatial autocorrelation, with high-scoring clusters in the south and centre and low-scoring clusters in the north. LISA analysis can identify not only the overall degree of clustering but also the specific locations of statistically significant high-high, low-low, and spatial outlier clusters, providing a more nuanced spatial diagnosis than the global Moran’s I alone.

The implication for PRG long-term planning and monitoring is that intervention zones should be designed at the cluster level rather than for individual census sections. A neighbourhood with a low sustainability score that is surrounded by other low-scoring neighbourhoods represents a fundamentally different planning challenge, and opportunity, than an isolated low scorer surrounded by high performers. The former may require area-wide regeneration strategies; the latter may benefit from targeted individual interventions or spill-over from adjacent high-quality infrastructure.

2.3 Transit Infrastructure and Land Value Theory

2.3.1 The Hedonic Pricing Model

The Hedonic Pricing Model (HPM), first formalized by [Alonso \(1964\)](#) and subsequently developed into a mainstream tool of urban economics, provides the theoretical framework for understanding how transit infrastructure is capitalized into property values. The fundamental insight is that a property's market price reflects the aggregate value that buyers place on its observable attributes: structural characteristics (S , such as floor area, age, and energy class); neighbourhood attributes (N , such as service accessibility, school quality, and perceived safety); and locational attributes (L , such as proximity to employment centres, transport nodes, and amenities). Formally: $P = f(S, N, L)$.

Transit proximity affects both N and L . It increases L by improving accessibility to employment, commerce, and services; it affects N by altering the character of the surrounding neighbourhood, either positively through increased economic activity and reduced car dependence, or negatively through increased noise, traffic, and social congestion ([Mohammad et al., 2013](#)).

The empirical literature on transit capitalization is extensive: the meta-analysis by [Mohammad et al. \(2013\)](#), covering over 100 empirical studies of rail projects in mature urban environments, finds average property value premiums of 5-12% within the immediate catchment area, with substantial variation depending on transit type, urban density, pre-existing accessibility, and distance to the station.

The meta-analysis by [Debrezion et al. \(2007\)](#) adds an important nuance: the distance-decay of capitalization differs between residential and commercial properties, with commercial properties benefiting the most by immediately adjacency to stations while residential properties achieve peak appreciation at intermediate distances.

For Italian cities, the evidence base has been growing steadily. The Banca d'Italia study by [Cascarano and Mocetti \(2022\)](#) on Rome's Metro C documents a 5-6% increase in residential property values for properties located within 500 m of new stations, using a quasi-experimental design that exploits the phased opening of the line.

The study by [Coluccia et al. \(2026\)](#) applies HPM methodology across 13 high-speed rail stations in 10 Italian cities and finds heterogeneous effects, with the largest capitalization observed in large cities with pre-existing high land values and the smallest in peripheral locations.

For Turin specifically, the post-industrial transformation literature documents announcement effects of 3-5% for Metro Line 1 ([Politecnico di Torino, 2016](#)), providing the most directly relevant Italian precedent for the Use Case 2 model.

2.3.2 The Inverted U-Curve: Nuisance versus Accessibility

The relationship between distance from a transit station and property value is not monotonic. Research from multiple urban contexts has established an "inverted U-curve" or "disamenity donut" pattern ([Seo et al., 2014](#)): residential properties immediately adjacent to stations (typically within 50-200 m) experience a discount relative

to more distant properties due to the concentration of nuisance effects, including construction-phase disruption, operational noise, congestion from passenger flows, and the social character of station areas.

Properties in an intermediate zone (typically 150-800 m, depending on urban density and transit type) capture the accessibility premium while being partially insulated from the immediate nuisances. Beyond the maximum pedestrian catchment, the premium decays to zero.

This pattern has been documented specifically for Italian cities. The study of Milan’s M4 and M5 metro lines, synthesized by Errera (2020), finds that “second-row” properties, those on parallel streets one block removed from the station entrance, consistently outperform “first-row” properties in residential value growth. The Rome Metro C literature (Cascarano and Mocetti, 2022; Marzolla et al., 2025) similarly identifies a nuisance discount in the immediate 100 m radius that suppresses what would otherwise be the highest-accessibility zone.

These findings directly inform the piecewise decay functions applied in the Use Case 2 model, where a nuisance buffer of 150 m from metro station centroids applies a linear penalty that inverts the score at the immediate proximity zone.

The GIS implementation of the inverted U-curve through piecewise distance standardization is discussed by Jiang et al. (2022), who demonstrate through a Beijing case study that distance-decay functions produce significantly better model fit than binary buffers for metro station ridership regression.

The methodological implication is that the choice of distance function is not merely a technical convenience but a substantive modelling decision with real consequences for which properties are identified as high-suitability and which are penalized.

2.3.3 Announcement and Anticipation Effects

A critical distinction in the transit capitalization literature is between *ex ante* capitalization, which occurs when property markets price in the expected future benefits of a transit investment before construction, and *ex post* capitalization, which occurs after the infrastructure is operational.

The study by Errera (2020) on Milan is particularly instructive: it documents statistically significant price increases in the M4 corridor at the time of project announcement, several years before construction began. Similar announcement effects have been observed for Rome’s Metro C (Cascarano and Mocetti, 2022) and for numerous transit projects in North America and Asia reviewed by Higgins and Kanaroglou (2016).

The analytical implication for this thesis is significant. Because Metro Line 2 Phase I is expected to open in approximately 2033, and because this thesis uses 2024-2025 OMI data, the current price data already incorporates whatever anticipation premium the market has attributed to the project since its formal approval.

The model developed in Chapter 7 therefore predicts the *total* expected premium from the project relative to a hypothetical no-transit counterfactual, rather than the incremental premium still to be realized above current prices. This distinction is made explicit in the sensitivity analysis (Section 7.5) and in the discussion of limitations (Chapter 9).

The *ex post* DID validation approach employed by Marzolla et al. (2025) for Rome Metro C represents the methodological standard to which the Use Case 2 predictions should ultimately be compared, and is proposed as a future research direction.

2.3.4 Accessibility Measurement: From Buffers to Indices

The history of accessibility measurement in the transit-land value literature reflects a broader methodological evolution in transport geography. Binary buffers, which assign all properties within a fixed distance of a station to the “accessible” category and all others to “inaccessible,” were the dominant approach in early HPM studies due to their simplicity and data requirements. Their inadequacy has been demonstrated repeatedly: binary

buffers misrepresent the continuous and non-linear decay of accessibility over distance, conflate properties with very different levels of effective access, and produce results that are sensitive to the arbitrary choice of threshold distance (Farhan and Murray, 2008).

The evolution towards continuous distance-decay functions, isochrone-based accessibility, and composite accessibility indices reflects both improved computational capabilities and a richer theoretical understanding. The Mobility Index, Competitiveness Index, and Accessibility Index framework developed by Zini et al. (2024) for Turin and Rome represents a sophisticated operationalization: the Competitiveness Index (CI) measures the share of the road network that is reachable by public transport at a competitive time cost relative to private car; the Accessibility Index (AI) measures the proportion of the population served by high-frequency transit. For Turin, the reported values of $CI = 0.18$ and $AI = 74\%$ indicate a city where public transport serves most residents but competes effectively with private car in a limited share of the network, with significant spatial inequality in the CI distribution (coefficient of variation 0.93; Moran's $I = 0.640$).

These findings motivate the F1.1 indicator (Performance of the Public Transport System) in the sustainability framework and the metro station proximity layer in the net suitability model, providing an empirically validated basis for the characterization of Turin's transit accessibility baseline.

2.3.5 Land Value Capture: Theory and Mechanisms

Land value capture (LVC) is grounded in the classical economic concept of the “unearned increment”: the increase in land value attributable to public infrastructure investment rather than to any productive activity of the landowner. John Stuart Mill, Henry George, and subsequent economists argued that this increment represents an appropriate target for public recapture, since the community whose investment created the value should receive a share of its benefits (Micelli, 2018). The contemporary LVC literature examines a range of instruments through which public agencies seek to capture this increment, including tax increment financing (TIF), betterment levies, developer contributions, joint development, and special assessment districts (Zhao et al., 2014).

In Italy, the primary mechanism for LVC in the context of transit infrastructure is the *Contributo Straordinario*, established by Article 16 of the Consolidated Building Regulations (D.P.R. 380/2001) (Governo Italiano, 2001). This contribution is levied on building permits for development that generates surplus value above a specified threshold, and is negotiated as a percentage of the attributable uplift.

The identification of Aree di Trasformazione, brownfield and PRG-designated redevelopment parcels, as the primary LVC targets reflects their status as the sites where development uplift from Metro Line 2 is both most concentrated and most subject to public planning control.

The Net Suitability Score developed in Chapter 7 provides a spatially explicit, parcel-level basis for estimating the uplift premium attributable to transit proximity (net of acoustic disamenity), which is the analytical foundation for Contributo Straordinario calculations.

Recent comparative research on European LVC mechanisms, including the study by Ferm and Moore-Cherry (2025) on the Grand Paris Express, underscores both the potential and the institutional complexity of transit-financed infrastructure. The Grand Paris experience demonstrates that value capture can generate substantial revenue, but that its success depends on institutional coordination, clear legal frameworks, and transparent valuation methodologies. The methodology developed in this thesis is designed to contribute precisely the kind of transparent, spatially explicit valuation that LVC negotiations require.

Regione Lombardia provides a relevant Italian precedent for LVC through urban development agreements (Accordi di Programma) (Micelli, 2018), demonstrating that Italian municipalities have existing legal tools for capturing development uplift that can be adapted to the metro corridor context.

2.3.6 GIS-Based Multi-Criteria Evaluation for Real Estate Suitability

The application of GIS-based MCE to transit-oriented real estate suitability analysis extends the theoretical work on HPM into a spatial planning tool. Rather than estimating the average capitalization effect across all properties, GIS-MCE produces spatially differentiated suitability maps that identify which specific locations are expected to benefit most from transit investment. [Malczewski \(1999\)](#) provides the foundational methodological framework; [Eastman \(1999\)](#) operationalizes it through fuzzy linear membership functions that translate raw distances into standardized suitability scores. [Jiang et al. \(2022\)](#) demonstrates that replacing binary buffers with distance-decay functions substantially improves model performance for metro station influence in dense urban environments.

The Use Case 2 model extends this literature in one significant respect: it separates the treatment of acoustic disamenity from the conventional WLC framework. In prior MCE studies of transit-oriented real estate suitability, noise is typically included as one weighted criterion among many, which implies that its impact on property values is proportional to its assigned weight and commensurable with other criteria. The economic literature, however, suggests a different logic: the noise penalty is not a dimension of suitability that can be offset by high scores on other criteria but a discount applied relative to a location's own accessibility baseline. The two-step normalization pipeline implemented in Chapter 3 operationalizes this insight.

2.4 Acoustic Noise as a Real Estate Disamenity

2.4.1 Evidence on Transit and Road Noise Penalties

The relationship between ambient noise and residential property values has been studied extensively in the HPM literature. Noise is a classic external cost: generated by road traffic, railways, and aircraft, it imposes costs on neighbouring residents that are not reflected in the prices of the noise-generating activities. These costs are partially revealed in property markets, where noise-exposed locations command lower prices than quieter alternatives, all else equal.

The empirical literature documents substantial variation in the estimated noise discount. Studies from European cities find a noise sensitivity depreciation index (NSDI) in the range of 0.3-0.9% per dB(A) for road traffic noise ([Andersson et al., 2021](#)).

Italian-specific evidence is more limited but consistent with this range: studies on Turin and Naples find property value decreases of 0.30-0.64% per additional dB(A) of ambient noise, with the lower end of this range typical for moderate noise environments and the upper end for severely noise-affected properties ([Beria et al., 2025](#)).

Broader European meta-analyses summarize the average effect as approximately -4% per 10 dB(A) increase above a baseline ambient level of 50-55 dB(A) ([Bjørner, 2003](#)).

Recent research using machine learning methods on property transaction data has refined these estimates considerably. The study by [Kounadi et al. \(2023\)](#) on Thessaloniki uses XGBoost models with SHAP interpretation to quantify noise's non-linear contribution to property price formation, finding that noise effects are particularly pronounced at high decibel levels and in residential zones where the contrast with expected ambient levels is greatest.

These methodological advances point towards a more granular treatment of noise penalties than the linear decay model applied in this thesis, and are noted as a direction for future research.

2.4.2 Legacy Tram Systems and Their Acoustic Profile

The acoustic impact of tram systems is substantially heterogeneous across fleet types and track configurations. Modern low-floor LRT systems operating on resilient rail fastenings in dedicated corridors generate sound pressure levels of approximately 65-75 dB(A) at 7.5 m from the track, with rapid attenuation due to modern wheel-rail contact geometries. Legacy embedded-track systems with older rolling stock, by contrast, generate significantly higher levels due to flange squeal on curves, track irregularities, and less effective noise barriers (Bocher et al., 2019).

Turin's GTT Series 2800 trams, which still account for a significant portion of the active GTT tram fleet, represent a severe case within the European legacy tram typology. Operating on embedded tracks laid in many cases during the 1950s and 1960s, these vehicles generate maximum noise levels of 80-85 dB(A) at stops during braking events, with sustained levels of 70-80 dB(A) at 20 m from the track during passing events on curved sections [Tram di Torino \(2024\)](#) (grey literature: operator website; used for fleet acoustic specification only).

The "first-row" effect documented in the broader noise literature is particularly pronounced for Turin trams: properties directly fronting a tram avenue are estimated to suffer a 10-12% value discount relative to comparable "second-row" properties on parallel streets, with the discount decaying to approximately 2-6% at 50 m and becoming negligible beyond 100 m (Beria et al., 2025).

The buffer parameters applied in this thesis (50 m for tram lines, 100 m for tram stops) are calibrated to the acoustic profile of the Series 2800 fleet rather than to general LRT literature values, reflecting the distinctiveness of Turin's mixed-vehicle tram network, and estimating "worse-case scenarios" in which a tram line uses primarily these legacy vehicles (e.g. Lines 16CD and 16CS).. These values are conservative relative to the maximum observed impact zone but represent the distance within which the penalty is large enough to be statistically detectable in HPM studies.

It should be acknowledged that GTT has embarked on a modernization project of its tram fleet, with an order of 70 new, low-floor, lower noise vehicles, with a final delivery date estimated by early 2027 ([Gruppo Torinese Trasporti, 2025](#)). As a future deliverable, the noise estimates produced in Use Case 2 should be updated to reflect the noise profiles of these new vehicles.

2.4.3 CNOSSOS-EU: The European Noise Modelling Standard

The Common Noise Assessment Methods in Europe (CNOSSOS-EU) framework, established by Commission Directive (EU) 2015/996 ([European Parliament and Council, 2015](#)) and transposed into Italian law by D.Lgs. 42/2017 ([Governo Italiano, 2017](#)), provides a standardized methodology for calculating noise levels from road traffic, railways, aircraft, and industry for strategic noise mapping purposes under the Environmental Noise Directive (2002/49/EC).

For road traffic noise, the framework employs A-weighted macro-equations that estimate total sound power per metre of road based on traffic flow, speed, and vehicle mix.

The foundational equations used in this thesis are:

$$L_{W,l} = 94.0 + 30 \cdot \log_{10}\left(\frac{v}{50}\right) \quad (2.1)$$

$$L_{W,h} = 106.0 + 20 \cdot \log_{10}\left(\frac{v}{50}\right) \quad (2.2)$$

where $L_{W,l}$ and $L_{W,h}$ are the A-weighted sound power levels per vehicle (in dB) for light ($m=1$) and heavy ($m=3$) vehicles respectively, and v is the mean vehicle speed in km/h with 50 km/h as the reference speed. The combined

line-source emission per metre of road integrates individual vehicle contributions through logarithmic addition of hourly flow rates.

Sound propagation from the road to a receiver is modelled using cylindrical geometric divergence:

$$L_p(d) = L'_{W,\text{total}} - 10 \cdot \log_{10}(d) - 5 \quad (2.3)$$

where $L_p(d)$ is the sound pressure level at distance d from the road centreline.

Inverting Equation (2.3) to find the buffer distance at which noise drops to a target threshold level L_{target} :

$$d = 10^{(L'_{W,\text{total}} - L_{\text{target}} - 5)/10} \quad (2.4)$$

In this thesis, $L_{\text{target}} = 60$ dB(A), corresponding to the Italian Class III mixed residential limit.

The output of Equation (2.4), applied to every road segment in Turin using Regione Piemonte's TGM (Traffico Giornaliero Medio) 2024 traffic count data, generates a variable-width noise buffer polygon for each road segment.

The variability in buffer width, ranging from near-zero for quiet residential streets to 80-150 m for major arterial roads, encodes the differential acoustic footprint of Turin's heterogeneous road network.

The CNOSSOS-EU macro-model represents a 2D free-field simplification that does not account for façade reflection, building absorption, or indoor sound propagation; these limitations are acknowledged explicitly in Chapter 9.

2.4.4 Integrating Noise into Suitability Models

The conventional treatment of noise in GIS-based suitability analysis is to include it as one weighted criterion among many, assigning it a weight that reflects its perceived importance relative to other factors. This approach is analytically consistent but economically imprecise: it implies that noise can be fully offset by high scores on other criteria, and that its impact is independent of a location's baseline accessibility quality.

The economic literature suggests a different logic. The noise penalty documented in HPM studies is consistently modelled as a *proportional discount* from a location's market value, not as an additive offset. A property worth €3,000/m² that is exposed to 70 dB(A) exterior noise suffers a larger absolute price reduction than a property worth €1,500/m² exposed to the same noise level, even if the percentage discount is similar [Trojanek et al. \(2017\)](#). This proportionality implies that noise should be applied to a normalized suitability surface rather than entered as a raw criterion.

The two-step normalization pipeline developed in this thesis operationalizes this insight. After computing the base positive suitability score from accessibility to metro stations and amenities (Step A) and normalizing it to a 0-100 scale (Step B), the acoustic disamenity penalties are subtracted in absolute points (Step C), and the result is re-normalized to 0-100 (Step D). This design ensures that a penalty of, say, −15 points from a major road represents a 15% reduction in the location's accessibility quality, regardless of the absolute value of that quality. Sites with a pre-penalty score of 80 that suffer a −15 point road noise penalty end up with a net score of approximately 65 (after re-normalization), reflecting a genuine 20% reduction from their quality-weighted potential. This is a methodological contribution to the GIS-MCE literature on transit suitability modelling.

2.5 Urban Decision-Support Systems and Dashboards

2.5.1 The Urban Dashboard: Genealogy and Critiques

Urban dashboards, as a category of planning tool, have their origins in the corporate management dashboards of the 1990s, which sought to present key performance indicators in real-time displays for executive decision-making. The translation of this paradigm to the urban context accelerated in the 2000s, driven by the “smart city” discourse promoted by IBM, Cisco, and other technology firms and adopted by municipalities worldwide [Mattern \(2015\)](#). IBM’s Smarter Cities initiative, Rio de Janeiro’s Intelligent Operations Centre (2010), and Chicago’s WindyGrid exemplify the genre: large-screen displays aggregating real-time data from sensors, cameras, and databases, presenting a simultaneous and “total” view of the city to operators and officials [Steenmans et al. \(2023\)](#).

[Kitchin et al. \(2015\)](#) provide the most incisive critical analysis of this genealogy. They argue that urban dashboards embody a particular form of “governance by numbers” that risks reducing the complexity and messiness of urban life to a set of metrics that can be optimized by technocratic intervention.

The dashboard’s apparent comprehensiveness, its aggregation of multiple indicators into a unified display, conceals the normative choices embedded in indicator selection, weighting, and presentation. In particular, the choice of what to measure and what to ignore is always a political decision, even when presented as purely technical. This critique is relevant to the sustainability dashboard developed in this thesis, which is designed with explicit acknowledgement of the normative choices in indicator selection and weighting, and with provisions for users to vary weights and interrogate methodology.

[Aminrad \(2024\)](#) extends this analysis through case studies of sustainability dashboards in Helsinki, Copenhagen, and Turin. Drawing on Star and Griesemer’s concept of the “boundary object” ([Star and Griesemer, 1989](#)), Aminrad argues that effective urban dashboards function as boundary objects: they maintain coherent meaning across different professional communities (planners, engineers, citizens, politicians) while allowing each community to interpret them through its own analytical lens.

This requires a “layered information architecture” in which the same underlying data is accessible at multiple levels of detail and technical complexity. The dashboard designed in Chapter 8 adopts this principle explicitly, providing different default views for each of the three target user groups while ensuring that all underlying data and methodology are accessible to any user who requests them.

2.5.2 Communicative Planning and Participatory GIS

The theoretical tradition of communicative planning, rooted in Habermas’s theory of communicative rationality ([Habermas, 1984](#)), provides a normative framework for evaluating urban dashboards as planning tools. Communicative planning theory holds that legitimate planning decisions are those arrived at through inclusive, transparent, and undistorted deliberation among all affected stakeholders, rather than through the unilateral exercise of technocratic expertise. The practical translation of this theory into planning practice has emphasized participatory methodologies, public consultation, and the design of planning processes that create genuine opportunities for non-expert voices to influence outcomes.

Participatory GIS (PGIS) extends this tradition into the spatial domain: it encompasses methodologies and tools that enable non-expert communities to contribute spatial knowledge, articulate spatial priorities, and interrogate spatial planning proposals ([Bibri and Krogstie, 2021](#)). The urban dashboard, from a PGIS perspective, should not merely display expert-generated data to passive audiences but should provide interfaces through which citizens can contribute their own spatial knowledge and exercise genuine agency over planning decisions.

The dashboard designed in this thesis does not fully realize the PGIS ideal, a limitation acknowledged in Chapter 9. Module 3, the residential suitability query interface, is designed to empower individual citizens to evaluate specific addresses without GIS expertise, which represents a step towards democratizing spatial analysis. However, the underlying indicator weights and model assumptions are not user-configurable in Module 3 (they are in Module 1 for planning officials), and the tool does not include mechanisms for crowd-sourced data contribution in its initial phase. These are identified as directions for future development.

2.5.3 Decision-Support Systems in Urban Planning

Decision-support systems (DSS) are distinguished from simple dashboards by their capacity to support not only the display of information but the analysis of scenarios, the evaluation of alternatives, and the modelling of consequences. The defining feature of a DSS is that it “augments” rather than replaces human decision-making: it processes data according to explicit, transparent rules and presents the results in a form that decision-makers can interpret, challenge, and act upon (Pettit et al., 2019).

In urban planning applications, DSS tools have been developed for a range of purposes: site suitability analysis, transport network optimization, flood risk assessment, and energy consumption modelling. A critical weakness of many urban planning DSS tools, however, is their limited accessibility to non-expert users. Tools designed for GIS specialists are inaccessible to elected officials, community representatives, or property investors who lack the technical background to interpret raster outputs or interrogate spatial joins.

This accessibility gap is a principal motivation for the three-module architecture of the dashboard developed in this thesis, which provides expert-level analytical functionality for Module 1 and 2 users while presenting the same results in plain-language form for Module 3 (retail investor / citizen) users.

The broader trajectory in urban informatics is towards cloud-based, API-accessible DSS tools that can ingest live data feeds and update their outputs in near-real-time (Bibri and Krogstie, 2021). The current iteration this thesis is based on, described in Chapter 8 represents a Phase I local deployment using Python and QGIS backends; the Phase II cloud architecture outlined in Section 8.7 establishes the pathway to a fully dynamic, continuously updated DSS.

2.5.4 Positioning This Thesis in the Literature

Three gaps in the existing literature are addressed by this thesis:

First, while neighbourhood sustainability assessment has been applied to Italian cities at metropolitan and regional scales (Dawodu et al., 2022; Taddeo et al., 2024), no published study applies an indicator harmonization framework at the statistical-zone level to Turin specifically.

Second, while the property value impacts of Italian metro projects have been studied using HPM and, for Rome, DID approaches (Cascarano and Mocetti, 2022; Marzolla et al., 2025), no published study develops a spatially explicit suitability model for the Metro Line 2 corridor that integrates acoustic disamenity as a post-normalization penalty subtraction rather than a standard weighted criterion.

Third, while urban dashboards combining sustainability monitoring and transit impact assessment exist in the smart city literature, the integration of neighbourhood sustainability monitoring, transit suitability, and acoustic noise assessment within a single DSS serving multiple professional user groups, including a plain-language residential suitability query for retail investors and citizens, is, to the author's knowledge, without direct precedent in the published literature.

Table 2.1 summarizes the four research streams reviewed in this chapter, the questions each body of literature addresses, its primary sources as represented in this review, and the residual gaps that this thesis is designed to fill.

Table 2.1: Research streams, coverage, primary sources, and residual gaps addressed by this thesis.

Research stream	Questions covered	Primary sources	Residual gap addressed
Urban sustainability monitoring & composite indices	How can multi-domain sustainability be measured at neighbourhood scale? Which indicator frameworks exist and how do they compare? What are the methodological pitfalls of WLC aggregation?	World Commission on Environment and Development (1987); Malczewski (1999); Dawodu et al. (2022); Taddeo et al. (2024); Moro et al. (2023); UN-Habitat (2022)	No published study applies the SNTool MED at <i>zona statistica</i> scale for Turin with full open-data reproducibility and discriminatory power vetting of indicators.
Transit infrastructure & land value capitalization	Does transit proximity capitalize into residential property prices? What distance-decay functions and buffer geometries best capture the effect? What is the Italian evidence base?	Debrezion et al. (2007); Higgins and Kanaroglou (2016); Cascarano and Mocetti (2022); Marzolla et al. (2025); Farhan and Murray (2008); Jiang et al. (2022)	No spatially explicit pixel-scale suitability surface for the Metro Line 2 corridor incorporates acoustic disamenity as a post-normalization penalty rather than a standard weighted criterion.
Acoustic noise as urban disamenity	How does road and rail noise affect residential property values? How should acoustic modelling be integrated with GIS suitability analysis?	Trojanek et al. (2017); Seo et al. (2014); European Parliament and Council (2002); European Commission CNOSSOS-EU documentation	No Italian study integrates CNOSSOS-EU road noise buffers with metro transit suitability scoring and hedonic uplift estimation at neighbourhood scale.
Urban DSS design & participatory GIS	What design principles distinguish effective urban dashboards from data displays? How do boundary object and communicative planning theories apply?	Kitchin et al. (2015); Aminrad (2024); Star and Griesemer (1989); Habermas (1984); Jankowski (2009)	No published DSS integrates neighbourhood sustainability monitoring, transit suitability, and acoustic noise assessment for multiple professional user groups within a single open-source browser-based platform.

Chapter 3

International Indicator Frameworks, GIS Methodology, and Study Area

This chapter serves three purposes. It begins by reviewing three leading international frameworks for urban sustainability assessment, comparing their structure, spatial scale, and thematic coverage, and justifying the selection of the Sustainable Neighbourhood Tool for Mediterranean Cities (SNTTool MED) as the primary analytical framework for this thesis (Section 3.1). It then presents the SNTTool MED methodology in detail, describing its hierarchical structure, contextualization process, and normalization approach (Section 3.2). Finally, it details the GIS methodologies employed in both use cases (Sections 3.3–3.4.3) and concludes with a profile of Turin’s urban context, public transport network, and real estate market (Sections 3.5.1–3.5.3).

3.1 International Indicator Frameworks for Urban Sustainability Assessment

Urban sustainability assessment is supported by a growing body of internationally recognized indicator frameworks, each with distinct institutional origins, spatial scales, and thematic emphases. For this thesis, three leading frameworks were systematically reviewed and compared: the Global Urban Monitoring Framework (GUMF) (UN-Habitat, 2022), the United for Smart Sustainable Cities (U4SSC) Collection Methodology for Key Performance Indicators for Smart Sustainable Cities (International Telecommunication Union, 2017), and the Sustainable Neighbourhood Tool for Mediterranean Cities (SNTTool MED) (Moro et al., 2023). Each framework was evaluated against five criteria: its institutional origin and credibility, the spatial scale at which it is designed to operate, the range of sustainability themes it addresses, the number and nature of its core indicators, and the practical feasibility of its application using open data at the neighbourhood level in an Italian city context. The comparative analysis presented below informed the selection of SNTTool MED as the framework applied throughout this thesis.

3.1.1 The Global Urban Monitoring Framework

The Global Urban Monitoring Framework (GUMF), published by UN-Habitat in 2022 with contributions from the OECD, UNESCO, WHO, and UNECE, is the most authoritative internationally endorsed framework for urban sustainability monitoring (UN-Habitat, 2022). Structured around five thematic domains and more than 50 core indicators aligned with SDG 11 and the New Urban Agenda, it is designed to support cross-national comparison and Voluntary Local Review (VLR) reporting at the *city or metropolitan scale*.

For the purposes of this thesis, the GUMF presents two fundamental limitations: its city-scale orientation does not offer the neighbourhood-level granularity required to distinguish the sustainability performance of Turin’s 94 *zone statistiche* or to identify Priority Intervention Zones within the PRG revision process; and several indicators require administrative microdata not available as open geospatial data in Italian cities at sub-municipal

level. These characteristics render it poorly matched to the spatial scale and open-data methodology of the present analysis, while remaining a valuable reference for future city-level VLR reporting.

3.1.2 The U4SSC Collection Methodology for Key Performance Indicators for Smart Sustainable Cities

The Collection Methodology for Key Performance Indicators for Smart Sustainable Cities, developed within the United for Smart Sustainable Cities (U4SSC) initiative led by the International Telecommunication Union (ITU), provides a standardized approach for cities to self-assess their sustainability and smart city performance against the SDGs (International Telecommunication Union, 2017). Its approximately 92 KPIs, organized across Economy, Environment, and Society and Culture dimensions, give particular prominence to ICT infrastructure, smart metering, and e-government provision — dimensions that distinguish it from purely environmental sustainability frameworks.

For the purposes of this thesis, the U4SSC methodology presents two structural limitations: it operates at the city scale with no provisions for sub-municipal disaggregation, making intra-urban differentiation across Turin's *zone statistiche* impossible; and its most distinctive indicators — broadband coverage, demand response penetration, e-procurement rates — are not available as open spatial data in Italian administrative systems and are tangential to the land use, mobility, social equity, and climate adaptation dimensions that constitute the analytical core of Use Case 1.

3.1.3 The SNTTool MED Framework

The Sustainable Neighbourhood Tool for Mediterranean Cities (SNTTool MED) was developed within the Sustainable MED Cities project, funded by the European Union through the ENI CBC MED Programme, under the scientific coordination of iiSBE Italia R&D (Moro et al., 2023). Its intellectual roots lie in the SBE (Sustainable Built Environment) Method developed by the international initiative for a Sustainable Built Environment (iiSBE) since 1996 through the Green Building Challenge initiative. The first version of SNTTool was developed within the CESBA MED Interreg project, led by the City of Turin. In the subsequent Sustainable MED Cities project, the tool was extended to the broader Mediterranean region, incorporating input from partner municipalities in Italy, Spain, Jordan, Tunisia, Lebanon, and Greece. Turin thus served as a founding partner city throughout SNTTool's evolution.

The SNTTool MED is the only one of the three frameworks reviewed here that is explicitly designed for the *neighbourhood scale*. Its 10 thematic issues — Land Use and Biodiversity, Energy, Water, Solid Waste, Environmental Quality, Transportation and Mobility, Social Aspects, Economy, Climate Change Mitigation and Adaptation, and Governance — cover the full sustainability spectrum but are operationalized through indicators that are measurable and meaningful within the boundaries of a single neighbourhood or small urban area. The framework is structured in four hierarchical levels (Issues, Categories, Criteria, and Indicators), encompassing 92 assessment criteria in total, and includes a mandatory set of Key Performance Indicators (KPIs) that enable cross-city comparison across the Mediterranean partner network. A detailed description of the framework's methodology, its normalization procedure, and the subset of indicators applied in this thesis is provided in Section 3.2.

3.1.4 Comparative Analysis of the Three Frameworks

Table 3.1 summarizes the principal structural and methodological characteristics of the three frameworks across the dimensions most relevant to the selection decision for this thesis.

Table 3.1: Comparison of the three international indicator frameworks reviewed for this thesis. KPI counts are approximate and refer to core or mandatory indicators; total indicator inventories (including optional or advanced items) are substantially larger for all three frameworks.

Characteristic	Global Urban Monitoring Framework	U4SSC Collection Methodology	SNTool MED
Developer / body	UN-Habitat, with OECD, UNESCO, WHO, UNECE, et al.	ITU, UN-Habitat, UNECE, UNESCO, and 11 UN agencies (U4SSC initiative)	iiSBE Italia R&D, ENI CBC MED Programme; City of Turin as founding partner
Publication year	2022	2017	2023 (v. 2023-A)
Primary spatial scale	City / functional urban area	City / municipal	Neighbourhood / small urban area
Thematic domains (number)	5 (Society, Economy, Environment, Culture, Governance)	3 (Economy, Environment, Society & Culture)	10 Issues (Land Use, Energy, Water, Waste, Environmental Quality, Mobility, Social, Economy, Climate, Governance)
Core indicators (approx.)	50+ mandatory	~60 core; ~32 advanced	92 criteria total; mandatory KPI set for transnational reporting
Geographic / institutional focus	Global; aligned with SDG 11 and New Urban Agenda	Global; smart city / ICT integration emphasis	Mediterranean cities; EU ENI CBC MED Programme context
Core orientation	SDG and NUA monitoring; Voluntary Local Reviews	Smart city performance; ICT contribution to sustainability	Neighbourhood sustainability assessment and local planning decision-support
Local contextualization	Limited; global benchmarks	Limited; standardized thresholds	Explicit: cities define local benchmarks and weights
Open-data feasibility (Italian cities)	Partial; several indicators require administrative data unavailable in open datasets	Low; ICT and smart metering data generally not available as open spatial data	High; methodology designed around data types available from municipal and public sources

Several observations emerge from this comparison. The most fundamental difference among the three frameworks is their intended spatial scale of operation. Both the GUMF and the U4SSC methodology are city-scale frameworks, producing aggregate metrics that characterize the city as a whole. Neither offers provisions for disaggregation to the neighbourhood or statistical zone level, nor does either framework include guidance on spatial data handling, geographic analysis, or intra-urban differentiation. The SNTTool MED, by contrast, was designed from the outset for application at sub-municipal scale: its indicator definitions, calculation methods, benchmarks, and normalization procedures are all calibrated to the neighbourhood as the primary unit of analysis.

A second important dimension of difference is thematic emphasis. The GUMF provides the broadest possible coverage, encompassing society, economy, environment, culture, and governance within a single framework explicitly anchored to SDG monitoring obligations. The U4SSC methodology shares this breadth but adds a distinctive ICT and smart city dimension that reflects its origin in the telecommunications sector. SNTTool MED, while also organized around 10 themes that parallel the GUMF and U4SSC domains, focuses these themes on dimensions that are both measurable and practically actionable at neighbourhood scale, omitting aspects — such as national-level climate finance or global health statistics — that are meaningful only at higher aggregation levels. From the perspective of the PRG monitoring and neighbourhood-level planning decisions that motivate this thesis, SNTTool MED's thematic scope is therefore better calibrated than either alternative.

The third significant difference is the degree of local contextualization each framework permits. The GUMF and U4SSC both operate with globally standardized indicator definitions and benchmarks, designed to enable cross-national comparison. SNTTool MED incorporates an explicit contextualization process through which each partner city selects the active criteria from the full 92-criterion inventory, defines local minimum-acceptable and excellent-performance benchmarks, and assigns domain weights that reflect local planning priorities. This design philosophy acknowledges that a benchmark appropriate for a dense Mediterranean city may be inappropriate for a Nordic suburban context, and that the value of a sustainability tool is determined as much by its local relevance as by its global comparability.

3.1.5 Selection of the SNTTool MED Framework

On the basis of the comparative analysis presented above, the SNTTool MED was selected as the indicator framework for this thesis. Four arguments support this choice, each addressing a distinct dimension of the framework's fitness for purpose in the Turin context.

Neighbourhood-scale design. The most decisive advantage of the SNTTool MED over its alternatives is its explicit design for the neighbourhood scale. The sustainability assessment developed in Use Case 1 requires an indicator framework that produces meaningful spatial differentiation across Turin's 94 *zone statistiche*, each with a mean area of approximately 1.4 km² and a mean population of roughly 9,000 residents. City-scale frameworks such as the GUMF and the U4SSC methodology collapse intra-urban variation into single municipal aggregates, making it impossible to identify neighbourhood-level disparities, Priority Intervention Zones, or the spatial gradient between Turin's southern residential districts and its post-industrial northern periphery. SNTTool MED is the only reviewed framework whose indicator definitions, benchmarks, and normalization procedures are designed and validated for precisely this scale of analysis.

Italian and Mediterranean context. The SNTTool MED was developed for and validated in the Mediterranean urban context, with particular attention to the regulatory, climatic, and socio-economic conditions of Southern European cities (Moro et al., 2023). Its benchmarks reflect Mediterranean norms for green space provision, building energy performance, water consumption, and transport accessibility, which differ meaningfully from the global standards embedded in the GUMF and U4SSC frameworks. Applying global benchmarks

uncritically to a dense Italian city like Turin would produce systematically distorted sustainability scores in several domains: population density thresholds calibrated for dispersed North American suburbs, for instance, would classify even Turin’s least compact districts as exceptionally dense. The SNTTool MED’s contextualization process mitigates this risk by requiring partner cities to define benchmarks that reflect local conditions.

Internationally recognized thematic architecture and sustainability at its core. The SNTTool MED’s ten-issue structure is aligned with internationally recognized sustainability dimensions and directly traceable to the SBE Method’s four decades of development across more than 25 countries (Moro et al., 2023). Its thematic coverage spans land use, energy, water, transport, social equity, economy, and climate change, providing a comprehensive sustainability lens that is not biased towards any single dimension. Unlike the U4SSC methodology, whose distinctive contribution lies in its ICT and smart city dimension, SNTTool MED places environmental, social, and economic sustainability at its core, consistent with the Brundtland three-pillar framework and the SDG architecture to which both the GUMF and U4SSC also aspire. The framework’s mandatory KPI set ensures that the indicators selected for this thesis can be aggregated and compared with those of other SNTTool MED partner cities across the Mediterranean, maintaining a link to international reporting even while enabling local planning application.

Turin as a founding partner city. Turin was a leading partner in the development of SNTTool MED from its inception, first as the leader of the CESBA MED project that produced the original framework, and subsequently as a key contributor to the Sustainable MED Cities project that extended it to the full Mediterranean region (Moro et al., 2023). This institutional history has two practical consequences for this thesis. First, the framework’s indicator definitions, benchmarks, and assessment methods have been developed and tested using Turin as a reference case, meaning that the data requirements, spatial units, and performance thresholds are already calibrated for the Turin urban environment. Second, the indicators and benchmarks selected in this thesis are not novel adaptations of a foreign tool but the legitimate application of a framework to one of its own founding cities, strengthening the analytical validity of the resulting sustainability scores.

Future work may incorporate the GUMF and the U4SSC Collection Methodology as complementary frameworks, extending the analysis to city-scale SDG reporting and smart city performance assessment as additional open datasets become available for Turin at fine spatial resolution. In particular, the GUMF’s cultural and governance domains, and the U4SSC methodology’s ICT infrastructure indicators, address dimensions that are absent from the five issues selected for this thesis and could enrich the sustainability picture in subsequent iterations of the composite index. Such integration would also support the preparation of Turin’s Voluntary Local Reviews, where alignment with the GUMF reporting architecture is increasingly expected (UN-Habitat, 2022).

3.2 The SNTTool MED Framework: Detailed Methodology

3.2.1 SNTTool MED — Sustainable Neighbourhood Tool for Mediterranean Cities

As introduced in Section 3.1.3, the SNTTool MED is based on the Sustainable Built Environment (SBE) Method developed by iiSBE since 1996 and has been adapted for the Mediterranean urban context through a multi-year collaborative process involving partner municipalities including Turin, Barcelona, and Tel Aviv (Moro et al., 2023). This section describes the framework’s internal methodology in the detail required to understand the assessment procedure applied in Use Case 1.

The SBE Method is organized around four hierarchical levels: Issues, Categories, Criteria, and Indicators. *Issues* describe broad thematic areas relevant to neighbourhood sustainability. *Categories* address particular aspects within each issue. *Criteria* represent the basic assessment entries, and *Indicators* are the measurable

quantities associated with each criterion. The SNTTool MED encompasses ten thematic issues (A through J), spanning land use and biodiversity, energy, water, solid waste, environmental quality, transportation and mobility, social aspects, economy, climate change mitigation and adaptation, and governance. Of these ten issues, five — A, F, G, H, and I — have been selected for this thesis on the basis of data availability and direct relevance to the PRG monitoring objectives. The remaining issues (B, C, D, E, and J) are identified as directions for future framework extension as the relevant open datasets become available for Turin at the neighbourhood scale. Future work could also incorporate the GUMF and U4SSC frameworks, as discussed in Section 3.1.5, once the necessary data infrastructure is in place.

A key feature of the SNTTool MED is its *contextualization process*: before applying the framework, each city selects the active criteria from the full set of 92 available criteria, defines local benchmarks reflecting minimum acceptable and excellent performance, and assigns domain weights reflecting local planning priorities. The normalization process maps indicator values to a -1 to $+5$ scale, where 0 represents minimum acceptable performance, $+5$ represents excellent performance, and -1 represents performance so poor as to actively detract from sustainability. For this thesis, the -1 to $+5$ scale is converted to a 0-100 equivalent to enable the WLC aggregation procedure and to facilitate comparison of domain scores across indicators with different original scales.

The SNTTool MED's designation of Key Performance Indicators (KPIs) provides a hierarchy within the indicator set: KPIs are mandatory for all partner cities and are linked directly to transnational sustainability reporting. Three KPIs are included in the indicator set applied in this thesis: F1.1 (Performance of the Public Transport System), F2.3 (Bicycle Network), and I3.3 (Permeability of Land).

3.3 GIS Methodology: Use Case 1 — Composite Sustainability Index

3.3.1 Spatial Unit and Coordinate Reference System

The primary spatial unit for Use Case 1 is the ISTAT 2021 "Zona Statistica" (Statistical Zone). Turin's administrative boundary contains 94 statistical zones, with a median area of approximately 1.4 km^2 and a median resident population of approximately 9,030 persons per zone.

Where indicator data are only available at coarser or different spatial resolutions, a two-step harmonization procedure is applied.

Step 1: Map values to census zones (zone di censimento)

- *OMI zone data* (economic indicators): Spatial join of census section centroids to the containing OMI zone, attributing the zone's median values to all contained sections.
- *CAP zone income data* (H1.1 indicator): spatial join of census section centroids to the containing CAP postal code zone, of which Turin has 33.
- *ISTAT zone-level data*: proportional area disaggregation to census sections where direct section-level data are unavailable.

Step 2: Aggregation at Statistical Zone The results from step 1 are then aggregated at the Statistical Zone level, which is a higher nested hierarchy level spatial unit than the census zone.

All vector datasets and spatial operations are conducted in EPSG:3003 (Monte Mario / Italy zone 1), a metric projection optimized for northern Italy. This CRS ensures that distance and area calculations are accurate in metric units without requiring on-the-fly projection, which is critical for the buffer and distance-transform operations used in both use cases.

3.3.2 Weighted Linear Combination for the Composite Index

Each indicator is normalized to a 0–100 suitability scale using the following procedure:

1. Where an external benchmark is available (WHO standard or SNTOL MED reference value), the indicator is normalized using a linear stretch from the minimum acceptable value (score 0) to the ideal value (score 100). For indicators where higher values are better (e.g., green space per capita), the benchmark minimum maps to 0 and the benchmark maximum maps to 100. For indicators where lower values are better (e.g., unemployment rate), the mapping is inverted.
2. Where no external benchmark is available, the indicator is normalized using percentile-based internal normalization: the 5th percentile of the Turin distribution maps to 0 and the 95th percentile maps to 100, clipping values outside this range.
3. SNTOL MED indicators on the -1 to $+5$ scale are converted to 0–100 by the transformation: $\text{Score}_{0-100} = \frac{\text{Score}_{-1 \text{ to } 5+1}}{6} \times 100$.

Domain-level scores are computed as unweighted averages of the normalized indicator scores within each domain. The Composite Sustainability Index is then computed by WLC:

$$\text{CSI} = \sum_{d \in \{A, F, G, H, I\}} w_d \cdot \bar{S}_d \quad (3.1)$$

where w_d is the weight assigned to domain d (summing to 1 across all domains) and $\bar{S}_d$ is the mean normalized score for domain d in the *zona statistica*. In the baseline scenario, equal weights of $w_d = 0.20$ are assigned to each domain. Scenario analysis (Section 6.3.2) varies these weights systematically.

3.3.3 Spatial Analysis Techniques for Use Case 1

Beyond the composite index computation, three spatial analysis techniques are employed for Use Case 1:

Global Moran's I : Applied to the composite index distribution to test for spatial autocorrelation across *zone statistiche*. Queen contiguity is used to define spatial neighbours. A statistically significant positive I indicates clustering of similar scores, validating the neighbourhood-scale interpretation of the index [Mawarni and Machdi \(2016\)](#).

LISA (Local Indicators of Spatial Association): Applied to identify statistically significant spatial clusters (high-high and low-low) and spatial outliers (high-low and low-high) in the composite index distribution ([Anselin, 1995](#)). LISA maps provide a spatially explicit diagnosis of where sustainability scores cluster and where unusual contrasts between adjacent neighbourhoods occur.

Spearman Rank Correlation: Applied to compare neighbourhood rankings across the baseline and three alternative weighting scenarios, identifying robust underperformers (consistently in the bottom quintile) and sensitive switchers (ranking varies substantially with weight changes) [Zar \(2005\)](#).

A cross-tabulation of composite sustainability scores against OMI zone property values is also conducted as an exploratory analysis to test the HPM prediction that neighbourhood quality (N in $P = f(S, N, L)$) is positively correlated with residential property prices.

3.4 GIS Methodology: Use Case 2 — Metro Line 2 Net Suitability Model

3.4.1 Model Architecture: The Two-Step Normalization Pipeline

The Use Case 2 model departs from a standard WLC suitability approach through a strict two-step normalization pipeline that reflects the distinct economic character of accessibility premiums and acoustic disamenity penalties. Figure 3.1 illustrates the pipeline architecture.

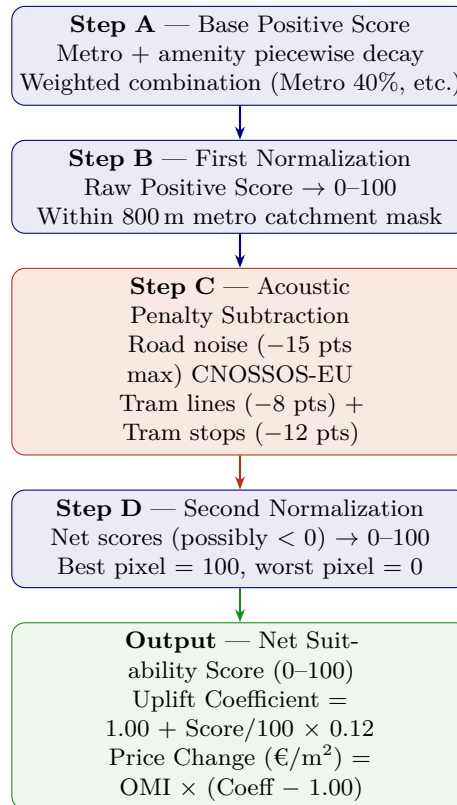


Figure 3.1: The two-step normalization pipeline for the Use Case 2 net suitability model. Positive accessibility scores (Steps A and B) are computed and normalized before acoustic disamenity penalties are subtracted (Step C). A second normalization pass (Step D) ensures the final Net Suitability Score spans the full 0–100 range. The pipeline ensures that noise penalties are proportional to each location’s own accessibility quality.

Step A: Base Positive Score. Euclidean distance from every 5x5m pixel to the nearest instance of each amenity type is calculated using the `distance_transform_edt` function from `scipy.ndimage`. Distances are converted to suitability scores using piecewise linear functions tailored to each feature typology (Table 3.2). A weighted combination of individual feature scores produces the Raw Positive Score.

Step B: First Normalization. The Raw Positive Score is normalized to the 0–100 range using the formula $S_{\text{norm}} = \frac{S - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \times 100$, computed strictly within the 800 m metro station catchment mask. Pixels outside the catchment are set to NaN throughout the pipeline. This first normalization is essential: it ensures that the subsequent noise penalties represent genuine *proportional* deductions from each location’s accessibility quality.

Step C: Acoustic Disamenity Subtraction. Three penalty surfaces are computed and subtracted

simultaneously from the normalized score:

1. *Road noise penalty*: Each pixel is mapped to its nearest road segment using `distance_transform_edt` with `return_indices=True`, which returns the coordinates of the nearest road pixel for every pixel in the study domain. The noise buffer distance for the nearest road segment (calculated from the CNOSSOS-EU formula, Equation 2.4) is retrieved, and a linear decay penalty is applied from the road centreline to the buffer edge, with a maximum penalty of -15 points at the centreline.
2. *Tram line penalty*: A static 50 m buffer from GTT tram line geometry, with a linear decay from -8 points at the line to 0 at the buffer edge.
3. *Tram stop penalty*: A static 100 m buffer from GTT tram stop point geometry, with a linear decay from -12 points at the stop to 0 at the buffer edge.

Step D: Second Normalization. The resulting net scores (which may fall below 0 in heavily penalized areas where multiple noise sources overlap) are re-normalized from 0 to 100 using the same formula as Step B. This second normalization ensures that the final Net Suitability Score spans the full 0–100 range within the metro catchment, enabling the linear economic uplift formula to produce meaningful output.

Table 3.2: Piecewise linear distance-decay parameters for Use Case 2 amenity layers. Detractor buffers create a nuisance zone adjacent to the feature where score rises from 0 (at the feature) to 100 (at the detractor boundary); booster zones reverse this, with score declining from 100 (at the inner booster boundary) to 0 (at the outer booster boundary). Pure detractors impose a score of 0 within the nuisance zone and 100 beyond it.

Feature Type	Layer	Weight (%)	Detractor Radius (m)	Booster Radius (m)	Type
Metro Line 2 stations (Phase I)	stazioni_lotto1	40	150	800	Dual
Metro Line 2 stations (All)	stazioni_linea2	40	150	800	Dual
Scuole d’Infanzia e Primarie	ISTRUZIONE_scuole_prim	15 (combined)	100	400	Dual
Scuole Secondarie (I & II grado)	ISTRUZIONE_scuole_sec		50	500	Dual
Markets	COMMERCIO_mercati	10	100	500	Dual
Hospitals	SOCIO_ospedali	15	300	—	Pure detractor
Carabinieri	SICUREZZA_carab.	5	100	800	Dual
Polizia Municipale	SICUREZZA_pol.m.	5	50	800	Dual
Polizia di Stato / Questure	SICUREZZA_ques.	5 (combined)	250	—	Pure detractor
Vigili del Fuoco	SICUREZZA_vvf		150	—	Pure detractor
Tram lines (noise penalty)	GTT tram geometry	—	50	—	Penalty: -8 pts
Tram stops (noise penalty)	GTT stop points	—	100	—	Penalty: -12 pts
Road noise (CNOSSOS-EU)	TGM segments	—	<i>dynamic</i>	—	Penalty: -15 pts

3.4.2 Technical Implementation

The model is implemented in Python 3.10 using the following libraries:

- **GeoPandas** (version ≥ 0.13): vector data I/O, reprojection to EPSG:3003, geometric operations.
- **Rasterio**: raster I/O, GeoTIFF export with metadata, raster arithmetic.

- `SciPy.ndimage.distance_transform_edt`: Euclidean distance transforms with optional index return for dynamic road noise mapping.
- `NumPy`: array masking, map algebra, logarithmic CNOSSOS-EU calculations, strict normalization.
- `Shapely`: geometry validation and buffering.
- `PyProj`: coordinate reference system handling.

The raster grid is defined at 5x5 m resolution within a bounding box encompassing the Metro Line 2 corridor. This resolution, 25 times finer than the 25x25 m grids used in comparable published studies, enables highly granular decay curves within individual urban blocks and the “acoustic shadow” analysis at sub-block level described in Section 2.4.4. The key algorithmic innovation is the use of `distance_transform_edt` with `return_indices=True`: this parameter causes the function to return not only the distance from each pixel to the nearest road (or amenity) geometry, but also the coordinates of the nearest pixel on that geometry. Because road noise buffer distances vary per road segment based on traffic count and speed data, this approach avoids the need to generate polygon buffers for thousands of individual road segments, enabling dynamic road-specific penalty decay for every pixel simultaneously without topological errors.

Output rasters are saved as GeoTIFF files with EPSG:3003 CRS metadata and hard-coded STATISTICS_MINIMUM and STATISTICS_MAXIMUM tags to ensure correct rendering in QGIS without random-sample approximation errors.

3.4.3 School Buffer Differentiation

Urban real estate literature demonstrates that educational facilities operate as *dual-character* amenities: properties within easy walking distance benefit from the positive accessibility externality of school proximity, yet properties located immediately adjacent to a school are frequently penalized by a set of localized disamenities collectively termed the “School Congestion Effect” or “Drop-off Externalities” (Owusu-Edusei Jr et al., 2007; Sah et al., 2016).

These externalities, including acute vehicular congestion, illegal parking, elevated ambient noise, and road-safety hazards concentrated in morning drop-off and afternoon pick-up windows, are well-documented in the hedonic pricing literature. Owusu-Edusei Jr et al. (2007), using continuous distance modelling, demonstrated empirically that homes located within approximately 150 m of a school sell for less than structurally equivalent homes at 300 m, directly quantifying the “disamenity donut” that justifies the piecewise model specification applied in this thesis. A conventional WLC approach that treats school proximity as a monotonically decaying benefit function would systematically overstate suitability scores for pixels in the immediate school vicinity and understate the relative quality of the sweet-spot ring at intermediate distances.

The magnitude of this proximity penalty is critically dependent on the grade level of the school, since this determines the dominant mobility mode of the student body (Muller-Judex et al., 2025). The net suitability model therefore distinguishes between two school typologies, each with independently calibrated piecewise parameters (Table 3.2):

Primary schools and kindergartens (*Scuole d’Infanzia e Primarie*). Younger children are consistently escorted to school by parents travelling by private vehicle, generating the highest volume of vehicular drop-off and collection traffic. A **detractor zone of 100 m** is applied immediately surrounding each primary school facility: within this radius, the suitability score reflects the congestion and noise disamenity rather than the accessibility benefit. The positive amenity value emerges in the **booster zone of 100–400 m**, a comfortable

adult walking distance with a child, where proximity to a primary school constitutes a clear residential advantage. [Muller-Judex et al. \(2025\)](#) document precisely this spatial pattern for primary schools in a dense European city context, finding that the negative capitalization effect is concentrated in the first 100–150 m and that residential desirability peaks at a slightly removed but still walkable distance.

Secondary schools (*Scuole Secondarie di I e II grado*). Middle and high school students in European urban contexts predominantly travel independently by active mobility (walking, cycling) or public transit, as documented in the mobility survey literature for Turin and comparable Italian cities ([Muller-Judex et al., 2025](#)). The vehicular congestion externality associated with primary school drop-off activity is therefore virtually absent. A narrower **detractor zone of only 50 m** is applied, primarily to capture localized noise from student congregation at school gates, social gathering activity in the immediate vicinity, and the acoustic footprint of school yards during breaks. The **booster zone extends correspondingly to 500 m**, reflecting the greater willingness of older students, and families considering future school commutes, to accept longer walking distances to access secondary education. [Sah et al. \(2016\)](#) confirm this asymmetry, noting that the proximity penalty for primary schools in a dense urban sample was approximately twice the magnitude observed for secondary school facilities, consistent with the differential mobility and congestion profiles.

Table 3.2 summarizes the confirmed parameters for both school typologies alongside all other amenity layers. The effect of these parameter choices on the net suitability surface is assessed as part of the compound disamenity analysis in Chapter 7 (Section 7.6).

3.4.4 Economic Uplift Coefficient Model

The Net Suitability Score is translated into an economic multiplier using a linear interpolation model:

$$\text{Coeff} = 1.00 + \frac{\text{Net_Score}}{100} \times 0.12 \quad (3.2)$$

The coefficient ranges from 1.00 (negligible uplift, corresponding to Net Score = 0) to 1.12 (maximum 12% premium, corresponding to Net Score = 100). The +12% ceiling is calibrated to the meta-analytic range for heavy rail and automated metro systems in dense European urban environments ([Higgins and Kanaroglou, 2016](#); [Mohammad et al., 2013](#)), adjusted downward from the upper end of the published range to reflect the pre-opening, anticipatory character of the predictions and the partial pre-capitalization already reflected in current OMI prices.

The projected price change per pixel is:

$$\Delta P (\text{€m}^2) = P_{\text{OMI}} \times (\text{Coeff} - 1.00) \quad (3.3)$$

where P_{OMI} is the OMI zone median sale price for “abitazione civile” in “normale” condition, spatially joined to each raster pixel via point-in-polygon intersection.

Because acoustic penalties are already embedded in the Net Suitability Score before the coefficient is calculated, no separate noise discount calculation is required: properties in high-noise zones naturally carry lower coefficients, directly reflecting how Italian real estate markets price the combination of transit accessibility and acoustic quality ([Beria et al., 2025](#); [Cascarano and Mocetti, 2022](#)).

3.5 Turin: Urban Context and Study Area Profile

3.5.1 Urban Structure and Post-Industrial Transformation

Turin's urban form reflects three distinct historical periods. The Baroque grid of the historic centre, planned during the House of Savoy's seventeenth-century urban expansion, established the orthogonal street network of the city's core [Kubetskaya and Kudryavtseva \(2023\)](#). The industrial expansion of the late nineteenth and early twentieth centuries extended the city northward and westward, creating dense working-class districts around FIAT's Mirafiori plant and the Lancia and Michelin factories, among others [Museimpresa \(nd\)](#). The post-war economic boom added peripheral residential districts to the south and east, often in the form of large-scale social housing blocks (*case popolari*) that concentrated immigrant labour from southern Italy [De Pieri \(2010\)](#).

The de-industrialization of the 1980s and 1990s transformed this geography profoundly. The closure or downsizing of major industrial facilities released large areas of brownfield land, particularly in the northern and western districts, which became both sites of urban renewal and centres of social deprivation as manufacturing employment declined ([Politecnico di Torino, 2016](#)).

The legacy of this transformation is visible today in the stark north-south gradient of the composite sustainability index expected from Use Case 1: the northern neighbourhoods of Barriera di Milano, Falchera, Rebaudengo, Aurora, and Lucento consistently rank lower on multiple sustainability dimensions than the southern and central areas of Crocetta, Cit Turin, Vanchiglia, and the city centre.

The ongoing PRG revision provides the immediate planning context for this thesis. The PRG (Piano Regolatore Generale) is Turin's master plan, establishing land use designations, development standards, and planning obligations across the entire municipality [Città di Torino \(1995\)](#). The revision process, which has been ongoing in various forms since the 2010s, aims to integrate sustainability commitments, climate adaptation measures, and housing affordability objectives into the regulatory framework. The composite sustainability index developed in this thesis is designed to provide the evidence base for precisely the kind of spatially differentiated, multi-dimensional assessment that a PRG revision and ongoing monitoring requires.

3.5.2 Public Transport Network and Metro Line 2

GTT (Gruppo Torinese Trasporti) operates Turin's integrated public transport network, comprising:

- **Metro Line 1:** Automated, driver-less metro using VAL 308 technology. 21 stations from Fermi (west) to Bengasi (south-east), passing through Porta Nuova and Porta Susa. Operates at a 90-second headway during peak hours [Gruppo Torinese Trasporti \(nd\)](#).
- **Tram network:** 15 active lines using a variety of rolling stock on embedded tracks. The network covers primarily the historic street grid of the city centre and inner residential districts [Tram di Torino \(2024\)](#).
- **Bus network:** Extensive network covering the full municipality and connections to the metropolitan area.

[Zini et al. \(2024\)](#) characterize Turin's PT competitiveness as moderate: the Accessibility Index of 74% indicates that most residents are served, but the Competitiveness Index of 0.18 reveals that PT competes effectively with private car in only 18% of the road network, concentrated in the city centre. The high Moran's *I* of 0.640 for the CI distribution confirms that PT quality is spatially clustered: the centre and Metro Line 1 corridor are well-served, while the northern periphery, precisely the Phase I alignment of Metro Line 2, represents the lowest CI quartile.

Metro Line 2 is designed to address this spatial equity deficit directly. The planned alignment of 23 stations across three phases, with Phase I covering the northern corridor from the Falchera and Rebaudengo districts to

the city centre via Porta Nuova, will extend rapid transit service to neighbourhoods where the current PT offer is limited primarily to surface bus lines. The strategic rationale is thus dual: to close the transport accessibility gap and to catalyze urban regeneration in the post-industrial northern districts [Infra.To \(nd\)](#). Both dimensions are relevant to this thesis, the first through the “Transportation and mobility” sustainability indicator and the second through the analysis of property value uplift and LVC potential.

3.5.3 Turin’s Real Estate Market and Aree di Trasformazione

The Agenzia delle Entrate’s OMI system divides Turin into 47 residential real estate zones, updated semi-annually with minimum, maximum, and median sale and rental prices per square metre for each property typology and condition category. For this thesis, “abitazione civile” in “normale” condition is used as the reference typology, representing the standard mid-range apartment stock that constitutes the majority of the residential market. The OMI values used in the uplift calculations are averages of the 2024 first and second semester data, and where available the first 2025 semester data [Agenzia delle Entrate \(nd\)](#).

The spatial structure of Turin’s real estate market reflects the urban inequality gradient documented above. Zone B areas (“semicentrale”) in the southern and central districts command median sale prices of €2,200–3,500/m². Zone C areas (“periferica”) in the intermediate ring range from €1,800–2,500/m². Zone D areas (“periferica distante”) in the northern periphery and outlying sub-municipalities fall in the range of €1,200–1,800/m². The northern areas targeted by Metro Line 2 Phase I sit predominantly in Zone D, implying that the absolute price change per square metre from the uplift model will be lower in absolute terms than in comparable southern Zone C locations, even where the Net Suitability Score is similar.

Aree di Trasformazione (ZUT — Zone urbane di trasformazione) are the PRG-designated brownfield and redevelopment parcels that represent the primary targets for Contributo Straordinario under D.P.R. 380/2001 ([Governo Italiano, 2001](#)). These parcels are concentrated in the post-industrial northern and western districts, and several are directly within or adjacent to the Metro Line 2 Phase I catchment (see [3.2](#)). The Net Suitability Score and resulting €/m² price change map provide the spatially explicit, parcel-level evidence base for Contributo Straordinario negotiations on these sites, enabling a more granular and transparent LVC basis than the zone-level average values previously available.

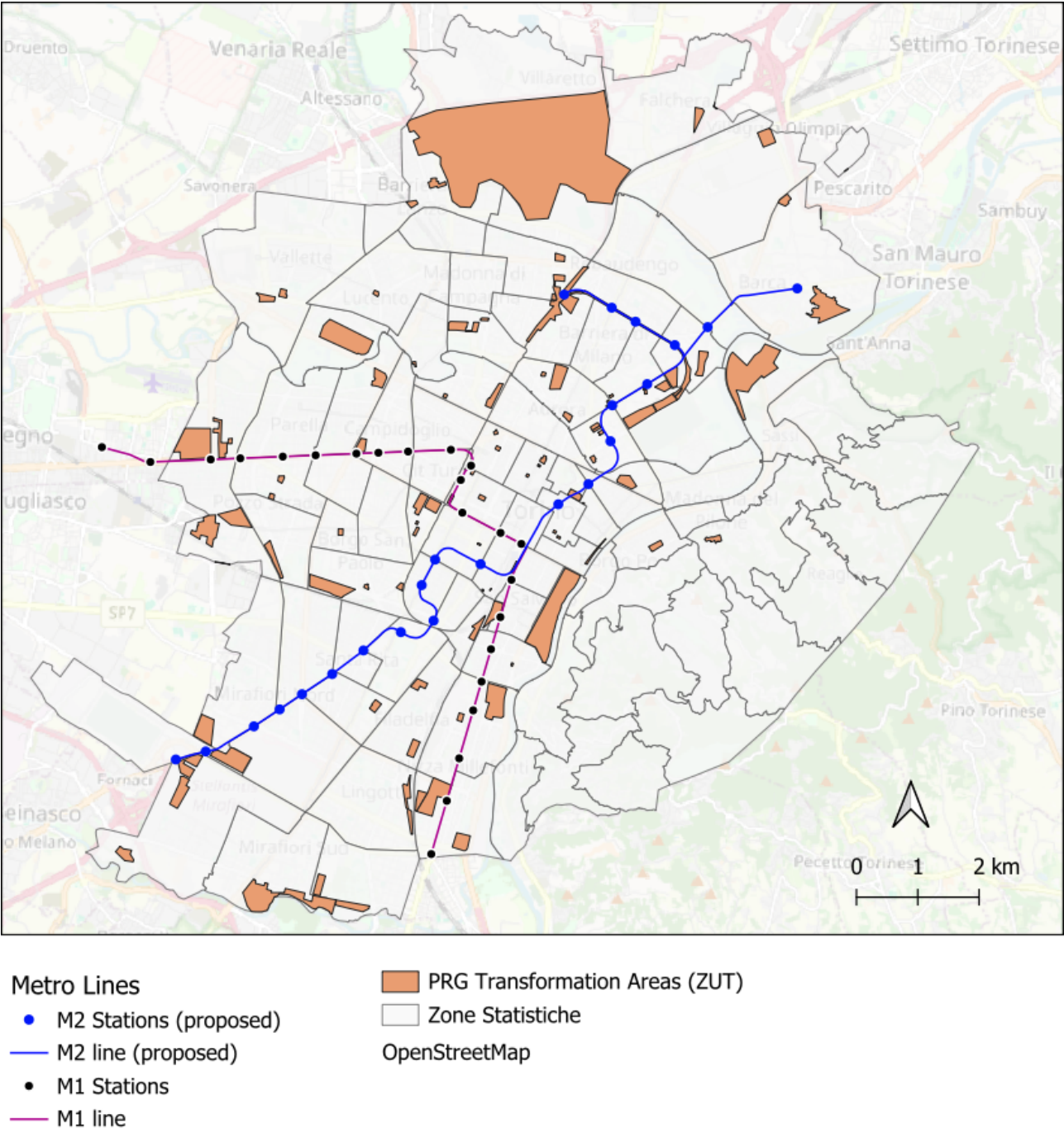


Figure 3.2: Study area overview: City of Turin with Metro Line 1, Metro Line 2, and Aree di Trasformazione (ZUT).

Chapter 4

Indicator Selection

Having reviewed three leading international indicator frameworks and justified the adoption of the SNTTool MED in Chapter 3, this chapter presents the methodology for selecting the specific sustainability indicators applied in Use Case 1. The SNTTool MED encompasses 92 assessment criteria across 10 thematic issues; the indicator selection process determines which subset of these criteria is both calculable from open data for Turin and directly relevant to the PRG monitoring objectives. The chapter provides domain-by-domain justification for each selected indicator with reference to the SNTTool MED framework and the broader literature, and concludes with a complete indicator inventory table (Table 4.1) covering all 24 indicators included in this thesis.

4.1 Selection Methodology

4.1.1 Guiding Principles

The indicator selection process is inspired by the systematic, multi-stage methodology described by [Pellerey and Torabi Moghadam \(2025\)](#) for assessing the effectiveness of Inclusive Climate Actions as Nature-Based Solutions. Their framework, which combines PRISMA-based literature review, Pareto analysis, qualitative compatibility checks, and Fuzzy Delphi Method prioritization involving 34 stakeholders, provides a rigorous and replicable model for evidence-based indicator selection. While the present study does not replicate the full participatory process, it adopts several of the core principles: beginning with a broad identification phase drawing on established frameworks, followed by a systematic refinement process applying explicit criteria.

Five guiding principles govern the selection:

1. **Data availability:** Indicators must be calculable from open data sources available for Turin. Primary sources are the *Geoportale della Città di Torino*, ISTAT (census and administrative data), GTT (GTFS transit data), OpenStreetMap (infrastructure geometry), Agenzia delle Entrate OMI (property market data), and Regione Piemonte (traffic counts, environmental data).
2. **Spatial computability:** Indicators must be computable at the *zona statistica* level. Indicators that are only available at coarser or different resolutions (e.g., CAP zone or zone OMI) are included with explicit documentation of the harmonization method.
3. **Theoretical grounding:** Each indicator must be grounded in the SNTTool MED framework and supported by the broader academic literature on urban sustainability assessment.
4. **Discriminatory power:** Indicators should show meaningful spatial variation across Turin's neighbourhoods. Indicators that exhibit very low variance across sections are retained for completeness if theoretically important, but are noted as candidates for reformulation.

5. **Non-redundancy:** Where two indicators measure closely related dimensions (e.g., green space per capita and green space accessibility), both may be retained if they capture distinct aspects of the same theme, following the SNTTool MED’s practice of using complementary paired indicators. Fully redundant indicators, defined as pairs with a Spearman correlation exceeding 0.95 across the Turin distribution, are reduced to one.

4.1.2 Framework Alignment and Indicator Mapping

A candidate indicator matrix was constructed mapping each SNTTool MED criterion against the five selected Issues (A, F, G, H, I) and the data availability criteria above. The final indicator set was confirmed through this process, with each included indicator traceable to a specific SNTTool MED criterion code. The three SNTTool MED Key Performance Indicators (KPIs) in the selected set, F1.1 (PT System Performance), F2.3 (Bicycle Network), and I3.3 (Land Permeability), were treated as mandatory inclusions. Additional indicators that are also endorsed by the academic literature and international monitoring practice (e.g., F1.1 public transport accessibility; H2.1 employment rate) are noted as having particularly strong theoretical grounding.

4.1.3 Completion Status

All 24 indicators in the analytical framework were fully calculated, validated against the INSPIRE metadata standard, and exported as GeoPackage datasets. Two indicators initially scoped within the SNTTool MED framework (F3.4 Traffic Fatalities, which requires accident geocoding data not yet released at the required spatial resolution; and I1.2 GHG Emissions from Residential Buildings, which requires consolidated building energy performance data) were excluded prior to calculation due to data availability constraints and are noted as future work in Chapter 9.

A post-calculation discriminatory power review, described in Chapter 9, identified that six of the 24 calculated indicators do not provide sufficient spatial variation across Turin’s 94 *zone statistiche* to contribute meaningfully to a composite index. The operative CSI therefore relies on 18 indicators. The present chapter documents the selection rationale and methodology for all 24; the exclusion criteria and individual results for the six non-discriminating indicators are discussed in Chapter 9 and presented in Chapter 6.

4.2 Domain A: Use of Land and Biodiversity

Domain A addresses the use of land and the ecological quality of the urban environment. Green space, urban compactness, and land use mix are foundational sustainability dimensions at neighbourhood scale: they determine the extent to which the built environment supports human health, ecological function, urban heat island mitigation, and climate adaptation (Artmann et al., 2019; Kabisch et al., 2016).

A1.1 Population Density measures the number of inhabitants per square kilometre in the built-up area of each neighbourhood. Population density is a fundamental descriptor of urban form included in virtually all neighbourhood sustainability frameworks (Jabareen, 2006). In the context of this thesis, it serves a dual role: as a sustainability indicator (higher density, within appropriate limits, implies more efficient use of land, infrastructure, and services) and as a spatial key for per-capita normalization of other indicators. The WHO’s criterion of 125 inhabitants/km² as the minimum for viable local service provision and 500 inhabitants/km² as the threshold for optimal service utilization provide the SNTTool MED benchmarks. Data are sourced from the ISTAT 2021 Census. For the specific case of Turin, a highly-urbanized and compact city with an estimated average of 6,585 ha/km² in 2026 (Istituto Nazionale di Statistica, 2026), these benchmarks need to be contextualized and adjusted.

A1.2 Urban Compactness expresses the ratio of building volume (m^3) to urban area (m^2), capturing the intensity of built form. More compact urban forms are associated with lower per-capita energy consumption for transport and heating (Jabareen, 2006) and with the efficient use of land. In Turin, urban compactness varies markedly between the dense historic centre (high compactness) and the peripheral areas characterized by post-war low-rise housing blocks interspersed with surface parking (low compactness). The building volume data are derived from the Geoportale’s *Unità Volumetrica* dataset using a height-weighted area calculation procedure.

A2.1 Availability of Green Urban Areas measures the percentage of each section’s area covered by publicly accessible green space. Green space availability is one of the most consistently identified sustainability priorities in the SNTTool MED and the broader urban sustainability literature (Kabisch et al., 2016; World Health Organization, 2016). The SNTTool MED benchmark of 30% as minimum and 40% as ideal reflects the Mediterranean urban context. Data are sourced from the Geoportale’s green areas layers (area verde and bosco).

A2.2 Green Areas in Relation to the Neighbourhood Population provides a per-capita complement to A2.1, measuring square metres of green space per resident. This dual approach, capturing both spatial coverage and per-capita provision, follows the SNTTool MED’s practice. The combination of A2.1 and A2.2 enables the distinction between areas that have large green spaces but low residential populations (common in peri-urban zones) and densely populated areas where a substantial green fraction still yields low per-capita provision.

A2.3 Green Area Accessibility measures the share of the census section’s residential population living within 300m of a publicly accessible green space of at least 0.5 ha. This accessibility measure goes beyond quantity to assess equitable distribution: a neighbourhood may have a high average green space percentage while concentrating it in areas inaccessible to residents without easy walking access. The 300m threshold reflects the SNTTool MED and aligns with WHO guidance (World Health Organization, 2016). The 0.5 ha minimum size distinguishes meaningful recreational green spaces from small traffic islands or building courtyards. An important limitation is the incomplete classification information between public and private green spaces (specially in the hill areas to the east), which may affect the true availability of a particular green area considered in the calculation of this indicator.

A3.2 Biodiversity in Green Zones assesses the ecological quality of green spaces through the proportion of green areas with significant biodiversity value, operationalized as the share of green area classified as “naturalness” Level 3 or above in the Geoportale classification. This indicator moves beyond quantitative green provision to capture qualitative ecological function, consistent with the Pellerey and Torabi Moghadam (2025) framework, which identified structural and functional connectivity of urban green and blue spaces as a top-ranked KPI in expert consultations. One important limitation is the availability of plant species data for the city, meaning the indicator is mainly relying on the biodiversity of catalogues trees (verde verticale).

4.3 Domain F: Transportation and Mobility

Domain F covers the transport and mobility systems that determine how well residents can move within and through their neighbourhood and the city, with attention to sustainability (modal shift away from private car), equity (accessibility for non-car-owning households), and safety.

F1.1 Performance of the Public Transport System (KPI) measures the percentage of residents within 400m walking distance of at least one public transport stop with a cumulative frequency of at least 20 trips per day. The 400m threshold reflects the SNTTool MED and the established transport planning literature on pedestrian access to transit (Cervero, 2013). The frequency threshold distinguishes “coverage” transit (stops served by infrequent lines) from “frequency” transit (stops with meaningful service throughout the day). As a designated SNTTool MED KPI, this indicator is mandatory for all partner cities. The data source is the GTT

GTFS feed of March 2026, processed using the True Average Daily Frequency methodology (Section 5.3.2).

F2.2 Electric Vehicle Infrastructure (Charging Stations) reports the number of EV charging points per inhabitant. This indicator reflects the European Green Deal’s emphasis on electromobility transition and the SNTTool MED’s Green Mobility category. Its discriminatory power across Turin neighbourhoods is expected to be limited but may reveal policy-relevant patterns in the spatial distribution of EV infrastructure relative to population density.

F2.3 Bicycle Network (KPI) measures the length of bicycle infrastructure per inhabitant (km/1,000 inhabitants). As a SNTTool MED KPI, this is a mandatory and core mobility sustainability dimension. Cycling infrastructure density is associated with modal shift towards active transport, reduced greenhouse gas emissions, and public health benefits (Pucher and Buehler, 2017). Data are sourced from OpenStreetMap highway cycle lane tags, validated against the Geoportale’s transport infrastructure layer.

F3.3 Safety of Bicycle Lanes measures the percentage of bicycle infrastructure that is physically separated from motor vehicle traffic (“dedicated” lanes). This indicator complements F2.3 by assessing quality in addition to quantity: separated infrastructure is substantially more effective than painted lanes at encouraging cycling uptake and reducing cyclist injuries (Pucher and Buehler, 2017). The distinction between painted cycle lanes (on-road markings only) and protected infrastructure (curb separation, dedicated paths) is made using tags for lane type ("POSIZIONE" = 'isolata').

F4.1 Cyclomatic Complexity and F4.2 Connectivity of the Street Network together capture the morphological quality of the urban street grid using space syntax metrics derived from network analysis (Hillier and Hanson, 1984). Cyclomatic complexity (the number of independent loops in the network) and intersection density (intersections per km²) both reflect the degree to which the street network supports multiple route choices, distributes traffic evenly, and facilitates walkability. Both indicators are computed from OSM road network data using *NetworkX* and *OSMnx* graph analysis libraries. A noticeable limitation for both indicators is that it does not account for one-way streets or limited-traffic zones (ZTL), which can significantly alter the connectivity of the street network in a neighbourhood.

4.4 Domain G: Social Aspects

Domain G addresses social sustainability at neighbourhood level, encompassing housing conditions, proximity to essential services, and dimensions of social inclusion. Pellerey and Torabi Moghadam (2025) found that social impact indicators received the highest number of selections as KPIs in their Fuzzy Delphi process, confirming the priority that expert stakeholders assign to social equity in sustainability assessment.

G2.1 and G2.2: Affordability of Housing Property and Rental measure the ratio of median housing costs (sale and rental respectively) to median household income. Housing affordability is a critical determinant of social equity and neighbourhood stability, and its measurement at neighbourhood scale is a central objective of the SNTTool MED’s Social Aspects domain.

The rental affordability calculation uses the formula:

$$\text{RAR} = \frac{P_{\text{rent}} \times S_{\text{unit}}}{\bar{I}_{\text{monthly}}} \quad (4.1)$$

where P_{rent} is the OMI median monthly rental price (EUR/m²), S_{unit} is the assumed unit size (56 m² for a small apartment; 90 m² for a family unit), and $\bar{I}_{\text{monthly}}$ is the mean monthly gross income from the IRPEF data. A ratio below 30% is classified as “healthy”; 30-40% as “strained”; above 40% as “crisis.”

Similarly, the affordability of housing property measures how many years of the mean income it takes to be able to purchase an average house (as per the definitions above) in each of the city’s neighbourhoods.

G2.3 Vacant Residential Units reports the percentage of unoccupied housing in each census section, calculated from ISTAT 2021 Census data. High vacancy rates may indicate neighbourhood decline, speculative holding, or structural housing market mismatches. A key limitation is related to how this data is categorized by ISTAT, in which both vacant and non-resident-occupied residences are reported together in the same field *A3 - Abitazioni vuote e abitazioni occupate solo da persone non residenti*.

G3.1 Availability and Proximity of Key Services measures the share of residents within an 800 m walking distance of at least three key services from a defined basket. The 800 m threshold and the basket composition (supermarkets, pharmacies, post offices, banks, primary healthcare clinics) follow the SNTTool MED contextualization for Turin. This indicator operationalizes the 15-minute city concept (Moreno et al., 2021) at the neighbourhood level.

G3.2 and G3.3: Availability and Proximity of Public Primary and Secondary Schools measure the share of the relevant residential population (census sections with children aged 6–10 for G3.2; sections with youth aged 11–18 for G3.3) within walking distance of public schools. These indicators are grounded in the SNTTool MED contextualization for Turin, which justified their inclusion by reference to the draft PRG revision’s priorities for educational facility accessibility.

G3.4 Availability and Proximity to Children’s Play Facilities measures the share of the population within 300 m of a designated children’s play area. Data are sourced from the *giochi_bimbi* attribute in the Geoportale’s green areas layer (060401_AREA_VERDE).

G3.5 Outdoor Public Spaces measures the percentage of the built-up area of the neighbourhood (urban areas excluding "green" and "blue" areas) that is open space for public use. Data was sourced from the *Carta Tecnica Comunale* (CTC), updated in November 2025 for roads, bike lanes and pedestrian zones. Data from GEOPORTALE SERVIZI was also incorporated to consider Public Markets, Sports Facilities, and cemeteries.

4.5 Domain H: Economy

Economic indicators capture the prosperity, employment conditions, and income levels that determine neighbourhood economic vitality. The economic domain links the sustainability framework to the property market analysis of Use Case 2: a positive correlation between economic domain scores and OMI property values would confirm that neighbourhood economic quality is capitalized into real estate prices, consistent with HPM theory.

H1.1 Average Annual Per-Capita Income provides a direct measure of economic prosperity using IRPEF (Imposta sul Reddito delle Persone Fisiche) data for 2023, available from the Ministry of Economy and Finance at the CAP postal code zone level. The “Reddito complessivo medio” (mean total declared income) is used as the primary variable. The spatial granularity is limited by the availability of IRPEF data at CAP level only (33 zones for Turin), representing a coarser spatial resolution than the census section. The indicator is joined to census sections through spatial attribution of the containing CAP zone.

H2.1 Employment Rate (Revised) This indicator has been revised from the original framework to track the employment rate of adults aged 25–64 as per the data provided by the 2021 IDISE publication by ISTAT at the sub-comune level (zona statistica) (Istituto Nazionale di Statistica, 2023a). Benchmarks have been set according to the national employment rate for the year 2021, the same year the IDISE data was compiled (Istituto Nazionale di Statistica, 2023b). This was supplemented by employment data in Trentino Alto-Adige, the Italian region with the highest human development index (Provincia Autonoma di Trento, 2024b).

H2.2 Youth Unemployment Rate This indicator has been revised to measure the proportion of individuals aged 15 to 29 that are Not in Employment, Education or Training (NEET). This data was provided by the 2021 IDISE publication by ISTAT and aggregated at the sub-comune level (zona statistica) (Istituto Nazionale di Statistica, 2023a). Benchmarks have also been customized based on the national Italian average for 2021,

where 23.3 percent of people aged 15 to 29 we classified as NEET (Istituto Nazionale di Statistica, 2021), with the optimal result (benchmark 5) being set to the average of Trentino Alto-Adige in 2021: 15.45 (Provincia Autonoma di Trento, 2024a).

4.6 Domain I: Climate Change

Climate and energy indicators address both Turin’s contribution to greenhouse gas emissions (mitigation) and its vulnerability to climate impacts (adaptation). Pellerey and Torabi Moghadam (2025) found that morbidity and mortality associated with climate change received the highest fuzzy score (0.707) of all 29 indicators evaluated in their expert consultation, confirming the priority stakeholders assign to climate-related assessment. Domain I is represented in this thesis by the SNTTool MED KPI I3.3 (Land Permeability). The GHG emissions indicator (I1.2) was scoped within the framework but excluded from the final set due to the unavailability of consolidated building energy performance data at the *zona statistica* level, and is designated as future work.

I3.3 Permeability of Land (KPI) measures the percentage of permeable surface (green areas, unsealed soils) relative to total urban area in each Statistical Zone. As a SNTTool MED KPI, this indicator captures both climate adaptation (storm water management, groundwater recharge) and biodiversity (soil ecosystem function) (European Environment Agency, 2024). The indicator was revised to reflect the available data and tracks the percentage of neighbourhood land covered by permeable surfaces as per the soil use categorization from Land Cover Piemonte 2023. Benchmarks were contextualized to reflect a dense urban environment of a city like Turin, with the optimal performance set to 80 percent of a neighbourhood’s land covered by permeable surfaces.

4.7 Complete Indicator Inventory

Table 4.1 provides a complete inventory of the 24 SNTTool MED indicators included in the sustainability framework. Columns indicate the indicator code, name, KPI designation, unit of measure, and benchmark thresholds where applicable.

Table 4.1: Complete indicator inventory for the Turin neighbourhood sustainability framework (24 SNTTool MED indicators).

Code	Indicator Name	FrameworkKPI	UoM	Benchmarks (min → target)
<i>Domain A — Land Use and Biodiversity (SNTTool MED Issue A)</i>				
A1.1	Population Density	SN	inh/km ²	125 → 500
A1.2	Urban Compactness	SN	m ³ /m ²	2 → 3
A2.1	Availability of Green Urban Areas	SN	%	30 → 40
A2.2	Green Areas per Inhabitant	SN	m ² /inh	5 → 50
A2.3	Green Area Accessibility (300 m)	SN	% pop	20 → 100

Continued on next page

(Table 4.1 continued)

Code	Indicator Name	Framework	KPI	UoM	Benchmarks
A3.2	Biodiversity in Green Zones	SN		%	0.001 → 1
<i>Domain F — Transportation and Mobility (SNTool MED Issue F)</i>					
F1.1	PT System Performance	SN	✓	% pop	30 → 70
F2.2	EV Charging Infrastructure	SN		n/inh	0.01 → 0.05
F2.3	Bicycle Network Density	SN	✓	km/1k inh	5 → 40
F3.3	Safety of Bicycle Lanes	SN		% ded.	20 → 50
F4.1	Street Network Cyclo-matic Complexity	SN		cycl. no.	30 → 100
F4.2	Street Network Connectivity	SN		inter/km ²	70 → 200
<i>Domain G — Social Aspects (SNTool MED Issue G)</i>					
G2.1	Housing Purchase Affordability	SN/U4		% income	20 → 30
G2.2	Housing Rental Affordability	SN/U4		% income	30 → 20
G2.3	Vacant Residential Units	SN		%	5 → 7
G3.1	Proximity of Key Services	SN		% pop	50 → 100
G3.2	Proximity to Primary Schools	SN		% pop	40 → 70
G3.3	Proximity to Secondary Schools	SN		% pop	30 → 80
G3.4	Proximity to Play Facilities	SN		% pop	20 → 40
G3.5	Outdoor Public Spaces	SN		Index	25 → 34
<i>Domain H — Economy (SNTool MED Issue H)</i>					
H1.1	Per-Capita Income	SN		%	60 → 90
H2.1	Employment Rate (25–64)	SN		%	58 → 78
H2.2	Youth NEET Rate (15–29)	SN		%	23 → 15
<i>Domain I — Climate Change: Mitigation and Adaptation (SNTool MED Issue I)</i>					
I3.3	Land Permeability	SN	✓	%	20 → 80

Key: SN = SNTool MED. KPI: ✓ = Key Performance Indicator (SNTool MED designation).

4.8 Discussion of Selection Approach

A notable feature of the final indicator set is the concentration of core sustainability dimensions that the academic literature identifies as essential at neighbourhood scale: public transport accessibility, cycling infrastructure, green space provision, housing affordability, employment, and land permeability are all included and have been fully calculated. The SNTTool MED's multi-city contextualization process, which includes Turin as a partner city, gives additional confidence that the benchmarks applied are appropriate for the Mediterranean urban context.

The primary methodological challenge encountered was spatial resolution harmonization. The SNTTool MED was designed for city-level reporting, and adapting its indicators to the *zona statistica* scale required careful attention to data availability and join methodology. The coarser resolution of income data (CAP level) and some employment/NEET data (sub-comune level) is a limitation that future work could address through access to ISTAT microdata or administrative tax records at finer spatial resolution.

Two indicators initially scoped within the SNTTool MED framework, F3.4 (Traffic Fatalities) and I1.2 (GHG Emissions from Residential Buildings), were excluded from the final set due to data availability constraints within the thesis timeline. Their exclusion is acknowledged as a limitation in Chapter 9, where it is also noted that their expected spatial patterns are broadly consistent with the indicators that are included.

City-average domain scores for Turin Here are the average scores for the 94 statistical zones in Turin, assigning equal weights to all domains and equal weights to all indicators within each issue.

Domain	Simple average	Population-weighted
A-Use of Land and Biodiversity	2.496	2.305
F-Transportation and mobility	0.749	0.935
G-Social Aspects	2.890	3.409
H-Economy	3.744	3.561
I-Climate Change	0.957	0.087
Mean overall score	2.1672	2.059

Table 4.2: SN Tool domain average scores for Turin

We present both the simple average for each domain and the population-weighted mean, based on the resident population in each statistical zone.

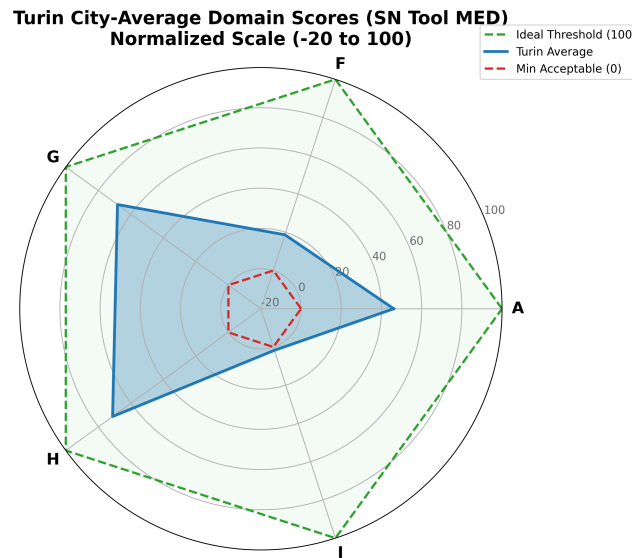


Figure 4.1: Radar chart of Turin city-average domain scores (A, F, G, H, I) on the -20–100 normalized scale, shown against the SNTool MED minimum acceptable threshold (score 0) and ideal threshold (score 100), population-weighted

A key step of the application of the SN Tool is contextualization to the local reality. This can be achieved by adjusting the score benchmarks (e.g. changing the minimum or ideal thresholds) or changing the way the scores are calculated. Details of how the SN Tool was contextualized to fit the local reality and allow for a meaningful comparison between Turin's neighbourhoods are detailed in the Use Case 1 chapter.

Chapter 5

Data Sources, Geoprocessing, and Indicator Calculation

This chapter documents the data sources, geoprocessing environment, and calculation procedures for all spatial outputs produced in this thesis. Section 5.1 catalogues the primary data sources with acquisition details and licensing information. Section 5.2 describes the technical stack. Sections 5.4–5.9 detail the calculation procedures for each indicator domain and for the Use Case 2 model. Section 5.10 summarizes INSPIRE metadata compliance. Section 5.11 discusses data limitations and uncertainty.

5.1 Data Sources and Acquisition

All data sources used in this thesis are open access, freely available for non-commercial research use, and documented with sufficient provenance information to ensure reproducibility.

5.1.1 Geoportale della Città di Torino

The Geoportale (<https://geoportale.comune.torino.it>) is the primary geospatial data repository for the City of Turin, maintained by the Settore Urbanizzazione Territorio (SUT). The following datasets are used:

- **Building Stock (020102_EDIFICIO)**: Vector polygon layer of all buildings in Turin with attributes including category of use (*CATEG_USO*), construction era (*EPOCA_COST*), number of floors (*NUM_PIANI*), and footprint area (*SUPERFICIE*). Derived layers include *EDIFICIO_RESIDENZIALE* (residential buildings filtered by category), *EDIFICIO_COMMERCIALE* (commercial), and *EDIFICIO_INDUSTRIALE* (industrial).
- **Volumetric Units (UNITA_VOLUMETRICA)**: A dataset linking each building to its volumetric partition, with gross volume calculated using floor height attribution. For units with a known floor height (*ALTEZZA_VO*), $\text{volume} = \text{footprint} \times \text{height}$. For units lacking height data, a standard floor height of 3.3 m is assumed per floor, derived from *NUM_PIANI*.
- **Green Areas (060401_AREA_VERDE)**: Polygon layer of all green spaces with typology attributes including park type and, critically, the *giochi_bimbi* attribute identifying children’s play facilities.
- **Educational Facilities (GEOPORTALE_ISTRUZIONE_scuole_geo)**: Point layer of all public and private schools with type classification enabling differentiation by school level.
- **Healthcare Facilities (GEOPORTALE_SOCIO_SANITARI_ospedali_geo)**: Point layer of hospitals.

- **Commercial facilities (GEOPORTALE_COMMERCIO_mercati_geo):** Polygon layer of markets.
- **Public Safety Facilities:** Point layers for Carabinieri, Polizia Municipale, Questure/Commissariati (Polizia di Stato), and Vigili del Fuoco.
- **Street Network:** Road centre line layer used for walkability service area analysis and CNOSSOS-EU noise buffer generation.

All Geoportale datasets are provided under the CC BY 3.0 IT licence (Attribution Italy).

5.1.2 ISTAT 2021 Census

The 2021 Population and Housing Census provides:

- **Sezioni di Censimento boundaries:** Administrative polygons defining the 1,800 census sections within Turin's administrative boundary. Projection: EPSG:4326; reprojected to EPSG:3003.
- **Population data:** Total resident population ($P1$) and total population including registered foreigners ($P1+ST1$) per section.
- **Housing data:** Total dwelling stock, occupied dwellings, and vacant dwellings (*Vacant_Invest_home_percent* field) per section.
- **Educational attainment:** Population by highest qualification, available as a supplementary dataset for future indicator development.

5.1.3 GTT GTFS Feed (March 2026)

The General Transit Feed Specification (GTFS) data package released by GTT for March 2026 (*gtt_gtfs.zip*) provides:

- **stops.txt:** Point geometry of all transit stops in the GTT network (bus, tram, Metro Line 1).
- **routes.txt, trips.txt:** Route and trip schedule data enabling frequency calculation.
- **calendar.txt, calendar_dates.txt:** Service calendar and exception dates (holidays, special events).
- **shapes.txt:** Line geometry for all routes, used to extract tram network geometry for noise buffer generation.

Processing steps are detailed in Section 5.3.2. The resulting high-frequency stop layer (*GTT_20_trip_stops_Mar_2026_3003.gpkg*) serves as the input for F1.1.

5.1.4 Regione Piemonte: TGM Traffic Data

The Traffico Giornaliero Medio (TGM) dataset from Regione Piemonte provides per-segment daily vehicle counts for Turin's road network. The key attributes used are:

- **mfwl_sum:** Total daily light vehicle count (both directions combined).
- **mfwp_sum:** Total daily heavy vehicle count.
- **aspd_med:** Mean vehicle speed in km/h. Where NULL or 0, a standard urban speed of 50 km/h is imputed.

These attributes are the inputs to the CNOSSOS-EU road noise buffer calculation (Section 5.8).

5.1.5 Agenzia delle Entrate: OMI Data

The Osservatorio del Mercato Immobiliare (OMI) data is downloaded from the Agenzia delle Entrate open data portal covering the period 2015–2025. The processing steps are:

1. Download “Prezzi” files for each semester from 2015S1 to 2025S1.
2. Standardize column headers and merge all semesters into a single table.
3. Calculate average sale price (*Compr_Medio*) as the mean of minimum and maximum reported prices.
4. Calculate average rental price (*Loc_Medio*) similarly.
5. Filter for *Tipologia* = “Abitazioni Civili” and *Stato* = “NORMALE” as the reference category.
6. Compute averages of the 2024S1, 2024S2, and (where available) 2025S1 semesters for the baseline property price used in the uplift model.
7. Join to the OMI zone polygon layer (*zone_omi_2025_3003_base*) for spatial attribution.

5.1.6 Ministry of Economy and Finance: IRPEF Data

Income data are sourced from the Ministry of Economy and Finance’s 2023 IRPEF sub-municipal dataset, providing tax declaration statistics at the CAP postal code zone level. The dataset includes mean total declared income (*Reddito_complessivo_medio*) and the percentage distribution of taxpayers across income brackets. After filtering for *Comune* = Torino and calculating zone-level averages, the data are joined to CAP zone polygons sourced from zornade.com (OpenStreetMap-derived boundaries under ODbL licence) and subsequently attributed to census sections via spatial join.

5.1.7 OpenStreetMap

OpenStreetMap (ODbL licence) data is used for cycling infrastructure (*highway=cycleway* and related tags) and pedestrian infrastructure assessment. Data are extracted using the *OSMnx* Python library and validated against the Geoportale’s street network where discrepancies are identified.

5.1.8 Land Cover Piemonte 2023 (LCP2023)

The Land Cover Piemonte 2023 (LCP2023) dataset, distributed by the Geoportale Infrastruttura Geografica Regionale (IGR) of Regione Piemonte, provides a detailed land cover classification of the Piedmont region. For this thesis, it serves as the primary data source for indicator I3.3 (Land Permeability), supplying a soil use classification from which permeable and impermeable surface categories are derived at neighbourhood scale. Each statistical zone’s permeability score is computed as the share of its area classified as permeable land cover under the LCP2023 taxonomy. The dataset is available under CC BY 3.0 IT licence (Attribution: Geoportale IGR Piemonte).

5.2 Geoprocessing Environment and Technical Stack

All spatial processing is conducted using Python 3.10 within a reproducible virtual environment. The core libraries and their primary functions are:

- **GeoPandas** (≥ 0.13): Vector data I/O (Shapefile, GeoPackage, GeoJSON), coordinate reference system operations, spatial joins, buffer generation, and dissolve operations.
- **Rasterio** (≥ 1.3): Raster I/O (GeoTIFF), raster arithmetic, coordinate transform, and GeoTIFF metadata management.
- **SciPy.ndimage**: Distance transform calculations (`distance_transform_edt` with `return_indices=True`) for amenity proximity and road noise penalty generation.
- **NumPy**: Array-based map algebra, logarithmic CNOSSOS-EU calculations, normalization, and `np.nan` masking.
- **Shapely**: Geometric validation, buffering, and polygon operations.
- **PyProj**: CRS definition and transformation.
- **OSMnx**: OpenStreetMap network extraction and graph analysis for street network indicators.
- **NetworkX**: Graph-theoretic calculations for cyclomatic complexity and connectivity indicators.
- **Fiona**: GeoPackage format I/O with CRS metadata preservation.
- **Pandas**: Tabular data manipulation for GTFS, IRPEF, and OMI datasets.

Visual quality assurance and cartographic output are produced in QGIS 3.34 LTS (Prizren). All vector outputs are exported as GeoPackage (.gpkg) format, conforming to the OGC standard and supporting multiple layers in a single file with embedded EPSG:3003 projection metadata. Raster outputs are exported as GeoTIFF with full EPSG:3003 georeferencing and STATISTICS metadata tags.

The coordinate reference system EPSG:3003 (Monte Mario / Italy zone 1) is used throughout. This CRS is a metric transverse Mercator projection optimized for northern Italy, ensuring that all distance and area calculations are performed in metres and square metres without geographic distortion.

5.3 Spatial Unit Definition and Population Attribution

5.3.1 Population Coefficient Methodology

For indicators requiring per-capita normalization at sub-section level, a population coefficient approach is employed. The ISTAT census provides total resident population ($P1$) and non-resident registered population ($ST1$) at section level. The ratio of residential population to total residential useful surface area ($Superficie_Utile$) within each section, calculated from the volumetric units dataset, provides a population coefficient expressed in inhabitants/m² of useful residential floor area:

$$k_{\text{res}} = \frac{P1}{\sum_i S_{\text{utile},i}} \quad (5.1)$$

where the sum is over all residential buildings i within the census section. This coefficient can be applied to individual buildings to estimate their resident population, enabling building-level population attribution for service accessibility indicators. The methodology is documented in the working metadata file `Population Coefficient.txt`.

5.3.2 PT Accessibility: GTT Stop Selection

The identification of high-frequency transit stops follows a three-stage procedure documented in detail in the working metadata file `Processing steps for GTFS data.txt`:

1. **Temporal expansion:** The GTFS calendar and calendar_dates files are cross-referenced to produce a service truth table listing, for each service ID, the specific dates on which it operated during the GTFS schedule period. This accounts for holiday reductions and special event additions.
2. **Route-level frequency:** For each route, average daily trips = total scheduled trips / total operating days.
3. **Stop-level aggregation and thresholding:** For each stop, the frequencies of all serving routes are summed. Stops with a cumulative total below 20 trips/day are excluded. The 20 trips/day threshold corresponds to approximately one service every 45 minutes over a 15-hour service day, the boundary between “coverage” and “frequency” transit as defined in transport planning practice.

The resulting dataset (`GTT_20_trip_stops_Mar_2026_3003.gpkg`) contains 1,247 high-frequency stops distributed across Turin. A 400 m service area (non-network Euclidean buffer) is generated from these stops; residential buildings with centroids within the service area are attributed with `within_400m_GTT = 1`. The F1.1 indicator score for each section is then the share of the section’s residential population (from the population coefficient) that is within 400 m of a high-frequency stop.

5.4 Indicator Calculation: Domain A — Land Use and Biodiversity

5.4.1 A1.1 Population Density

Resident population ($P1$) from ISTAT 2021 divided by built-up area in km^2 (section area minus water bodies and non-urban land). Benchmark normalization: $\leq 125 \text{ inh}/\text{km}^2$ maps to score 0; $\geq 500 \text{ inh}/\text{km}^2$ maps to score 100.

5.4.2 A1.2 Urban Compactness

Total building volume within the section (from `UNITA_VOLUMETRICA`) divided by section area. Benchmark: $\leq 2 \text{ m}^3/\text{m}^2$ maps to score 0; $\geq 3 \text{ m}^3/\text{m}^2$ maps to score 100.

5.4.3 A2.1 Green Space Coverage

Total area of Geoportale green space polygons within each section, divided by section area. Benchmark: $\leq 30\%$ maps to score 0; $\geq 40\%$ maps to score 100.

5.4.4 A2.2 Green Space per Capita

Total green space area within section / resident population. Benchmark: $\leq 5 \text{ m}^2/\text{inh}$ maps to score 0; $\geq 50 \text{ m}^2/\text{inh}$ maps to score 100.

5.4.5 A2.3 Green Space Accessibility

For each residential building centroid, a 300 m buffer is generated. The building is classified as “within 300 m” if the buffer intersects a green space polygon of ≥ 0.5 ha. The section score is the share of residential population in buildings meeting this criterion.

5.4.6 A3.2 Biodiversity in Green Zones

The share of the section’s green space area classified as “naturalness Level 3 or above” in the Geoportale typology. The indicator is scored so that a higher share of high-naturalness green space maps to a higher score. As noted in Chapter 9, this indicator was ultimately excluded from the composite CSI due to data limitations that restrict the biodiversity measure to catalogued tree species only, limiting its discriminatory power across *zone statistiche*.

5.5 Indicator Calculation: Domain F — Transport and Mobility

5.5.1 F1.1 PT System Performance

Procedure detailed in Section 5.3.2. Score: share of section residential population within 400 m of a ≥ 20 trips/day GTT stop. Benchmark: $\leq 30\%$ maps to score 0; $\geq 70\%$ maps to score 100.

5.5.2 F2.2 EV Charging Infrastructure

Number of publicly accessible EV charging points within the section (sourced from the Geoportale EV layer) divided by resident population $\times 1,000$. Benchmark: ≤ 0.01 points/1k inh maps to score 0; ≥ 0.05 maps to score 100.

5.5.3 F2.3 Bicycle Network Density

Total length of bicycle infrastructure within the section (km, from OSM cycleway tags validated against Geoportale) divided by resident population $\times 1,000$. Benchmark: ≤ 5 km/1k inh maps to score 0; ≥ 40 maps to score 100.

5.5.4 F3.3 Safety of Bicycle Lanes

Length of physically separated (protected) bicycle infrastructure / total bicycle infrastructure length. Benchmark: $\leq 20\%$ maps to score 0; $\geq 50\%$ maps to score 100.

5.5.5 F4.1–F4.2 Street Network Morphology

The street network for each section is extracted from OSM using **OSMnx**. Cyclomatic complexity is calculated as $m - n + 1$, where m is the number of edges and n the number of nodes in the section’s network subgraph. Connectivity is calculated as intersections/km².

5.6 Indicator Calculation: Domain G — Social Aspects

5.6.1 G2.1 and G2.2: Housing Affordability

The price-to-income ratio (median multiple - for buying a property) and rental affordability ratio (rental) are computed using 2024-2025 average OMI zone prices joined to Statistical Zones and IRPEF income data joined at CAP level, following the formulas documented in the working metadata file `Housing Affordability.txt`.

To calculate affordability, a hypothetical, entry-level housing unit for a family of 4 is used. This is estimated as an apartment of 56 m², based on the minimum size requirements for 4 people: *For the first 4 inhabitants: At least 14 m² per person (14 x 4 = 56 m²)* (Ministero della Sanità, 1975).

The estimated monthly rental price is calculated by multiplying the average monthly rental for the period 2024-2025 for "abitazione civile", with a 'stato' of "normale" in the OMI zones (Agenzia delle Entrate, nd) corresponding to the Statistical Zone in question by 56.

Since the OMI zones do not correspond to the Statistical Zones, a two-step process is used to assign the OMI-zone average price to all residential properties in the city (EDIFICIO RESIDENZIALE - point on surface), then calculate the average of these prices at the Statistical Zone level (See detailed methodology appendix for further information).

A similar process is used to estimate the average sale price for the entry-level, 56 m² property in those zones.

An annual income of €15,000 is used a simple way to represent low income status for the calculation purposes, in line with *Regione Piemonte* legislation that determines regional taxes to be collected (Regione Piemonte, 2022).

Since income information is only available at the CAP-level, a two-step process was also applied to determine the average income at the Statistical Zone level, with Census Zone (Zone di Censimento - point on surface) used as an intermediary (See detailed methodology appendix for further information).

Benchmarks were established from Q4-2025 rental market data compiled by *idealista* (grey literature; used for benchmark calibration only) (idealista/news, 2026) and can be defined as follows:

Benchmark 0: (minimum acceptable) 40 percent of monthly salary spent on rent Benchmark 5: (ideal) 20 percent of monthly salary spent on rent.

Individuals spending more than 40 percent of their monthly salary on rent can be considered to be in a critical situation (score -1).

To estimate and contrast the affordability of buying an entry-level property, we have used the median multiple of how many years of the average and low income salaries it takes to purchase an entry level small and family-sized units in various neighbourhoods. The benchmarks were established in line with the national average in 2025, according to *idealista* (Idealista, 2025) (grey literature; used for benchmark calibration only).

5.6.2 G2.3 Vacant Residential Units

Directly from the ISTAT 2021 census section dataset, field `Vacant_Invest_home_percent`.

5.6.3 G3.1–G3.4: Service and Facility Proximity

For each service type, residential building centroids within the specified walking distance are identified using Euclidean distance. The section score is the share of the section's residential population in buildings meeting the distance criterion, using the population coefficient from Section 5.3.1.

5.7 Indicator Calculation: Domains H and I

5.7.1 H1.1 Per-Capita Income

Mean total declared income (*Reddito_complessivo_medio*) from the 2023 IRPEF dataset at CAP level, joined to census sections via spatial containment. The benchmark score reflects the section's mean income as a percentage of the national average (approximately €26,000 annually). Benchmark: $\leq 60\%$ maps to score 0; $\geq 90\%$ maps to score 100.

5.7.2 H2.1 Employment Rate (25–64)

Employment rate data are sourced from the 2021 IDISE publication by ISTAT ([Istituto Nazionale di Statistica, 2023a](#)), which provides sub-municipal employment statistics disaggregated to the *zona statistica* level. The indicator measures the share of the population aged 25–64 that is employed. Benchmarks are anchored to the Italian national employment rate for 2021 (approximately 58%) as the minimum acceptable threshold, and the employment rate of Trentino-Alto Adige (approximately 78%) as the target value: Benchmark: $\leq 58\%$ maps to score 0; $\geq 78\%$ maps to score 100. Output: `ASC_H2_1_Employment_Rate_IND.gpkg`.

5.7.3 H2.2 Youth NEET Rate (15–29)

The NEET (Not in Employment, Education, or Training) rate for the 15–29 age cohort is sourced from the 2021 IDISE publication by ISTAT ([Istituto Nazionale di Statistica, 2023a](#)). The indicator is inverted for scoring purposes, since lower NEET rates represent better performance. Benchmarks are set to the national Italian average for 2021 (23.3%) as the maximum acceptable threshold and to the Trentino-Alto Adige average (15.45%) as the target value ([Provincia Autonoma di Trento, 2024a](#)). Benchmark: $\geq 23\%$ maps to score 0; $\leq 15\%$ maps to score 100. Output: `ASC_H2_2_Youth_Unemployment_IND.gpkg`.

5.7.4 G3.5 Outdoor Public Spaces

Data for this indicator were sourced from the *Carta Tecnica Comunale* (CTC), updated November 2025 for roads, bike lanes, and pedestrian zones, supplemented by the Geoportale SERVIZI layer for public markets, sports facilities, and cemeteries. The indicator measures the percentage of the built-up area of each zone (urban area excluding green and blue spaces) that is publicly accessible open space. Benchmark: $\leq 25\%$ maps to score 0; $\geq 34\%$ maps to score 100. Output: `ASC_G3_5_Outdoor_Public_Spaces_IND.gpkg`.

5.7.5 I3.3 Permeability of Land (KPI)

Permeable surface area within each statistical zone is derived from the Land Cover Piemonte 2023 (LCP2023) dataset, using the soil use classification to identify permeable land cover categories (green areas, unsealed soils, natural surfaces). The zone score is the share of its total area classified as permeable. Benchmarks are contextualized to reflect Turin's dense urban environment: $\leq 20\%$ maps to score 0; $\geq 80\%$ maps to score 100. Output: `ASC_permeable.gpkg`.

5.8 CNOSSOS-EU Road Noise Buffer Calculation

The road noise buffer calculation applies the CNOSSOS-EU simplified A-weighted macro equations to every road segment in the TGM dataset with non-zero traffic counts. The procedure, documented in the methodology

file `Torino_Noise_Buffer_Methodology.txt`, consists of five steps:

Step 1: Hourly flow conversion.

$$Q_l = \frac{\text{mfwl_sum}}{24} \qquad Q_h = \frac{\text{mfwp_sum}}{24} \qquad (5.2)$$

Step 2: Single-vehicle sound power.

$$L_{W,l} = 94.0 + 30 \cdot \log_{10}\left(\frac{v}{50}\right) \qquad (5.3)$$

$$L_{W,h} = 106.0 + 20 \cdot \log_{10}\left(\frac{v}{50}\right) \qquad (5.4)$$

Step 3: Line-source emission per metre of road.

$$L'_{W,l} = L_{W,l} + 10 \cdot \log_{10}\left(\frac{Q_l}{v}\right) - 30 \qquad (5.5)$$

$$L'_{W,h} = L_{W,h} + 10 \cdot \log_{10}\left(\frac{Q_h}{v}\right) - 30 \qquad (5.6)$$

$$L'_{W,\text{total}} = 10 \cdot \log_{10}\left(10^{L'_{W,l}/10} + 10^{L'_{W,h}/10}\right) \qquad (5.7)$$

Step 4: Buffer distance calculation.

Using cylindrical geometric divergence propagation and inverting for the 60 dB(A) Class III mixed residential threshold:

$$d = 10^{(L'_{W,\text{total}} - 60 - 5)/10} \qquad (5.8)$$

Road segments with $d < 0$ (baseline noise already below threshold at zero metres) receive a 0 m buffer.

Step 5: GeoPackage export.

Buffers are generated using the GeoPandas `.buffer(d)` method in EPSG:3003 and exported as polygon features with the calculated buffer distance stored as an attribute. The resulting variable-width polygon dataset is the primary input to the city-wide noise exposure map and to the UC2 road noise penalty raster.

5.9 UC2 Geoprocessing: Raster Pipeline

The raster-based net suitability model for Metro Line 2 is implemented as described in Chapter 3, Section 3.4. The key intermediate outputs and their GeoTIFF file descriptions are:

- `Raw_Positive_Score.tif`: Weighted sum of individual amenity decay surfaces before first normalization. Range: 0 to 100 (raw scale).
- `Normalized_Positive_Score.tif`: Raw Positive Score normalized to 0–100 within the 800 m metro catchment mask. Values outside the catchment are NaN.
- `Road_Noise_Penalty.tif`: Road CNOSSOS-EU penalty surface, values in $[-15, 0]$.
- `Tram_Line_Penalty.tif`: Tram line 50 m buffer penalty surface, values in $[-8, 0]$.
- `Tram_Stop_Penalty.tif`: Tram stop 100 m buffer penalty surface, values in $[-12, 0]$.
- `Combined_Penalty.tif`: Sum of the three penalty surfaces.
- `Net_Score_Prenorm.tif`: Normalized Positive Score minus Combined Penalty. May fall below 0 in compound nuisance zones.

- `Net_Suitability_Score_PhaseI.tif`: Second normalization applied to Phase I catchment. Final output: 0–100.
- `Net_Suitability_Score_AllPhases.tif`: Same for All Phases scenario.
- `Uplift_Coefficient_PhaseI.tif`: $\text{Coefficient} = 1.00 + \text{Score}/100 \times 0.12$. Range: 1.00–1.12.
- `Price_Change_EUR_m2_PhaseI.tif`: $\text{Price change} = \text{OMI zone price} \times (\text{Coefficient} - 1.00)$. Units: €/m².

5.10 INSPIRE Metadata Compliance

All spatial datasets produced in this thesis are documented with INSPIRE-compliant metadata conforming to ISO 19115:2003 and ISO 19139:2007, as required by Commission Regulation (EC) No 1205/2008 implementing the INSPIRE Directive (2007/2/EC) ([European Parliament and Council, 2007](#); [International Organization for Standardization, 2003](#)). Full metadata records are compiled in two dedicated documents: *INSPIRE Metadata: SN Tool Indicators* (covering the 24 indicator GeoPackages) and *INSPIRE Metadata: Ancillary and Supporting Datasets* (covering 18 auxiliary GeoPackages). Each record contains all mandatory INSPIRE elements: identification, classification and keywords, geographic and temporal reference, data quality and lineage, conformity declaration against Commission Regulation (EU) No 1089/2010, access and use constraints, and responsible organization (Politecnico di Torino; author: Roderick William Tossato Silva). Common metadata across all datasets: Metadata Date 2026-05-13; CRS EPSG:3003 (Monte Mario / Italy zone 1); distribution format GeoPackage (.gpkg); access restricted to academic and research purposes.

5.10.1 SN Tool Indicator Datasets (24 GeoPackages)

Table 5.1 lists all 24 SN Tool indicator GeoPackage files with their INSPIRE spatial data theme and primary data source reference year.

Table 5.1: INSPIRE-documented SN Tool indicator GeoPackages (all in EPSG:3003).

Code	Indicator	GeoPackage filename	INSPIRE Theme
A1.1	Population Density	ZONE_CENSIMENTO_POPULATION_DENSITY_IND.gpkg	Population /
A1.2	Urban Compactness	ASC_URBAN_COMPACTNESS_INDIC.gpkg	Demography
A2.1	Green Space Coverage	ASC_AVAIL_GREEN_URBAN_AREA_INDIC.gpkg	Buildings
A2.2	Green Space per Capita	ASC_AVAIL_GREEN_URBAN_AREA_INDIC.gpkg	Land use
A2.3	Green Space Accessibility	ASC_GREEN_AREA_ACCESS_INDIC.gpkg	Population /
A3.2	Biodiversity in Green Zones	ASC_BIODIVERSITY_GREEN_ZONES.gpkg	Demography
			Land use
			Species
			distribution
F1.1	PT System Performance	ASC_PER_PUBLIC_TRANSPORT_2026_IND.gpkg	Transport networks
F2.2	EV Charging Infrastructure	ELE_CHAR_ST_INDIC.gpkg	Transport networks
F2.3	Bicycle Network Density	ASC_F2_3_Bicycle_Network.gpkg	Transport networks
F3.3	Safety of Bicycle Lanes	ASC_F3_3_Safety_of_bicycle_lanes.gpkg	Transport networks
F4.1	Street Network Cyclomatic Complexity	ASC_F4_1_Cyclomatic_Complexity_IND.gpkg	Transport networks
F4.2	Street Network Connectivity	ASC_F4_2_Connectivity_Street_Network_IND.gpkg	Transport networks
G2.1	Housing Purchase Affordability	zone_OMI_G2_1_Property_Affordability_IND.gpkg	Statistical units
G2.2	Housing Rental Affordability	zone_OMI_G2_2_Rental_Affordability_IND.gpkg	Statistical units
G2.3	Vacant Residential Units	ZONE_CENS_VACANT_RES_UNIT_IND.gpkg	Buildings
G3.1	Proximity of Key Services	ASC_Availability and Proximity of Key Services.gpkg	Gov. services
G3.2	Proximity to Primary Schools	ASC_G3.2_Availability and Proximity of a Public Primary School.gpkg	Gov. services
G3.3	Proximity to Secondary Schools	ASC_G3_3_Availability and Proximity to a Public Secondary School - I grado.gpkg	Gov. services
G3.4	Proximity to Play Facilities	ASC_G3.4_Availability & Proximity to Childrens Play Facilities.gpkg	Gov. services
G3.5	Outdoor Public Spaces	ASC_G3_5_Outdoor_Public_Spaces_IND.gpkg	Land use
H1.1	Per-Capita Income	ASC_H1_1_Avg_Annual_Income_IND.gpkg	Statistical units
H2.1	Employment Rate (25–64)	ASC_H2_1_Employment_Rate_IND.gpkg	Statistical units
H2.2	Youth NEET Rate (15–29)	ASC_H2_2_Youth_Unemployment_IND.gpkg	Statistical units
I3.3	Land Permeability	ASC_permeable.gpkg	Land cover

5.10.2 Ancillary and Supporting Datasets (18 GeoPackages)

Table 5.2 lists the 18 ancillary GeoPackages documented in the companion metadata file. These include intermediate processing layers, custom non-SN Tool indicators, and derivative data layers supporting the DSS dashboard.

Table 5.2: INSPIRE-documented ancillary GeoPackages (all in EPSG:3003).
Geoportale-derived datasets are licensed under CC BY 3.0 IT.

GeoPackage filename	Description
ASC_Availability and Proximity to a public scuola_ d_infanzia.gpkg	Custom G3-extension: proximity to <i>scuola d'infanzia</i>
CAP_ZN_IRPEF_2023.gpkg	IRPEF 2023 income data by CAP postal zone
EDIFICIO_ALTEZZA_MEDIA.gpkg	Building dataset with area-weighted height estimates
EDIFICIO_COMERCIALE.gpkg	Commercial building layer
EDIFICIO_INDUSTRIALE.gpkg	Industrial building layer
ED_RES_PUNTI_GTT_SUP_UTILE.gpkg	Residential building points with useful surface and GTT proximity
Food_shops_heatmap.gpkg	KDE food shop spatial density heatmap
GTT_stops_clipped_3003.gpkg	GTT transit stops (clipped to Turin boundary)
IRPEF_data_2023_subcomunale.gpkg	IRPEF 2023 sub-municipal income tabular data
Mid-Large_Industrial_BLD_100m_noise.gpkg	Noise impact buffers around mid-to-large industrial buildings
ZONE_CENS_VACANT_RES_UNIT_IND.gpkg	Non-primary residence ratio by <i>zona di censimento</i>
PUNTI_RESIDENZIALE_GTT_SUP_UTILE_POP_COEF.gpkg	Residential points with population density coefficients
ASC_Proximity to a Butcher Shop.gpkg	Custom food-access indicator: proximity to butcher shops
RES_PRIME_AFF_RETROFIT_POTENTIAL.gpkg	Primary residence retrofit potential for affordable buildings
Residential_points_SVC_INC_PRVAL.gpkg	Residential points with income and property price data
UNITA_VOLUMETRICA_2025_GP.gpkg	Volumetric units with gross volume estimates (2025)
Residential_points_walkability.gpkg	Walkability flags for 10 service categories per building
zone_OMI_unregistered_residences_2025.gpkg	Non-primary residence ratio by OMI zone (2025)

Full individual metadata records for all 42 GeoPackages are provided in [Appendix A](#).

5.11 Data Limitations and Uncertainty

Six primary data limitations are acknowledged:

1. **Temporal heterogeneity:** The analysis combines data from multiple reference periods. ISTAT census data are from 2021, GTFS transit data from March 2026, OMI property prices from 2024–2025, and TGM road traffic counts from Regione Piemonte are from 2024). Neighbourhood-level changes between 2021 and 2026, in population, transit service, or economic conditions, are not captured.
2. **Excluded indicators:** Two indicators initially scoped within the SNTTool MED framework were excluded from the final 24-indicator set due to data availability constraints: F3.4 (Traffic Fatalities, requiring geocoded accident records not yet released for the full reference period) and I1.2 (GHG Emissions from Residential Buildings, requiring consolidated building energy performance data not yet available at the *zona statistica* level). Domain I in the composite index therefore reflects only I3.3 (Land Permeability); the energy performance dimension is designated as future work.
3. **CNOSSOS-EU model limitations:** The simplified A-weighted macro equations used for road noise buffer generation represent a 2D free-field approximation. They do not account for:
 - Façade reflection and canyon amplification (which increases noise levels in narrow streets).
 - Building absorption (which attenuates noise behind sound barriers).
 - Indoor noise transmission (which determines actual resident exposure).

- Directional emission patterns from vehicle exhaust, tyres, and engine sources.

The model buffers therefore represent an indicative acoustic footprint rather than a certified noise assessment. This limitation is consistent with the “macro-modelling for strategic planning” purpose for which CNOSSOS-EU was designed (Kephelopoulos et al., 2012).

4. **OSM data completeness:** Cycling infrastructure data from OSM is subject to varying levels of completeness across Turin. Peripheral areas and recently constructed infrastructure may be underrepresented. The Geoportale’s transport infrastructure layer provides partial validation but is not comprehensively synchronised with OSM.
5. **OMI zone granularity:** OMI values are zone-level medians, not individual property transaction prices. Within-zone price variation, which can be substantial in large peripheral zones, is not captured. Parcel-level data from the Catasto (Land Registry) would improve precision but is not openly available.
6. **UC2 predictive limitation:** The net suitability model produces a planning-grade *prediction* of property value uplift from Metro Line 2, not an econometrically causal estimate. The model does not control for all confounding factors, does not account for within-zone price variation, and cannot distinguish the announcement effect already capitalized into current OMI prices from the increment still to be realized. These limitations are treated in the Discussion (Chapter 9).

Spatial coverage and resolution comparison of primary data sources

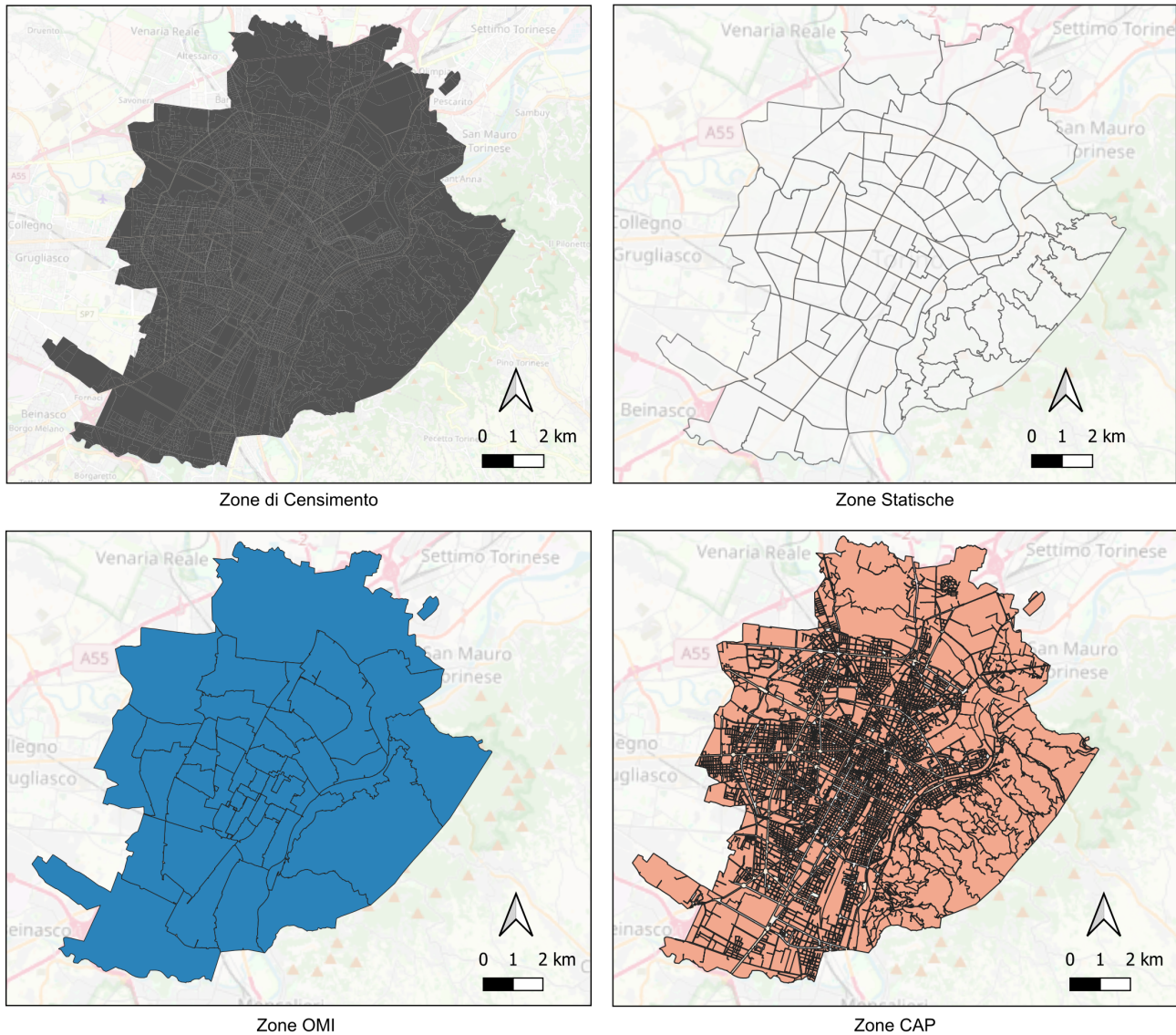


Figure 5.1: Spatial coverage and resolution comparison of primary data sources. ISTAT census sections provide the finest resolution. OMI zones and IRPEF CAP zones represent coarser administrative units used for economic indicators. All boundaries are shown within the Turin administrative boundary in EPSG:3003.

Chapter 6

Use Case 1 — PRG Sustainability Monitoring and Acoustic Noise Assessment

This chapter presents the spatial analysis results for Use Case 1. Sections 6.1–6.2 cover the domain-by-domain indicator results. Section 6.3 presents the Composite Sustainability Index, scenario analysis, and spatial autocorrelation findings. Section 6.4 explores the correlation between sustainability scores and property values. Section 6.5 maps Priority Intervention Zones and Dual Dividend areas. Section 6.5.1 presents the full city-wide acoustic noise impact assessment, including the noise penalty parameter table, results, and cross-linkage with sustainability scores and property values.

6.1 Overview and Stakeholder Context

Use Case 1 is designed to support Turin’s PRG revision by providing a spatially granular, multi-dimensional sustainability baseline for all 94 statistical zones (*zone statistiche*). The primary end-users are urban planning professionals who need to identify underperforming neighbourhoods, assess sensitivity to weighting priorities, and export evidence for EU-level sustainability reporting. The acoustic noise extension (Section 6.5.1) adds an environmental quality dimension of direct relevance to residential planning, health impact assessment, and property market dynamics.

The analysis in this chapter is based on the 24 SNTool MED indicators listed in Table 4.1, all of which have been fully calculated and are distributed across Domains A, F, G, H, and I. Two indicators initially scoped within the framework, F3.4 (Traffic Fatalities) and I1.2 (GHG Emissions from Residential Buildings), were excluded prior to calculation due to data availability constraints and are discussed as future work in Chapter 9. The chapter notes where these indicators would be expected to affect the spatial pattern of results if included.

Sections 6.2 and 6.5.1 present domain-by-domain spatial results for all 24 calculated indicators. However, the composite CSI scoring in Section 6.3 is based on the 18 indicators that meet the discriminatory power criterion for the Turin context; the six excluded indicators are discussed in Chapter 9 (Section 9.1.1).

6.2 Domain-by-Domain Spatial Results

6.2.1 Domain A: Land Use and Biodiversity

The Domain A spatial pattern reveals significant green space inequality across Turin. The highest A-domain scores, concentrated in the hills on the eastern part of the city, reflecting the low-density character of the area where houses are often surrounded by gardens and green space. The lowest A-domain scores are found in the city centre and the densely built northern and north-western districts (Barriera di Milano, Regio Parco, and

Aurora) and in the south-western industrial fringe (Mirafiori Sud), where the ratio of building volume to green space is highest and per-capita green provision is lowest.

Given that Torino is the 4th most densely-populated city in Italy ([Istituto Nazionale di Statistica, 2026](#)), the results from this indicator confirm that most areas of the city are at or beyond the minimum number of residents per km² to optimize service provisioning and use of the urban space.

Indicator A1.2, Urban compactness reveals a typical core urban pattern, where central areas (part of the historical city), as well as northern and southern districts constructed during the post-war industrial expansion phase, show a high degree of urban compactness in the built environment (m³/m²). The eastern areas on the hills reflect a different, almost suburban reality with low rise buildings, surrounded by private gardens and green space.

Indicator A2.1 Availability of green urban areas shows a predictable pattern given the majority of green and forested areas can be found on the eastern hills.

Indicator A2.2 Green Areas in Relation to the Neighbourhood Population shows a major deficit in the highly-populated and densely-built central areas where green spaces are either not present or insufficient for the number of residents.

Green space accessibility (A2.3) shows a broadly similar spatial pattern but with important nuances due to the presence of urban parks and green space meeting the 0.5 hectare size threshold. It is important to note that this indicator only considers public green spaces (parks and similar spaces), which explains why some areas in the eastern hills scored lower. This is explained by the presence of private gardens and conservation areas (forests) that may not be publicly-accessible.

The biodiversity indicator (A3.2) shows a distinctive spatial pattern compared to the quantity-based green space indicators: it highlights the ecological quality of green spaces rather than their extent by quantifying the different number of plant species present in each area. A critical limitation is that only tree species are considered in the calculation due to data limitations. Since the available data and the application of the indicator does not allow for a meaningful comparison between statistical areas, our suggestion is to either drop this indicator or significantly lower its weight within the overall issue.

The calculated, domain A scores for all 94 statistical areas can be visualized on the following map: [6.1](#).

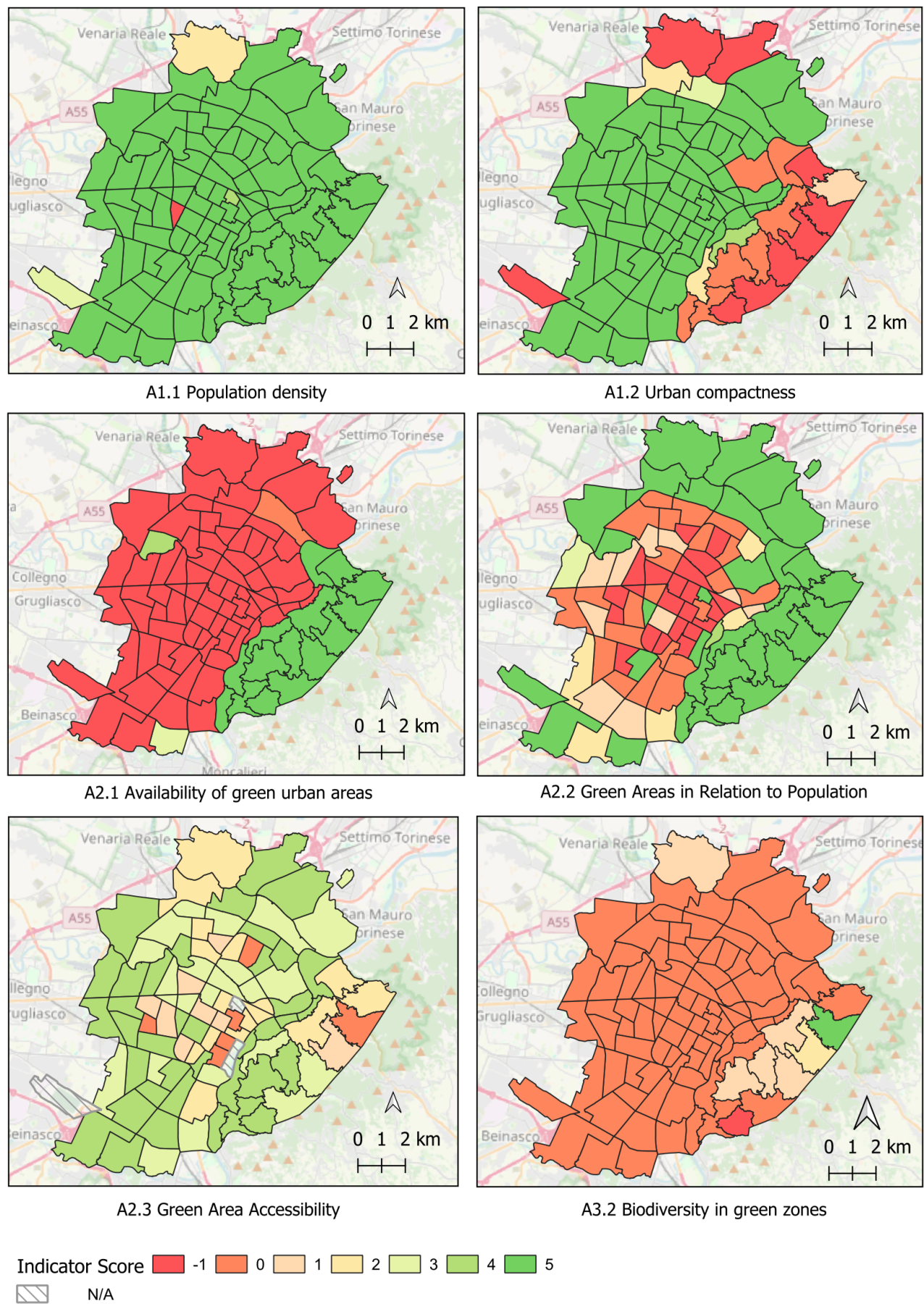


Figure 6.1: Domain A - Land Use and Biodiversity: Indicator score maps.

PRG implication: the A-domain results provide a spatially explicit basis for identifying green space deficit zones that should be prioritized in the PRG revision’s urban greening provisions, including the designation of new green infrastructure requirements for brownfield redevelopment sites.

The high concentration of green areas and forested areas in the eastern hills section, contrasted with the rest of the city can be seen in figure 6.2.

[H]

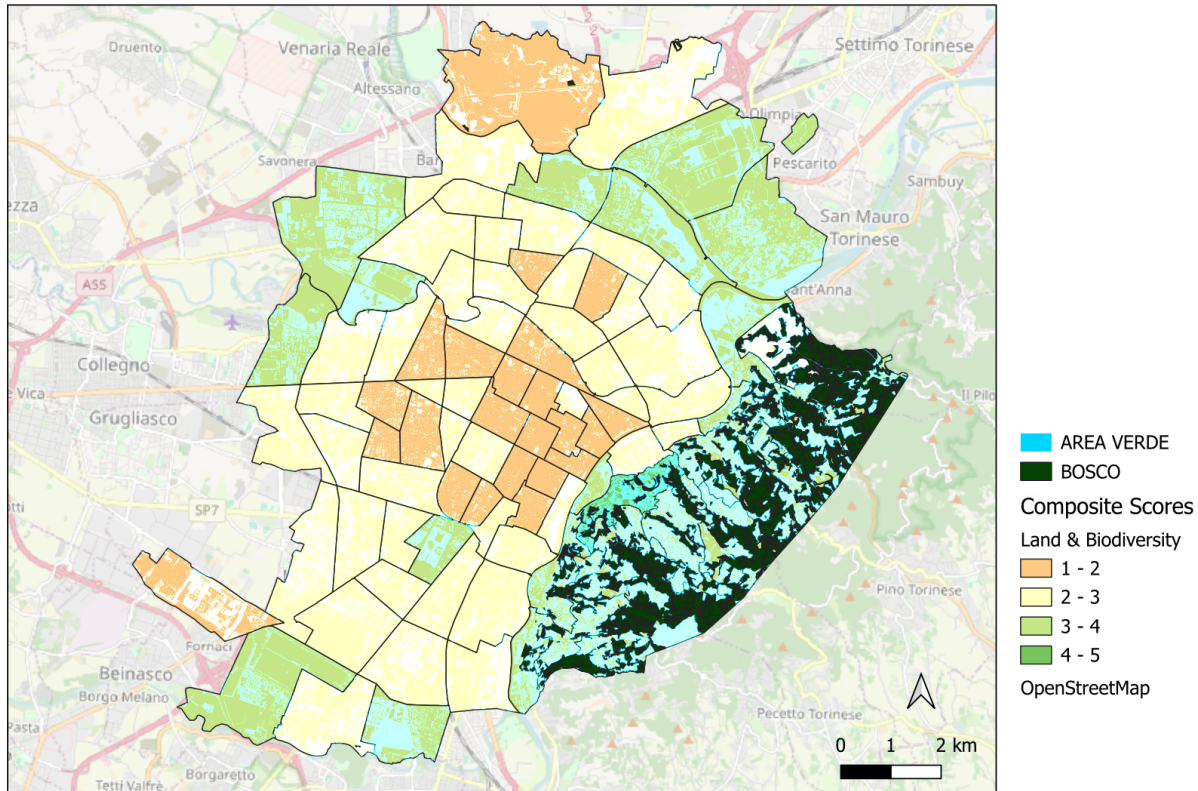


Figure 6.2: Domain A (Land Use and Biodiversity) composite score by statistical zone, with major green spaces overlaid.

6.2.2 Domain F: Transport and Mobility

The F-domain results are among the most analytically significant for this thesis, as they provide the direct link between Use Case 1 (sustainability monitoring) and Use Case 2 (Metro Line 2 suitability).

Indicator F1.1 tracks the percentage of the population that are within 400 meters walking distance of at least one public transportation service stop that has at least 20 scheduled daily trips. Given the extent of the Public Transport network in the city of Turin, the majority of statistical zones scores very high against the standard benchmarks.

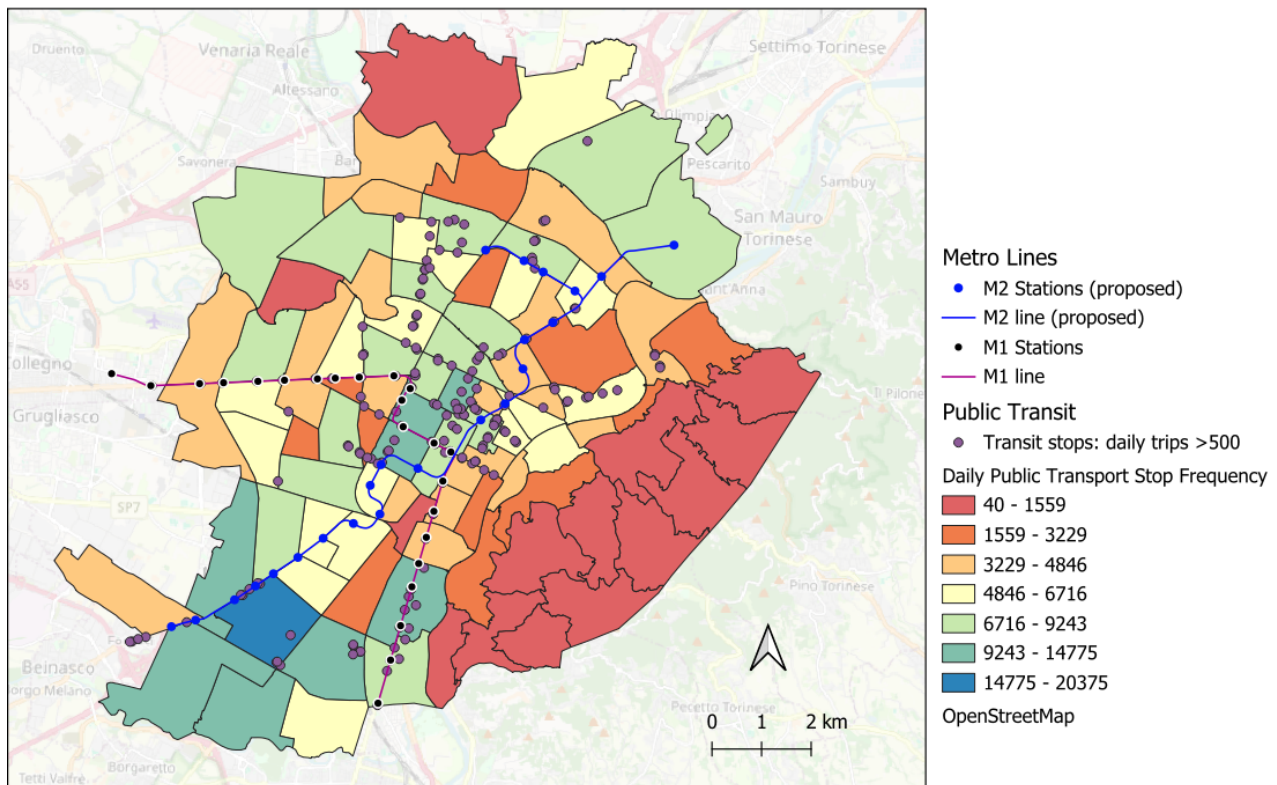


Figure 6.3: Performance of the public transport system, classified by the frequency of daily trips.

An alternative way to assess the performance of the public transport system is to look at the frequency of daily trips at each transit stop. Stops with less than 500 daily scheduled trips were excluded from the map. The daily public transit stop frequency number displayed on the map is the aggregate of all scheduled daily stops inside a statistical area.

This alternative view reproduces, at a statistical area level, the Competitiveness Index pattern described by Zini et al. (2024): a high-accessibility core centred on the Metro Line 1 alignment and the major tram and bus corridors, with pronounced drops in service quality in the eastern hills, which is expected due to the low-rise, car-centric nature of the area.

Indicator F2.2 Electric Vehicle Infrastructure (charging station) reveals a critical shortage of publicly-available charging stations throughout the city. This is specially problematic in a city like Turin where only 16% of residences have access to a private garage or box auto where a charging column could be installed ([idealista/news, 2024](#)).

The cycling infrastructure indicators (F2.3 and F3.3) reveal a chronic shortage of bike lanes, both at grade or grade-separated. No statistical area in the city has met the minimum acceptable value (benchmark 0) for the length of bicycle paths in the neighbourhood per inhabitant.

Indicator F3.3 Safety of bicycle lanes, reveals a city where the majority of bicycle lanes (when they exist) are not separated from vehicular traffic, making them less attractive and less safe for cyclists.

F4.1 and F4.2 (street network morphology) show that Turin's historical grid in the centre and inner districts achieves high connectivity values, while the large post-war residential superblocks in the northern and southern periphery, with their internal cul-de-sacs and limited street connections, score significantly lower. This

morphological pattern has implications beyond cycling: it affects emergency access, pedestrian safety, and the general walkability of these areas.

The calculated domain F scores for all 94 statistical areas can be visualized on the following map: [6.4](#)

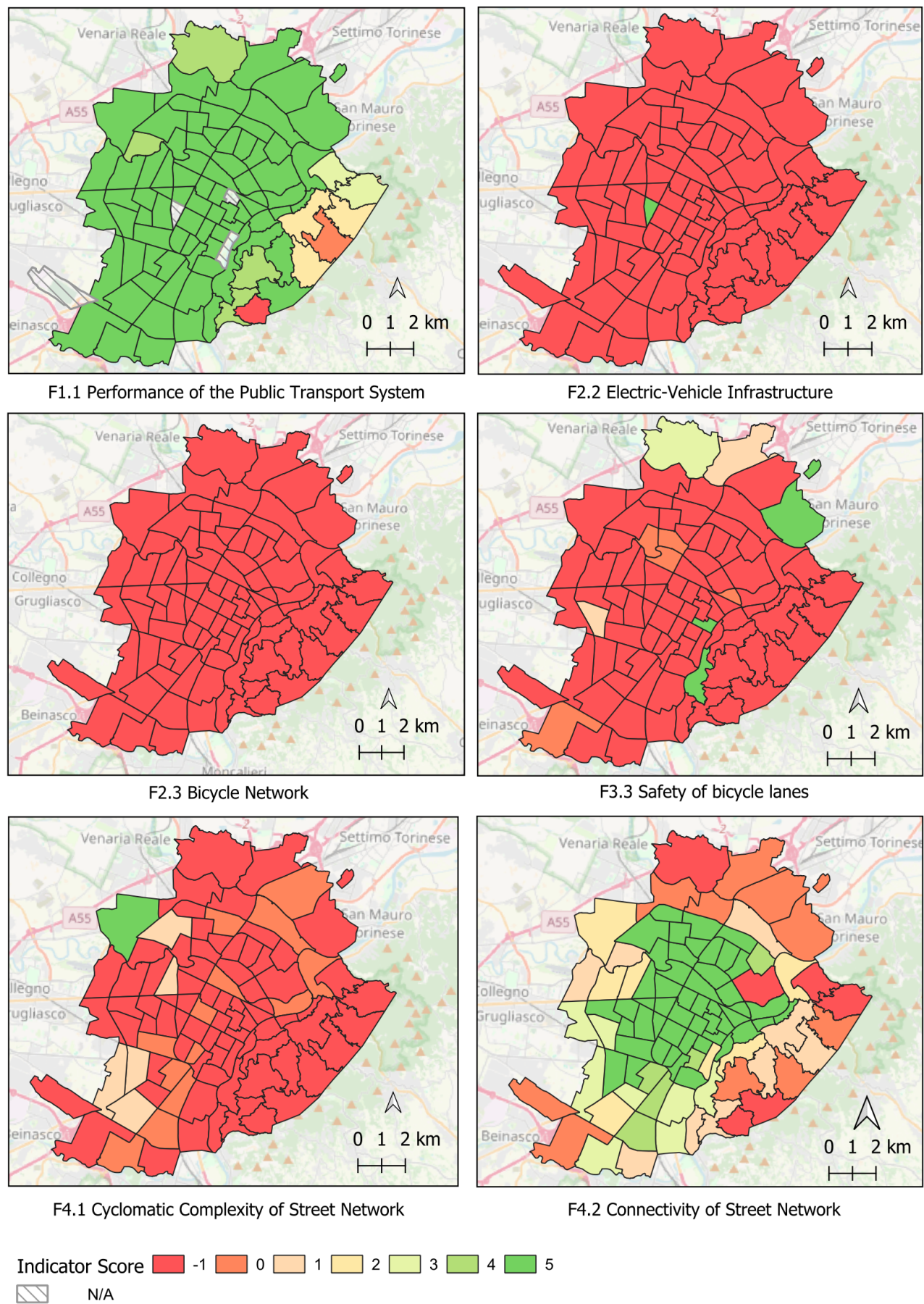


Figure 6.4: Domain F - Transport and Mobility: Indicator Score Maps

PRG implication: the F-domain results provide the quantitative transport equity argument for prioritizing Metro Line 2's Phase I northern corridor, where the lowest-CI northern sections coincide with some the lowest F-domain scores across the city (excluding the low-density eastern hills). A visual representation of the Transport-domain composite score for the entire city can be seen in 6.5.

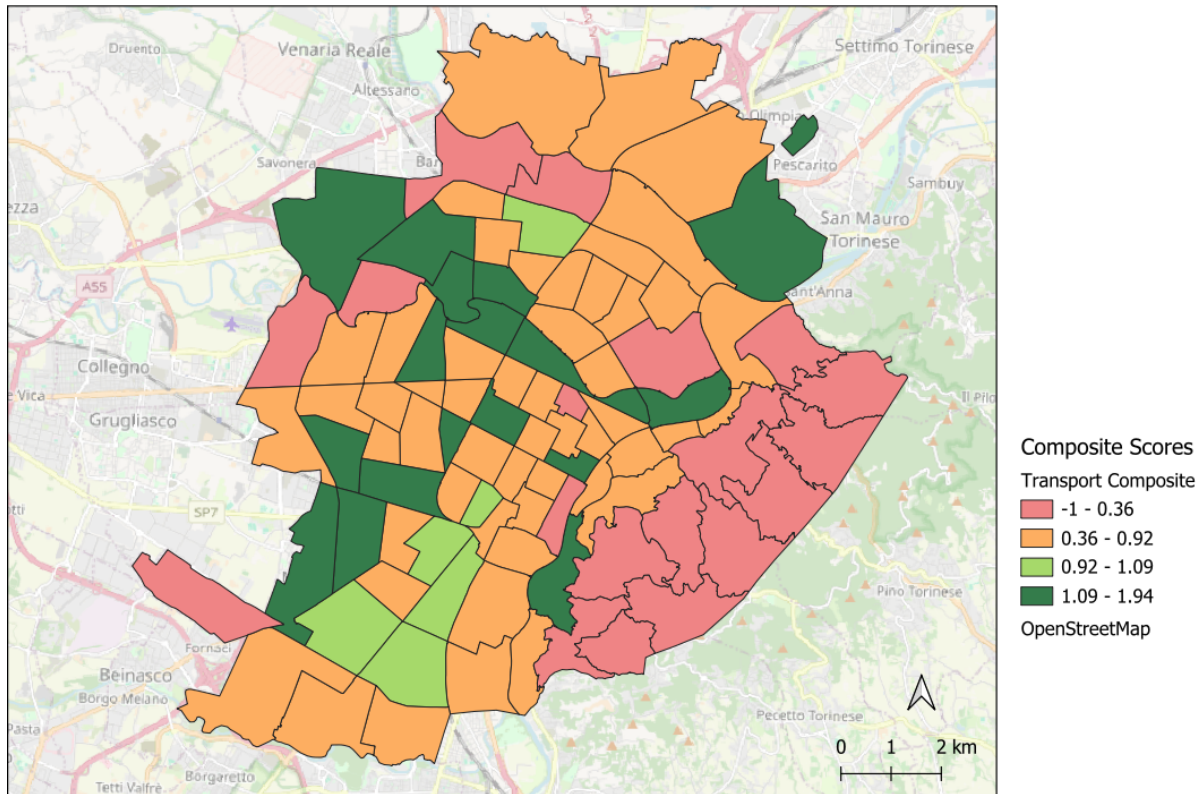


Figure 6.5: Domain F - Transport - Composite Score

6.2.3 Domain G: Social Equity

The G-domain results confirm and quantify the social vulnerability gradient that qualitative analyzes of Turin's urban structure have long identified (Politecnico di Torino, 2016). The social indicators (vacancy rates, housing affordability, and service proximity) converge on a pattern of concentrated disadvantage in the northern industrial districts (Barriera di Milano, Falchera, Regio Parco, Lucento) and, to a lesser extent, the south-western periphery (Mirafiori Sud, Basse di Stura).

Housing affordability (G2.1 and G2.2) shows a counterintuitive pattern in parts of the city: some of the lowest-income statistical zones (as measured by IRPEF data) in the northern periphery achieve relatively good rental affordability scores precisely because OMI rental prices in those areas are low, reflecting the combined effect of low desirability and limited transit access.

This “affordability trap” dynamic, where lower rents are sustained by low neighbourhood quality rather than by active affordability policy, is a significant planning insight: improving sustainability scores in these areas without managing housing market dynamics risks triggering gentrification that eliminates the affordability advantage.

Indicator G2.3 - Vacant and non-resident occupied units seems to show a pattern of higher occupancy rates

by long-term residents in the peripheral areas in respect to more central areas, where temporary residents, commercial uses (e.g. doctors or professional offices) or short term rentals may take up a higher percentage of the housing stock. A notable exception is the eastern hills area, which typically would be expected to be primarily composed of long-term residents. Additional data is needed to understand the reasons behind this apparent loss of long-term residents.

Indicator G3.1 shows a predictable pattern where areas in the eastern hills have fewer residences within an 800-m walking distance of key services (schools, clinics, sport facilities, food shops, banks, post offices, etc). This is to be expected given the low-rise, suburban nature of the zone. It does however make residents in the area to be more car-dependent to access these key services when compared to their peers in other areas of the city.

School accessibility and proximity indicators (G3.2 and G3.3) reveal consistent gaps in the peripheral areas, not just in the eastern hills, like indicator G3.1, but also in the northern and southern areas, constructed primarily during the post-war industrial boom period.

It is worth noting a methodological distinction between how school proximity is treated in UC1 and UC2. The G3.2 and G3.3 indicators measure school access as a straightforward positive amenity at the *zona statistica* scale: the closer a neighbourhood is to school facilities, the higher its score. This aggregate framing is appropriate for sustainability monitoring, where the question is whether residents have reasonable access to educational infrastructure.

The UC2 net suitability model, by contrast, applies a piecewise “dual-character” specification grounded in hedonic pricing literature (Owusu-Edusei Jr et al., 2007; Sah et al., 2016): a detractor zone immediately adjacent to the school (100 m for primary schools, 50 m for secondary schools) captures the School Congestion Effect and drop-off externalities that suppress property values in the immediate vicinity, while the positive amenity value is realized only beyond this congestion radius.

The G3.2 and G3.3 sustainability indicators and the UC2 school scoring model are therefore measuring the same infrastructure at different spatial and analytical resolutions, with the latter providing the finer-grained treatment required for pixel-level real estate suitability scoring. The full specification and academic justification for the differentiated school buffers are presented in Chapter 3 (Section 3.4.3).

Indicator G3.4 shows that most areas of the city, except the eastern hills and the historical city centre are well served of children’s play facilities within walking distance of most residences. Additional data, such as the number of children residing on each area could be used to further enhance the analysis and target interventions such as the provisioning of new playgrounds or parkettes that promote play-based learning and children’s sports.

Indicator G3.5 Outdoor Public Spaces shows the percentage of the built-up area of the neighbourhood that is open for public use. An interesting pattern is again revealed where most areas of the city are well served of publicly-accessible spaces, except for outlying areas that were built to serve a mixed industrial-residential purpose, or areas in the eastern hills where the low-density character of the neighbourhood, with the presence of private gardens and other fenced-off areas reduces the overall availability of public space.

The calculated domain F scores for all 94 statistical areas can be visualized on the following maps: 6.6 and 6.7

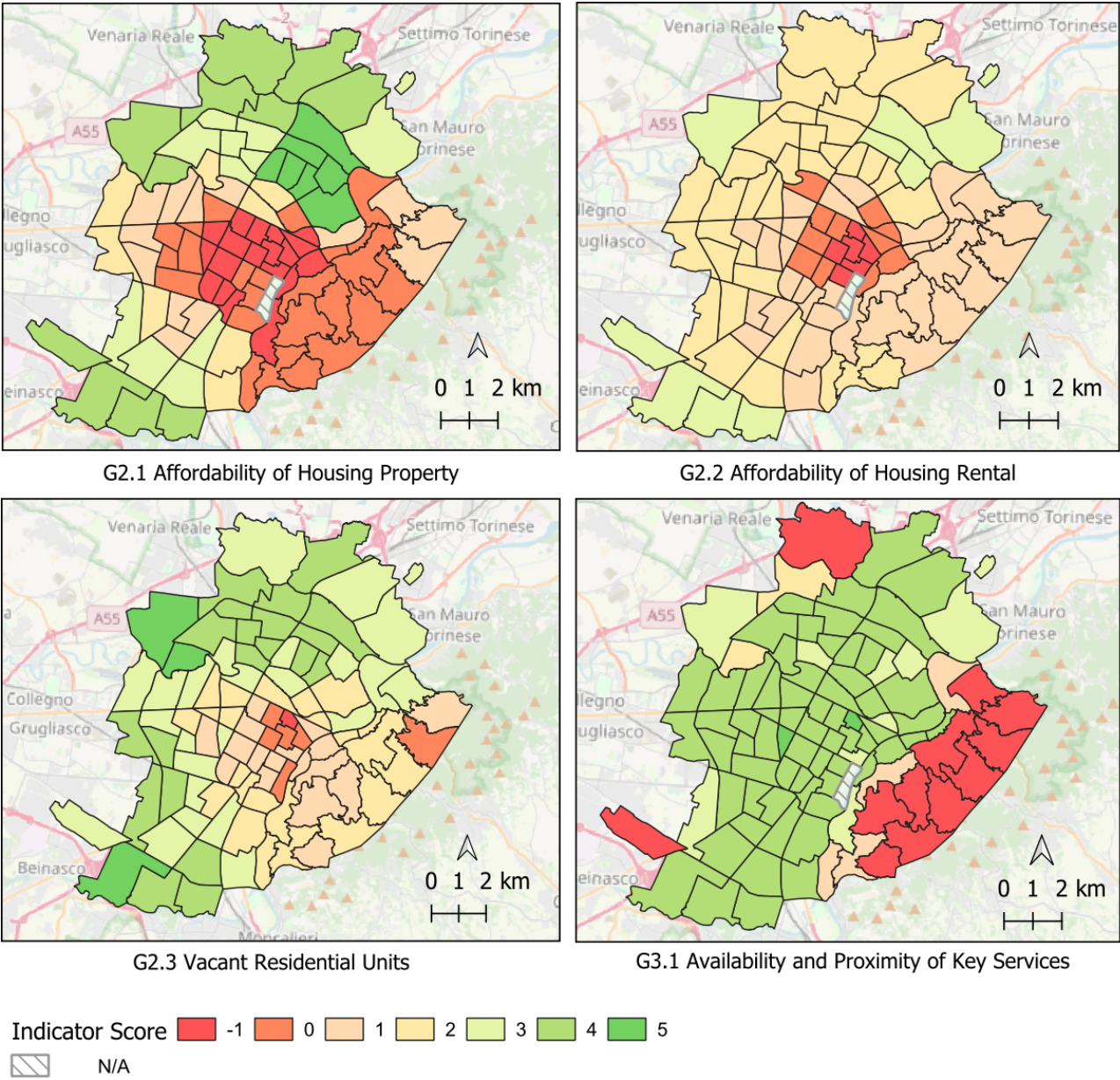


Figure 6.6: Domain G - Social Aspects: Indicator Score Maps (set A)

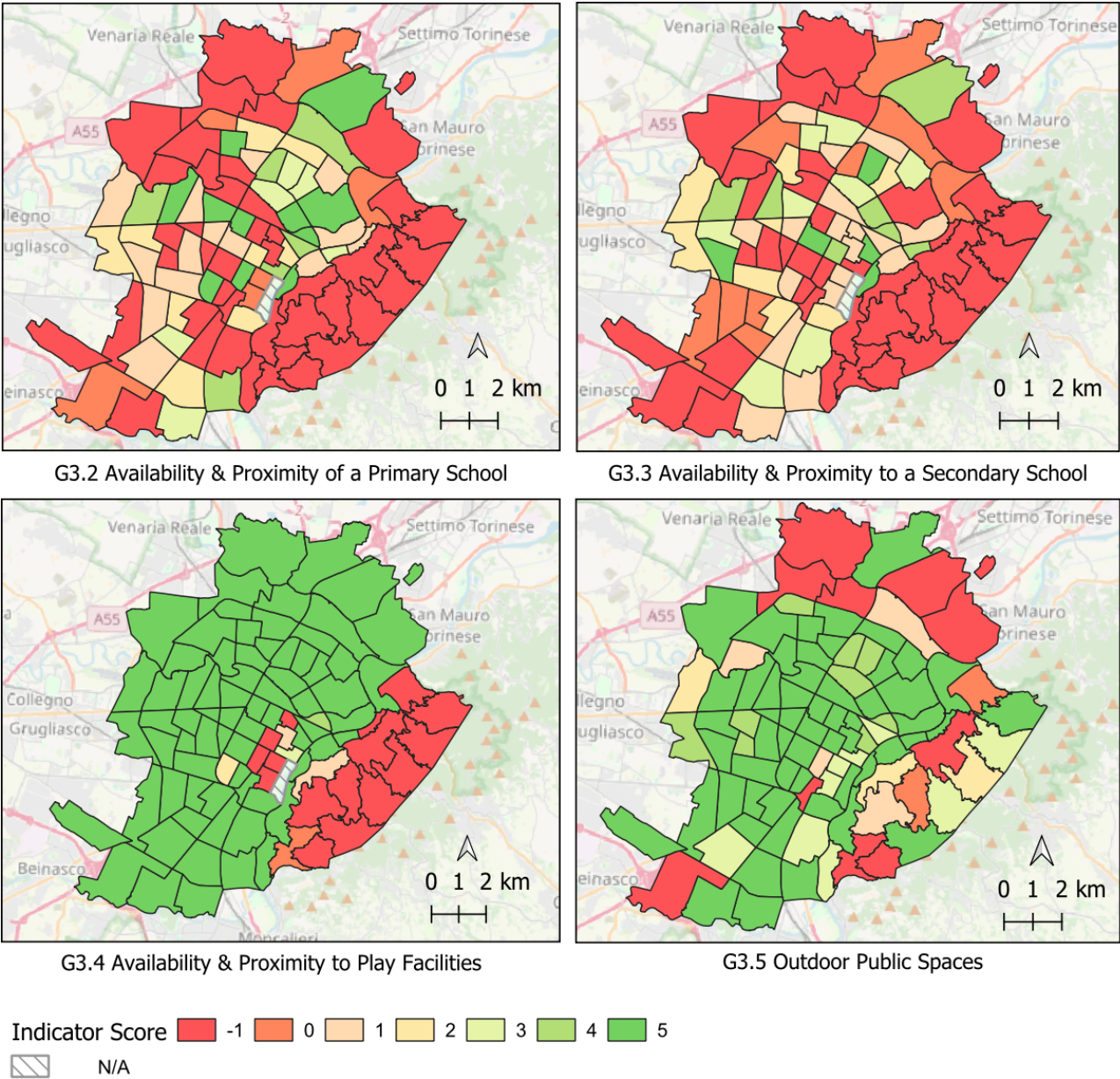


Figure 6.7: Domain G - Social Aspects: Indicator Score Maps (set B)

Composite scores for all 8 indicators in the Social Aspects domain, assigning equal weights to all indicators can be seen in 6.8.

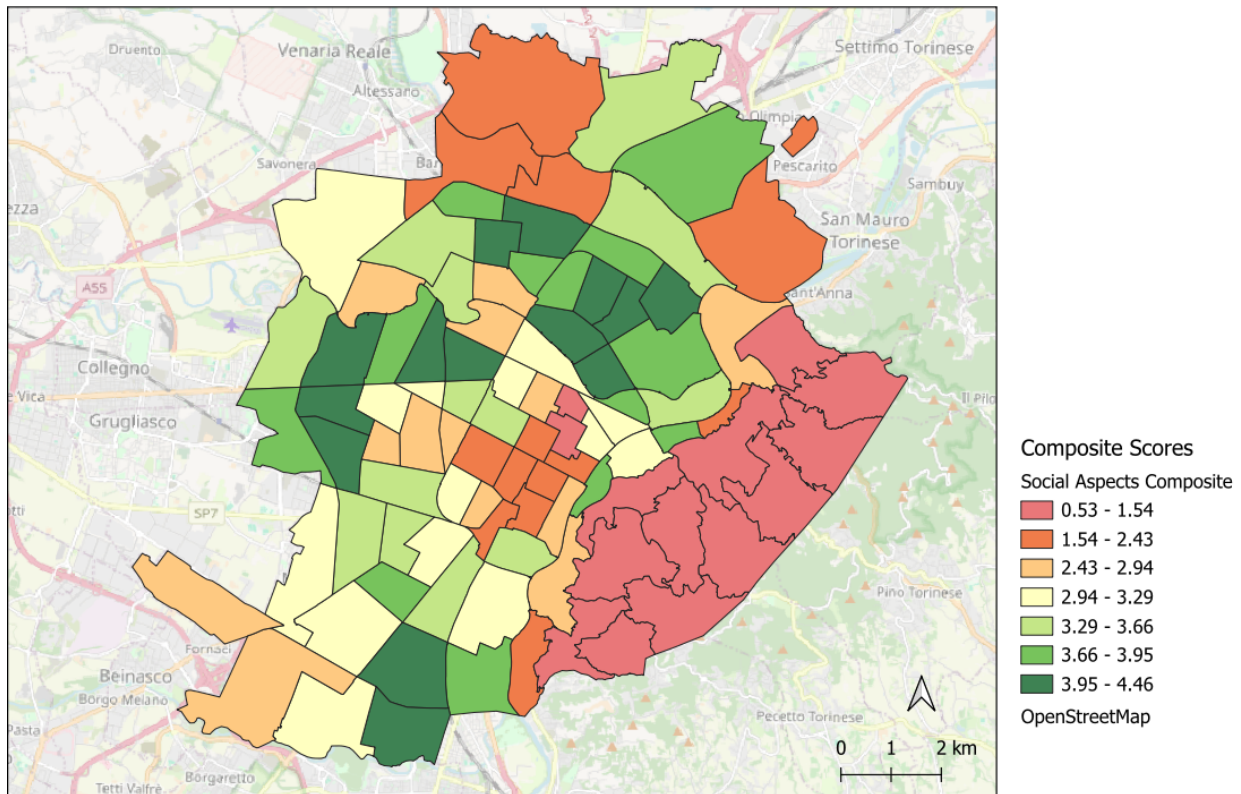


Figure 6.8: Social Aspects Composite Scores

A clear pattern emerges showing areas in the eastern hills suffer from a lack of publicly-accessible services within walking distance of residential areas, forcing residents to be more car-dependent. This is further exacerbated by the hilly terrain in the zone, making walking a less desirable choice. It is also interesting to note that disadvantaged areas like the northern neighbourhoods of Barriera di Milano, Monterosa, and Montebianco, achieve a higher composite score on this domain. This can be explained by their higher performance on indicators such as G2.1, G2.2, and G2.3 (housing affordability and Vacancy rates), as well as G3.1, Availability and Proximity of Key Services.

Areas near the city centre also scored lower on this domain, denoting the mixed use (commercial-residential) nature of the zone. Paradoxically, areas in the city centre and in the eastern hills are among the most expensive in the city, showing that residents seem to not mind the lack of key services within walking distance of their homes.

6.2.4 Domain H: Economy

The H1.1 income indicator confirms the north-south income gradient at the CAP zone level, with the northern CAP zones (10154, 10155, 10156, 10157) reporting mean declared incomes approximately 20–35% below the Turin city average of approximately €28,925 (estimated from the IRPEF dataset). The southern and central zones (10121, 10122, 10123, 10128) report incomes 15–30% above the city average.

The H2.1 employment rate indicator (adults aged 25–64, sourced from ISTAT IDISE 2021) and the H2.2 youth NEET rate (individuals aged 15–29 not in employment, education, or training, also from IDISE 2021) have been completed and show spatial patterns consistent with the income gradient.

The northern sub-municipalities recording the lowest H1.1 income scores also record the lowest employment rates and the highest NEET proportions, confirming the multi-dimensional character of economic disadvantage in the post-industrial northern districts (Politecnico di Torino, 2016).

The calculated domain H scores for all 94 statistical areas can be visualized on the following map: 6.9.

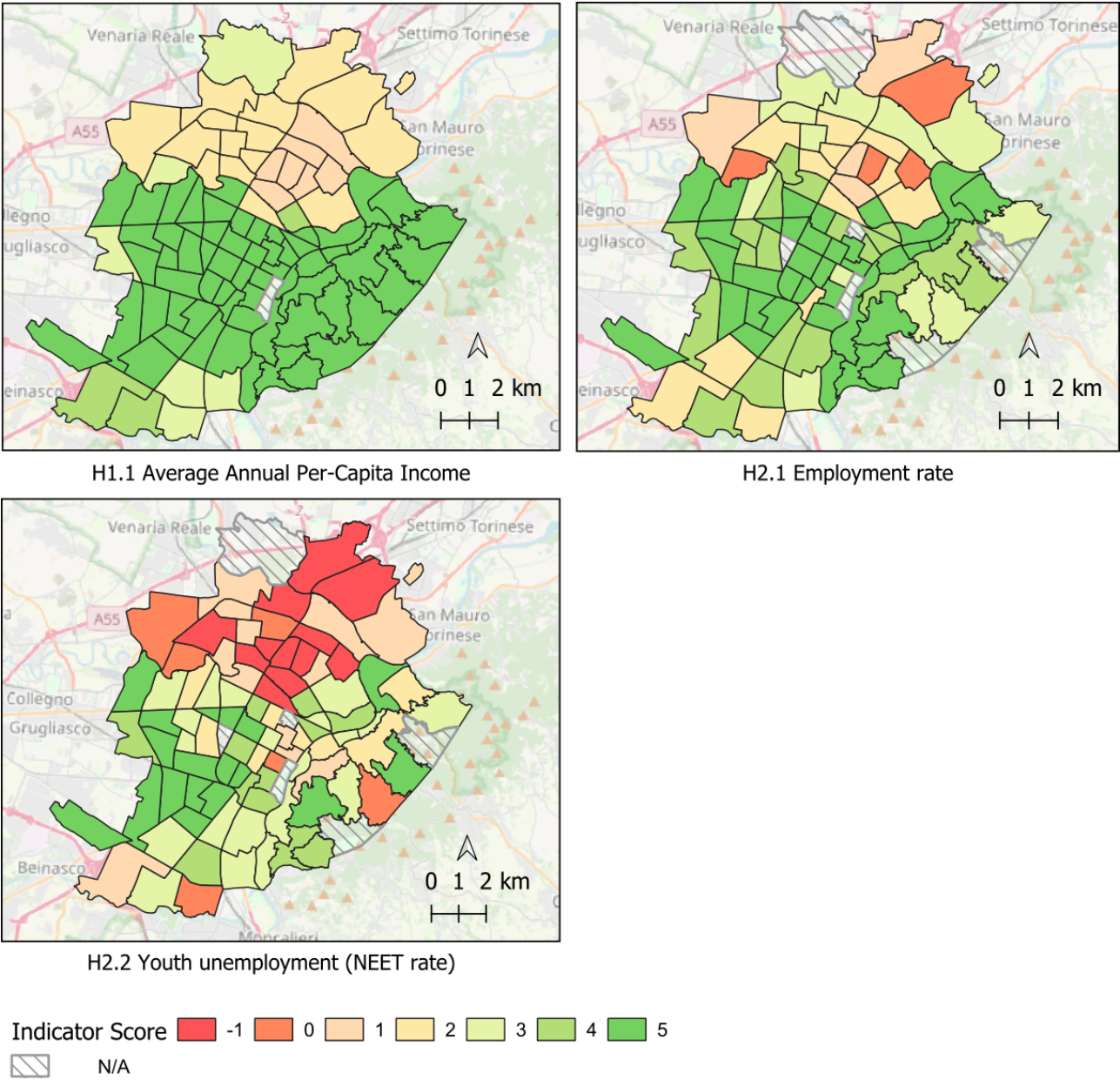


Figure 6.9: Domain H - Economy: Indicator Score Maps

As illustrated by figure 6.10, the composite score for this domain results in the most pronounced North-South divide denoting structural disadvantages in those areas.

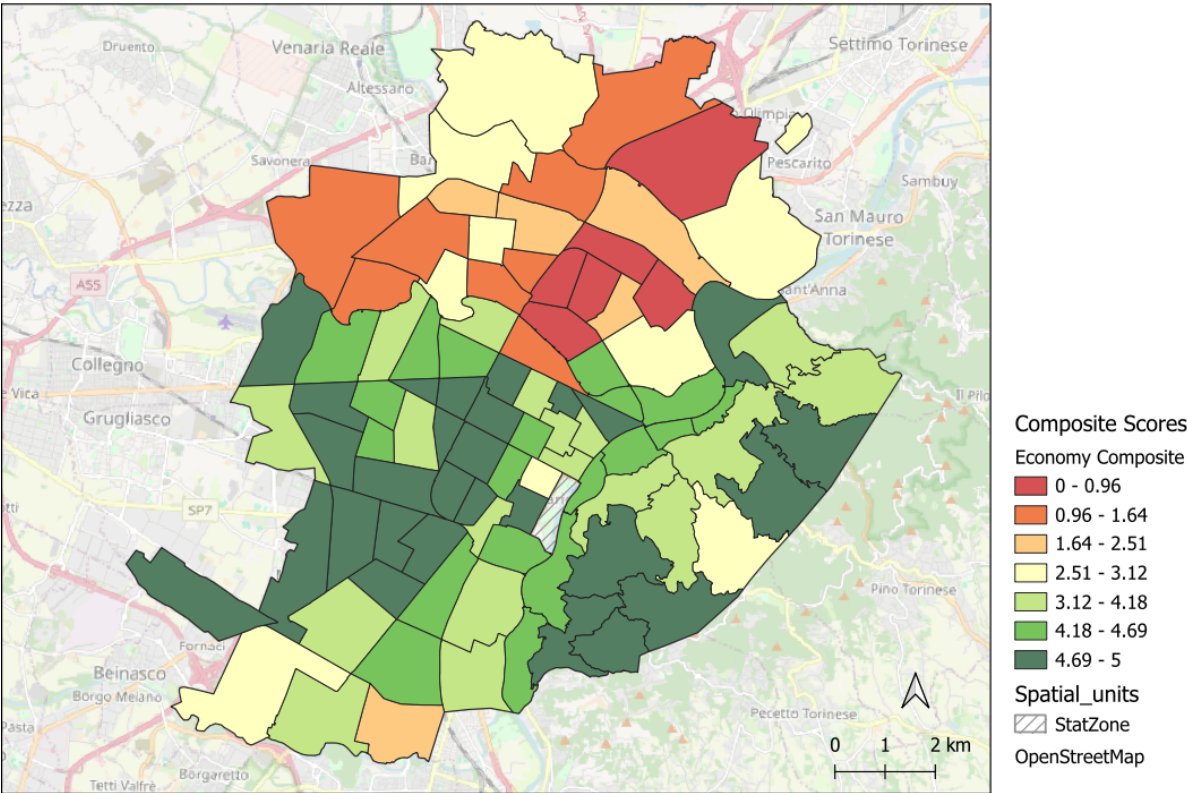


Figure 6.10: Domain H - Economy - Composite Scores

6.2.5 Domain I: Climate and Energy

Domain I is represented in the composite index by the sole completed indicator, I3.3 (Land Permeability), derived from the Land Cover Piemonte 2023 dataset.

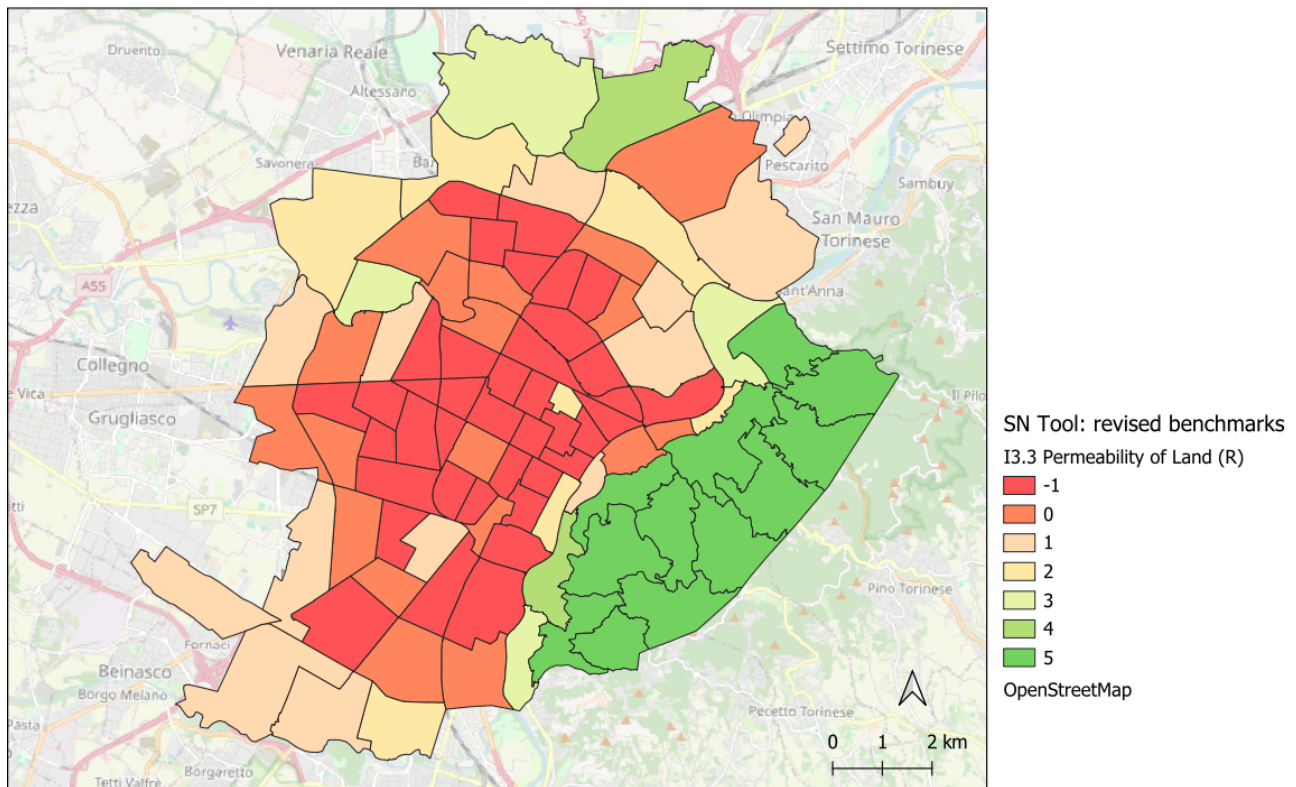


Figure 6.11: Permeability of Land

The spatial pattern of land permeability reflects Turin’s urban morphology: the highest permeability scores are found in the eastern hill districts (Precollina, Collina, Sassi), where large areas of natural vegetation and unsealed soils remain, and in the southern periphery where low-density residential development alternates with green spaces. The lowest permeability scores are concentrated in the densely built northern and central districts, where impervious surfaces (buildings, roads, paved lots) cover the majority of each zone’s area.

The I1.2 greenhouse gas emissions indicator (residential buildings) remains pending. Its absence means Domain I scores in the composite index reflect only the land cover dimension of climate sustainability; the energy performance dimension will be incorporated in future work as building energy data are consolidated.

PRG implication: the I3.3 permeability map provides a base for the PRG’s urban drainage and climate adaptation provisions, identifying priority zones for green infrastructure investment such as permeable pavement, rain gardens, and urban de-sealing projects.

6.3 Composite Sustainability Index

6.3.1 Baseline Composite Score

The Composite Sustainability Index (CSI) is computed using equal domain weights ($w_d = 0.20$ for each of the five domains) over the 24 completed SN Tool MED indicators. Domain scores are simple averages of their constituent indicator scores.

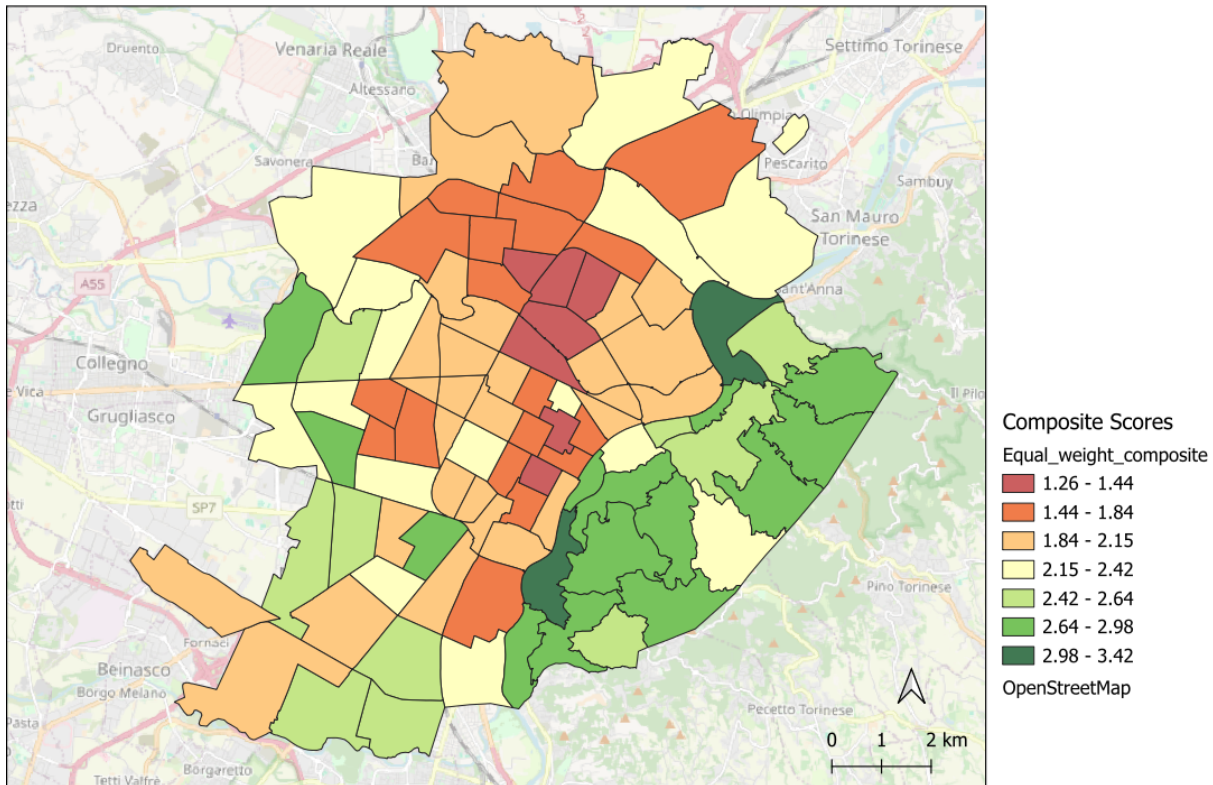


Figure 6.12: Composite Index - equal weights

The composite index map (6.12), illustrates the importance of contextualization and assigning different weights to both issues and indicators within issues to produce a more meaningful comparison.

Although the differences between statistical areas are very subtle when it comes to the application of the composite index, some patterns begin to emerge, most notably on how the areas on the eastern hills seem to score higher at this level, with some exceptions, as seen on table 6.1.

Table 6.1: Statistical areas with the highest composite scores

ZONASTAT	ASC	SCORE
70	Pilonetto	3.42
72	Borgata Sassi - Meisino	3.10
75	Villa della Regina - Val Salice	2.98
87	Cavoretto - Val Pattonera	2.92
85	San Vito - Val Salice	2.89
86	Parco della Rimembranza	2.89
69	Fioccardo - Alberoni	2.81
71	Madonna del Pilone	2.77
54	Stadio Comunale	2.77
83	Santa Margherita	2.76

Conversely, zones in the north and central areas tend to score lower on the composite score, as observed in table 6.2.

Table 6.2: Statistical areas with the lowest composite scores

ZONASTAT	ASC	SCORE
10	Borgo San Secondo – Stazione Porta Nuova	1.59
04	Piazza San Carlo – Piazza Carlo Felice	1.59
03	Palazzo Carignano – Vecchio Ospedale (Borgo Nuovo)	1.44
42	Borgata Vittoria	1.38
24	Borgata Aurora	1.36
39	Borgata Montebianco	1.34
12	Borgo Dora – Valdocco	1.33
38	Borgata Monterosa	1.27
09	Piazza Madama Cristina (Borgo San Salvatio)	1.26

6.3.2 Scenario Analysis: Weight Sensitivity Testing

Three alternative weighting scenarios are computed to assess the robustness of the composite index rankings:

Scenario T — Transport-Prioritized : F-domain weight doubled ($w_F = 0.40$); remaining domains weighted equally ($w_A = w_G = w_H = w_I = 0.15$).

Scenario S — Social-Equity-Prioritized : G-domain weight doubled ($w_G = 0.40$); remaining domains weighted equally.

Scenario C — Economy-Prioritized : H-domain weight doubled ($w_H = 0.40$); remaining domains weighted equally.

Spearman rank correlation between the baseline and each scenario ranking is calculated. Sections with Spearman $\rho > 0.95$ relative to the baseline are “stable” in their ranking. “Robust underperformers” are defined as sections falling in the bottom quintile under *all four* scenarios (baseline + 3 alternatives). “Sensitive switchers” are sections that move by more than two quintiles between their best and worst scenario rankings.

Transport-prioritized

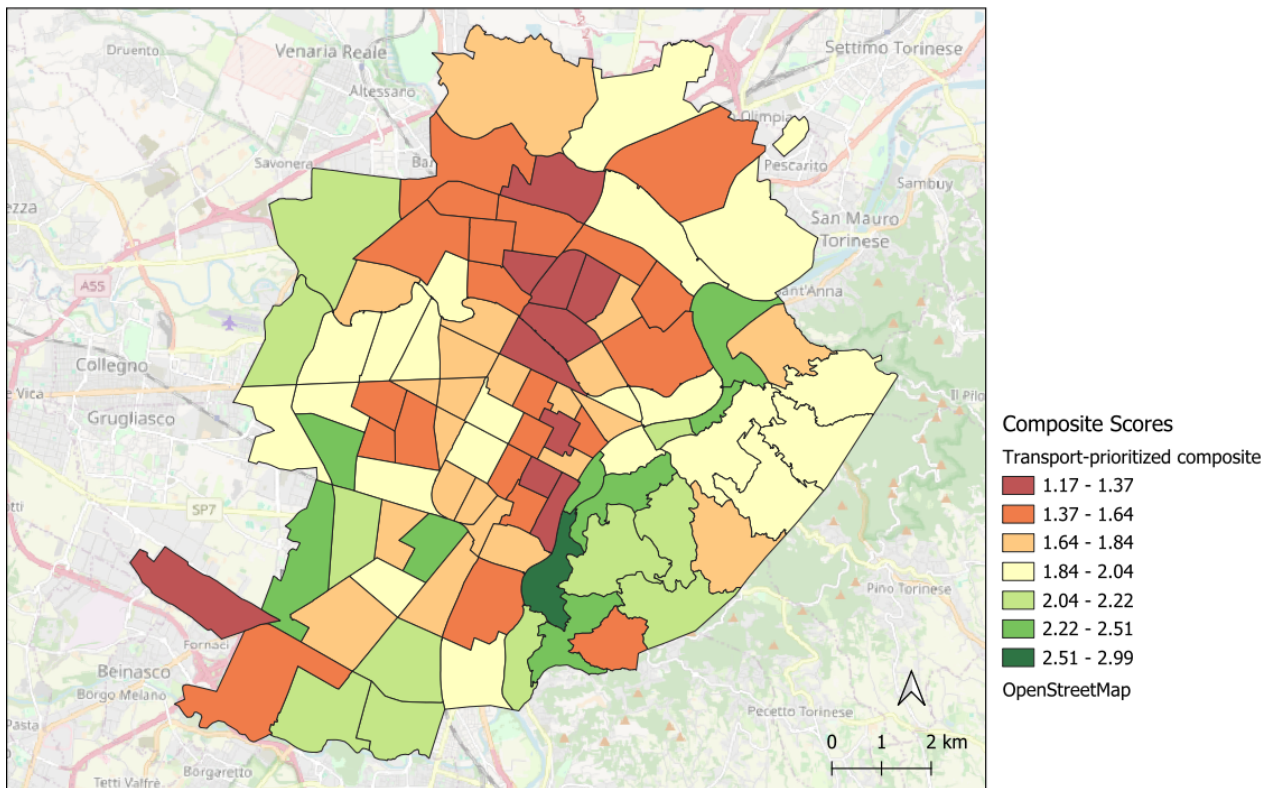


Figure 6.13: Transport-prioritized

The transport-prioritized weight assignments result in a noticeable score decrease for the areas in the eastern hills, where public transport, cycling infrastructure as well as street connectivity have a lower performance than the central areas, as illustrated in figure 6.13.

Social-Equity-prioritized

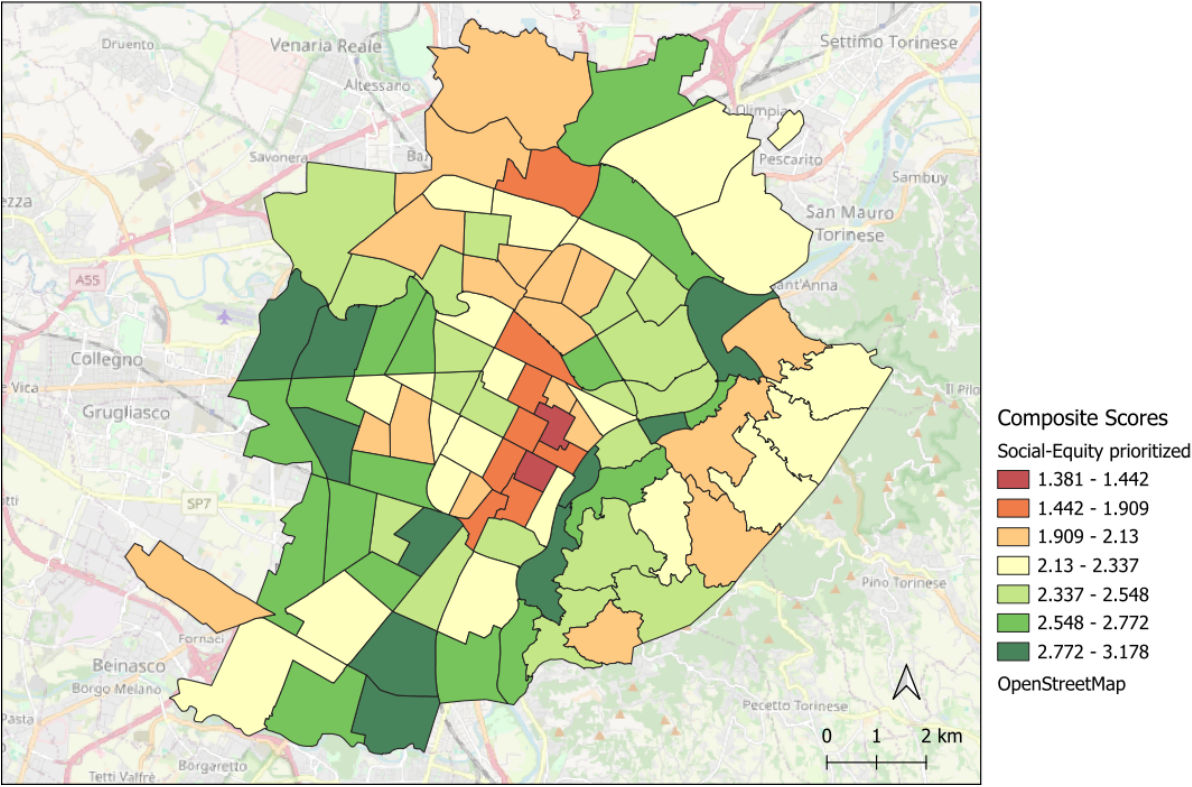


Figure 6.14: Social-Equity-prioritized

A similar, redistributive effect can be observed on the social-equity-prioritized weight assignment, with well-connected neighbourhoods with lower property prices scoring higher, as seen on figure 6.14.

Economy-prioritized

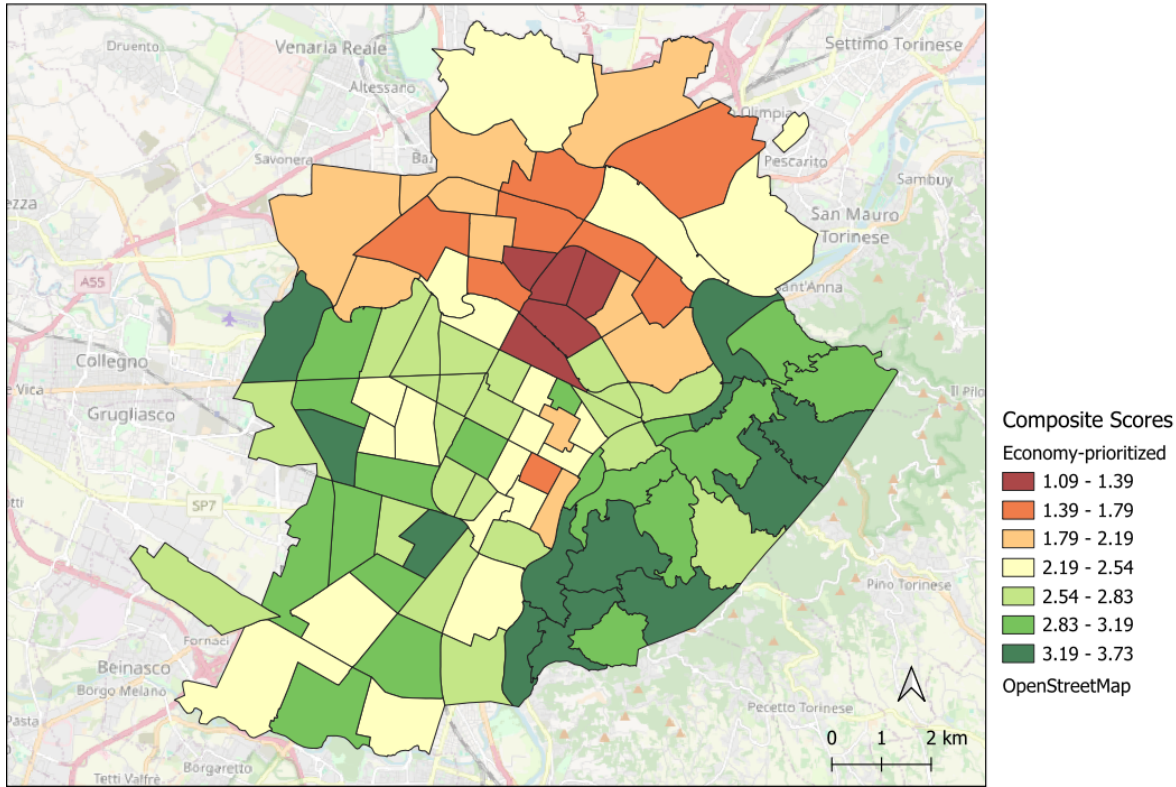


Figure 6.15: Economy-prioritized Composite Sustainability Index (CSI) scores.

Although domain H - Economy is comprises only 3 calculated indicators, they offer a good representation of the perceived neighbourhood quality, since income, employment rate and youth unemployment, can be interpreted as a gauge on human development and consequently the quality of life of the interested area.

The composite sustainability index scores for all 94 Statistical Areas can be seen on figure 6.15.

6.4 Correlation with Property Values

An exploratory cross-analysis is conducted by joining the statistical-zone composite sustainability scores to the OMI zone median residential prices (€/m²). This analysis tests the HPM prediction that neighbourhood quality (N in $P = f(S, N, L)$) is positively correlated with residential property prices (Debrezion et al., 2007; Mohammad et al., 2013). The join assigns the OMI zone price to each section based on spatial containment of the section centroid within the OMI zone.

The expected result is a significant positive Spearman rank correlation between CSI and OMI prices, consistent with the Turin-specific evidence from Bottero et al. (2023) (who document that proximity to high-quality urban parks is capitalized into Turin residential prices using a Geographically Weighted Regression approach) and the broader HPM literature. Quantifying this correlation, if it can be observed, would provide the analytical bridge between Use Case 1 and Use Case 2: suggesting that sustainability investment in currently low-scoring northern neighbourhoods could generate private-sector property value increases that could subsequently be partially recaptured through LVC mechanisms.

The first scatter plot produced uses the equal-weighted composite scores for all 94 statistical zones, in which all issues are assigned the same weight (20%) and indicators within an issue are also weighted equally.

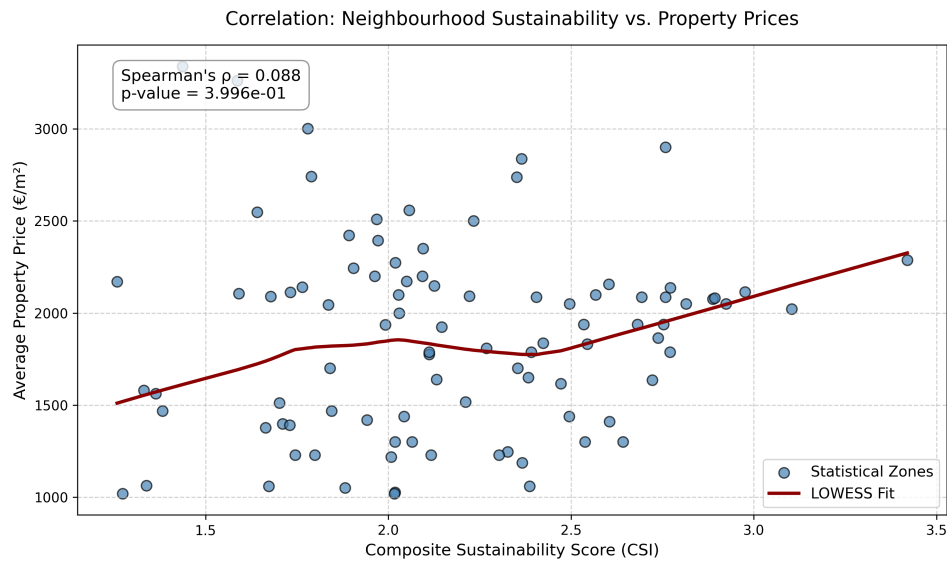


Figure 6.16: Equal-weight CSI vs Price scatter plot

Using just the equal-weight CSI scores vs property prices shows a clear lack of correlation (see 6.16). The Spearman's rho of 0.088 indicates a remarkably weak, almost non-existent positive relationship between the two variables. Areas in the historic centre, which have a lower than expected CSI have one of the highest average property prices per m2.

A second scatter plot was produced, this time using the economy-prioritized CSI scores for each of the 94 statistical zones.

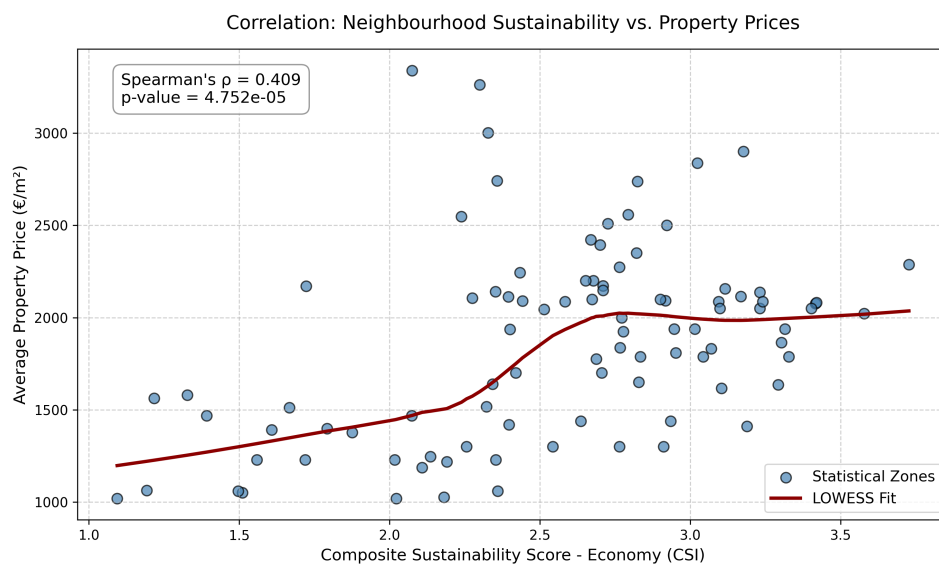


Figure 6.17: Economy-prioritized CSI vs Price scatter plot

Using the economy-prioritized scores seems to indicate a moderate positive correlation between the two variables (see 6.17). Since the economy issue includes indicators like income, employment rate and youth

unemployment rate, it was expected that areas with higher scores are more affluent and therefore command higher prices per m². The few outliers may be explained by central areas where the residential price per m² can be distorted by the high presence of short-term rentals, or commercial uses of residential spaces (e.g. offices, small private clinics, etc.). It is important to note that these assumptions are based on the author's own observations of the built environment on these areas, and were not validated against actual data, such as a register of short-term rentals, or commercial activity in residential buildings. They should not be interpreted as empirical evidence of this phenomenon, and simply be taken as a possible explanation, to be further investigated. These results, however, seem to indicate that contextualization is needed, and that sustainability indicators should be carefully selected if they are to produce locally-meaningful results.

6.5 Vulnerability Mapping and PRG Priority Zones

Priority Intervention Zones are defined as statistical zones that score below the 25th percentile of the Turin CSI distribution on three or more domains simultaneously. This definition identifies areas of compound disadvantage where low sustainability performance is not domain-specific but reflects a structural deficit across multiple dimensions. These are the sections where PRG intervention is both most urgently needed and most likely to generate cross-domain improvements.

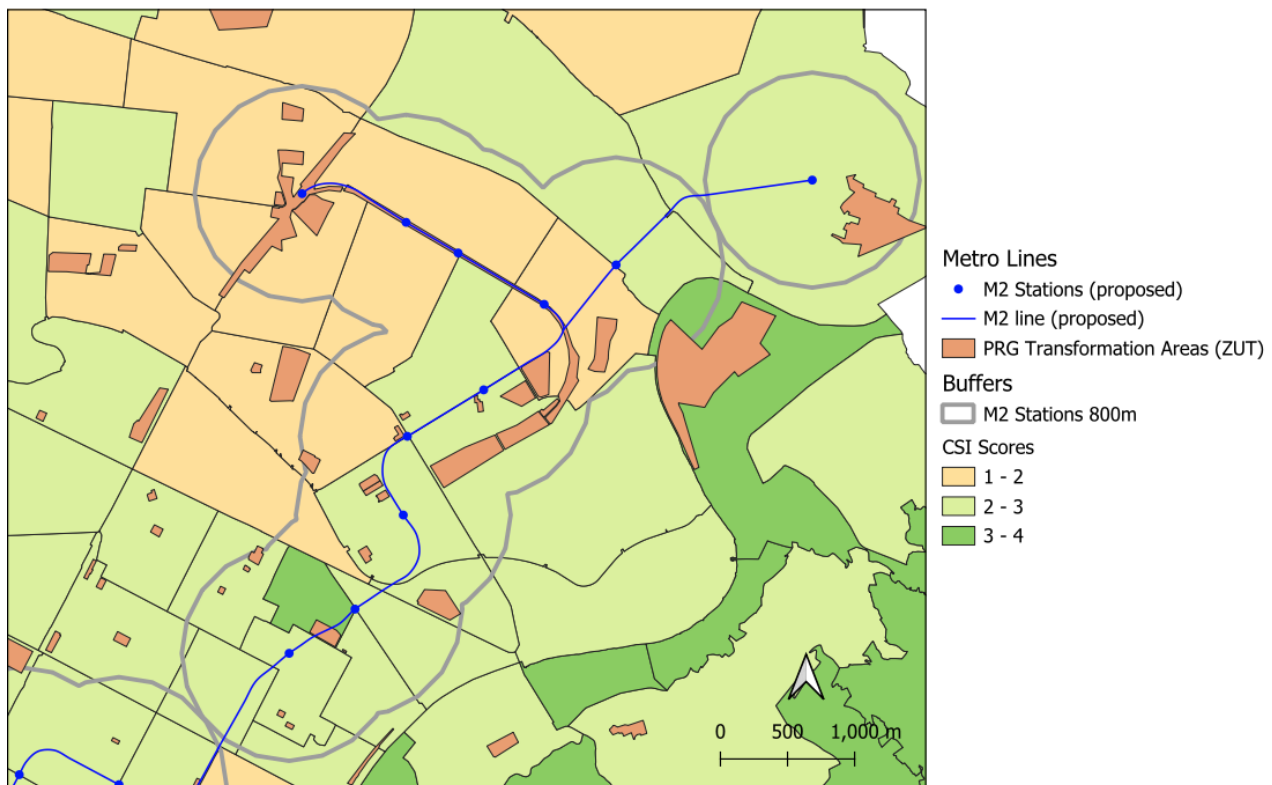


Figure 6.18: Composite CSI scores and proposed Metro Line 2, showing potential "dual dividend" areas.

The "Dual Dividend" areas are identified by overlaying the 800 m Metro Line 2 Phase I catchment with a CSI score map of the 94 statistical areas of Turin. (see figure 6.18)

Low-scoring sections within the planned metro line 2 influence zone, specially in the northern urban neighbourhoods of Bariera di Milano, Montebianco and Monterosa, represent areas where transit investment could generate a combined benefit of transport equity improvement (through F-domain score enhancement), private-sector property value uplift (through Use Case 2's Net Suitability Score), and potential LVC recapture for reinvestment in additional sustainability infrastructure.

These findings suggest a correlative basis for considering LVC mechanisms. The multivariate OLS analysis in Section 6.5.1 indicates that, holding noise and commercial concentration constant, each unit increase in the economy-prioritized CSI score is associated with an increase of approximately €479.82/m² in average OMI property values. The LVC opportunity could lie in public investments that raise economic sustainability scores in currently underperforming zones, while leveraging sustainable infrastructure (e.g. zero-emissions public transit) to improve the local property market. These associations are correlative in nature and should be read with the methodological caveats set out in Section 6.5.1.

6.5.1 Cross-Linkage: Noise, Sustainability, and Property Values

Three cross-readings are performed to explore the relationship between the noise exposure map, the composite sustainability scores, and the local property market. Rather than confirming initial hypotheses of compound deprivation, the empirical data seems to indicate a highly nuanced urban market dynamic where sustainability, quietness, and economic vitality may interact to drive Land Value Capture (LVC) potential.

Cross-reading 1: Noise and Sustainability Synergy (The “Green Oasis” Effect). The noise exposure map was overlaid with the Composite Sustainability Index (CSI) scores to test the relationship between sustainable neighbourhoods and acoustic quality. The expected result was a pattern of compound deprivation (low sustainability correlating with high noise). However, the analysis yielded a strong, statistically significant positive correlation (Spearman's $\rho = 0.623$, $p < 0.001$).

Because the noise exposure score is inverted (higher scores indicate *quieter* areas), this result demonstrates a synergistic “Green Oasis” effect. Neighbourhoods scoring highest on the CSI are also the quietest. This suggests that urban sustainability features, such as pedestrianized zones, reduced speed limits, and active mobility infrastructure, may function as noise buffers. Rather than competing forces, public investment in spatial sustainability, could improve acoustic quality. Since the noise scores were primarily calculated using road and traffic noise, it is expected that areas with less traffic, lower concentration of heavier vehicles and lower overall speed limits (e.g. residential roads), would score higher.

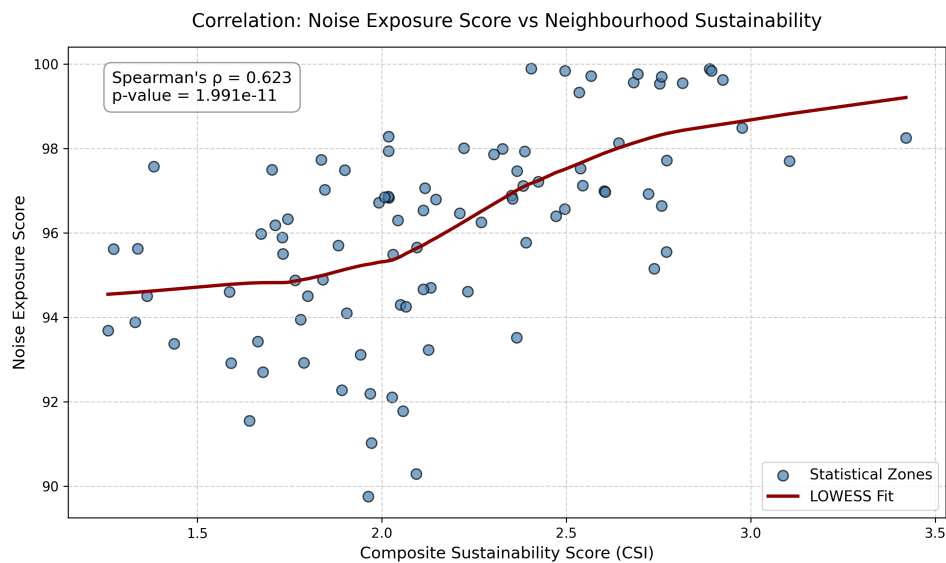


Figure 6.19: Correlation between CSI and Noise Exposure Score (higher score = quieter environment). The strong positive trend illustrates the synergistic relationship between sustainability and acoustic quality.

Cross-reading 2: Noise and OMI Property Values (The Accessibility Premium). To assess how the private market prices this acoustic quality, noise scores were correlated with mean OMI residential property values (€/m²). This bivariate analysis seems to reveal a weak-to-moderate negative correlation (Spearman's $\rho = -0.280$, $p = 0.006$).

While counterintuitive, implying that quieter areas command lower property values, this dynamic highlights a classic urban accessibility premium. The absolute quietest zones are often peripheral, sprawling suburbs lacking commercial vitality. Conversely, noisier areas are heavily concentrated near the city centre and along major arterial corridors. The higher property values in these areas seems to indicate that the private market may prioritize centrality, retail density, and transit access, accepting the resulting noise as an unavoidable byproduct of urban vitality.

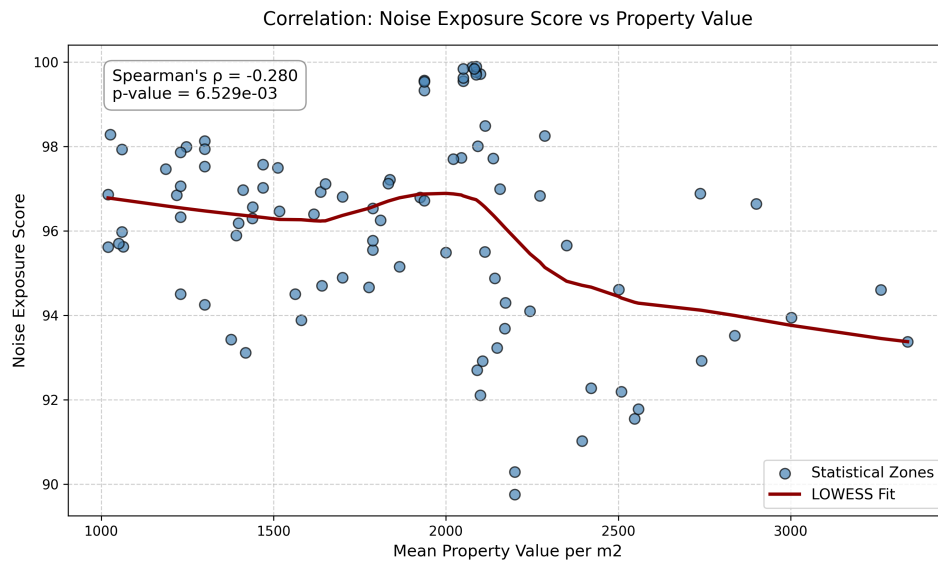


Figure 6.20: Correlation between Noise Exposure Score and Mean Property Value. The negative trend highlights the market premium placed on noisier, highly accessible central locations over quieter peripheral zones.

Cross-reading 3: Multivariable OLS Regression, Commercial Vitality, and LVC Implications.

Because the bivariate tests suffered from omitted variable bias, conflating the value of quietness with the value of centrality, a multivariable Ordinary Least Squares (OLS) regression was conducted. The analysis was performed on 93 *zone statistiche*; zone 09bis (Parco del Valentino) was excluded because no OMI residential price data is available for that predominantly parkland zone. The initial model specified OMI price as the dependent variable, with the economy-prioritized CSI score and the noise exposure score as independent variables ($n = 93$, $R^2 = 0.375$, $p < 0.001$). This two-predictor specification yielded a positive coefficient for the CSI score (€505.75/m² per index unit) and a negative coefficient for the quietness score (–€101.93/m² per unit), a pattern attributed in Cross-reading 2 to the commercial vitality that co-occurs with higher noise levels in central zones.

To examine this urban vitality hypothesis directly, the number of commercial activity locations per statistical zone was introduced as a third predictor (data source: *Attività Commerciali*, OGC WFS from GeoPortale Piemonte). Commercial establishment counts were log-transformed ($\ln(1 + \text{count})$) prior to inclusion, as the raw distribution is strongly right-skewed (ranging from 0 to 1,223 establishments across the 93 zones). The log-transformation is standard practice for count variables of this type and yields a coefficient interpretable as the change in property value associated with a proportional increase in commercial density.

The expanded three-predictor OLS model produces the following results ($n = 93$, $R^2 = 0.383$, adjusted $R^2 = 0.362$, $F_{3,89} = 18.40$, $p < 0.001$):

- **Economic sustainability premium:** Holding noise and commercial vitality constant, a 1-unit increase in the economy-prioritized CSI score is associated with an increase of approximately €479.82/m² in average property prices ($p < 0.001$). This estimate is directionally consistent with the two-predictor model, suggesting the economic sustainability association is stable to the addition of the commercial variable.
- **Quietness effect:** Holding the economic score and commercial count constant, a 1-unit increase in the quietness score is associated with a decrease of approximately €115.61/m² ($p < 0.001$). The slightly larger absolute magnitude relative to the two-predictor specification reflects a partial separation of the quietness and commercial dimensions.

- Commercial vitality:** The log-transformed commercial establishment count is not independently significant in the three-predictor model ($\beta = -41.13$, $p = 0.287$). This result is itself analytically informative: the Spearman correlation between the log-commercial count and the noise exposure score is moderate and negative ($\rho = -0.581$, $p < 0.001$), confirming that noisier zones are also those with higher commercial concentration. The non-significance of the commercial coefficient in the OLS model therefore indicates that the noise exposure variable is already proxying the commercial vitality effect, consistent with the interpretation advanced in Cross-reading 2. Taken together, these findings suggest that the residential market's positive valuation of noisier central zones reflects the commercial animation those areas offer, not acoustic exposure per se.

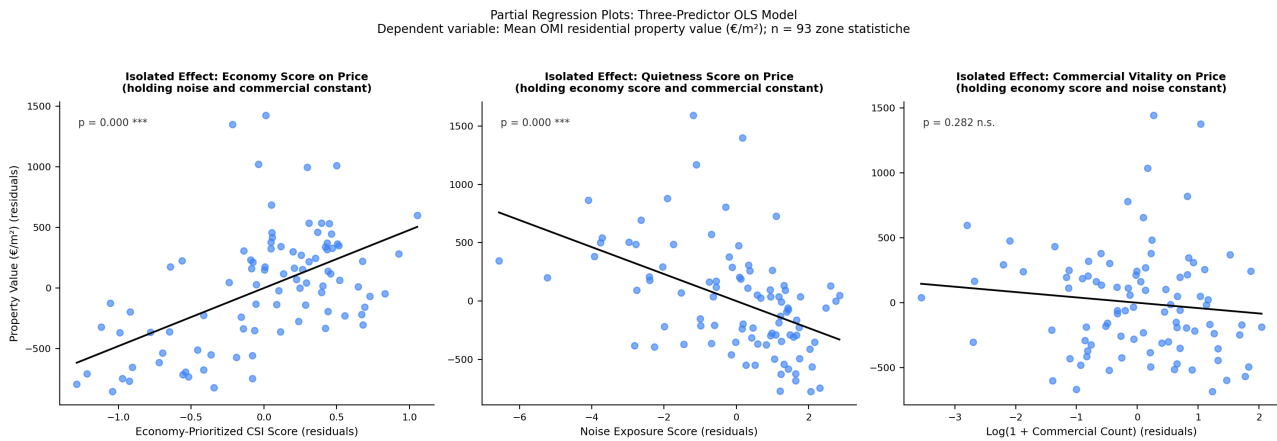


Figure 6.21: Partial regression plots isolating the independent effects of the economy-prioritized CSI score (left), noise exposure score (centre), and log-transformed commercial establishment count (right) on average OMI property values. All plots are based on the three-predictor OLS model ($n = 93$ zone statistiche). The non-significant slope of the commercial vitality panel ($p = 0.287$) indicates that once noise exposure and economic sustainability are controlled for, commercial establishment count does not contribute independent explanatory power.

Regression diagnostics. Two standard diagnostics were applied to the three-predictor model. First, the Variance Inflation Factor (VIF) was computed for each predictor to assess multicollinearity: $VIF = 1.22$ for the economy-prioritized CSI, $VIF = 1.60$ for the noise exposure score, and $VIF = 1.74$ for the log-commercial count. All values fall well below the conventional threshold of 5, indicating that multicollinearity is not a material concern and that the coefficient estimates can be interpreted independently. Second, the Breusch-Pagan test for heteroscedasticity of the residuals yields a Lagrange Multiplier statistic of 3.33 ($p = 0.344$), providing no evidence to reject the null hypothesis of constant error variance. Standard OLS standard errors are therefore appropriate for this dataset, and the reported significance levels do not require heteroscedastic-robust correction.

Contextual Limitations: Spatial Autocorrelation, Historical Dynamics, and Correlative Framing. The findings presented above are exploratory and correlative in character. The observed associations between sustainability scores, noise exposure, commercial vitality, and property values are consistent with the Hedonic Pricing Model literature, but should not be interpreted as evidence of causal mechanisms. Several methodological boundaries limit the conclusions that can be drawn from this cross-sectional OLS analysis.

First, while the Breusch-Pagan test confirms homoscedastic residuals, Moran's I on the regression residuals has not been computed, and spatial dependence in the error term cannot be ruled out. As demonstrated in recent

analyses of Turin’s property submarkets, real estate values and territorial vulnerabilities are highly clustered ([Barreca et al., 2017](#)), and standard OLS assumes independent error terms. Consequently, the coefficients derived from the OLS model may conflate the genuine associations between sustainability and property value with the baseline spatial clustering of both variables across Turin’s urban structure. Addressing this through spatial autoregressive models or Exploratory Spatial Data Analysis (ESDA) remains a necessary direction for future work to more rigorously isolate the hedonic signal ([Barreca et al., 2021](#)).

Second, the spatial distribution of noise, sustainability, and property values across Turin is not merely a product of contemporary market preferences, but is deeply entrenched in the city’s historical socioeconomic structure. Turin’s transition from a Fordist industrial powerhouse to a post-industrial landscape has left a legacy of stratified urban spaces and predefined marginality ([Bonini Baraldi et al., 2019](#)). The observed correlations therefore capture a compound signal that cannot be fully decomposed into its contemporary and historical components using cross-sectional zone-level data alone.

Chapter 7

Use Case 2 — Metro Line 2: Net Suitability and Property Value Uplift

7.1 Turin Public Transport Baseline and Equity Case

Turin’s public transport network has been shaped by two overlapping historical geographies: the radial tram grid inherited from the early twentieth century and the single automated metro corridor (Line 1) inaugurated in 2006 and subsequently extended to *Bengasi* in 2011. The legacy tram network operated by GTT currently comprises 15 active lines spanning approximately 180 route-kilometres, supplemented by an extensive bus fleet. Despite its breadth, however, the surface network suffers from structural speed penalties associated with at-grade mixed-traffic operations: average commercial speeds on GTT tram routes rarely exceed 14–16 km/h (Zini et al., 2024), rendering many cross-city journeys uncompetitive with private car use.

The spatial distribution of this accessibility deficit is not uniform. Analysis of the GTT GTFS feed (March 2026) used in Use Case 1 (Chapter 6) reveals a pronounced north-south asymmetry in aggregate daily frequency. Zone statistiche north of Piazza della Repubblica — encompassing the circoscrizioni of Aurora, Barriera di Milano, and Falchera — record average stop-level daily frequencies in the lowest quintile of the city-wide distribution, notwithstanding their comparatively high population density and elevated social vulnerability as captured by ISTAT 2021 deprivation indices. This configuration is emblematic of the broader “transit equity gap” documented in Italian metropolitan areas (Bornioli and Parkhurst, 2024): the neighbourhoods least well served by rapid transit are often those whose residents are most dependent upon it.

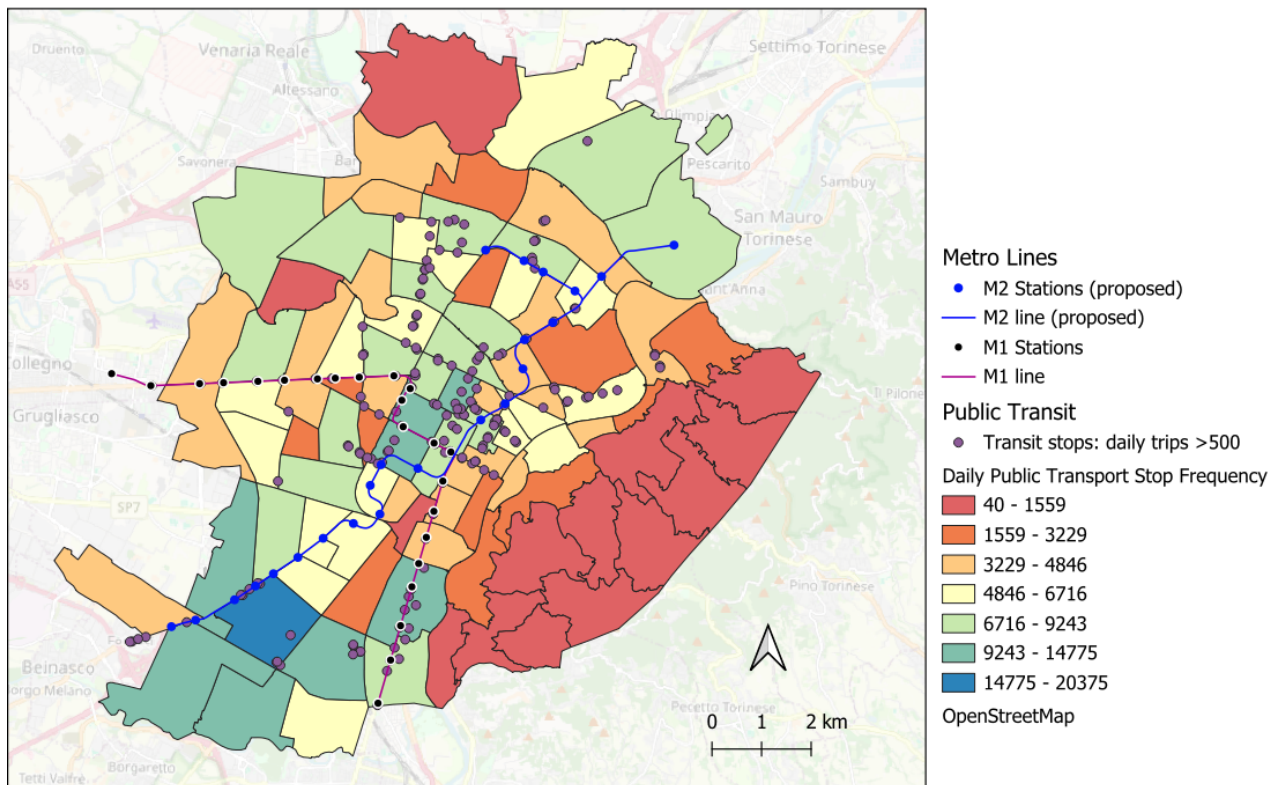


Figure 7.1: Performance of the public transport system - planned metro line 2, base map shows the number of daily PT trip stops.

The equity case for Metro Line 2 therefore rests on two complementary arguments. First, the infrastructure argument: a grade-separated metro corridor would inject a step-change in journey-time competitiveness along the east–west axis that no surface-level frequency enhancement can replicate, given the constraints imposed by Turin’s historic street fabric. Second, the distributional argument: if the alignment is designed to serve the underserved northern and north-eastern circoscrizioni — as the current Phase I corridor through *Barriera di Milano* and the planned Phase II extension towards *Falchera* and *Rebaudengo* suggest — the project can simultaneously reduce aggregate transport inequality and generate the land value uplift that funds a portion of its own construction costs through Land Value Capture instruments.

The following sections analyze UC2 through the lens of the net suitability raster model developed for this thesis: a high-resolution (5x5 m) spatial decision-support layer that operationalizes the accessibility premium and disamenity discount simultaneously.

7.2 Metro Line 2 Project Context

7.2.1 Alignment and Station Programme

The Turin Metro Line 2 project is a planned fully automated rapid transit line whose first construction lot (Lotto 1 — hereafter *Phase I*) was in the advanced design and environmental impact assessment phase as of the April 2026 data cut used for this analysis. Phase I spans from *Rebaudengo* in the north through the city centre, with stations at *Barriera di Milano*, *Nizza*, *Bengasi*, and a southern interchange node provisionally identified near

Porta Nuova. The complete alignment (*All Phases*) extends this corridor further south towards Mirafiori and south-east towards Lingotto and Millefonti, ultimately connecting with Line 1 at Bengasi to form a cross-shaped rapid transit skeleton.

For the purposes of this chapter, the spatial analysis is structured around two study footprints:

- **Phase I corridor:** defined as the 800 m pedestrian catchment union of all Phase I stations, clipped to the administrative boundary of the Comune di Torino. Vector layer: `stazioni_linea2_3003_lotto1`.
- **All Phases corridor:** defined as the 800 m catchment union of all planned stations across all phases. Vector layer: `stazioni_linea2_3003`.

The 800 m threshold is grounded in the pedestrian access literature: [Jiang et al. \(2022\)](#) demonstrate that ridership models employing this catchment outperform smaller buffers for automated metro systems in dense urban environments. [Farhan and Murray \(2008\)](#) provide the theoretical justification in terms of diminishing accessibility returns beyond the walking-speed isochrone.

It should be noted that all catchment geometries in this analysis are defined using Euclidean (straight-line) buffers rather than network-based pedestrian catchments derived from the actual street graph. Euclidean buffers are a standard simplification in transit suitability studies where computational efficiency is a priority and street network data at sufficient detail may not be uniformly available; they are consistent with the methodological approach of [Debrezion et al. \(2007\)](#) and the studies reviewed in Chapter 2. However, network-based catchments would produce more accurate accessibility estimates, particularly in areas where the street grid is irregular or where physical barriers (railway lines, arterials, waterways) reduce actual pedestrian accessibility below what the Euclidean distance implies. The replacement of Euclidean buffers with network-based pedestrian catchments derived from the OpenStreetMap Torino routing graph is identified as a priority methodological refinement for future work, and is the single modification most likely to materially alter the spatial distribution of net suitability scores in peripheral zones where street connectivity is lower than in the historic centre.

7.2.2 Urban Regeneration Context

The Phase I alignment traverses one of Turin’s most heterogeneous urban sequences. The northern segment (Rebaudengo–Barriera di Milano) passes through a zone characterized by high immigrant-origin population shares, elevated social vulnerability, and a mosaic of early twentieth-century residential stock and post-war industrial conversion. The central segment (Porta Palazzo–Piazza Repubblica) intersects the high-intensity commercial and hospitality zone that generates the “Movida” disamenity documented in Section 7.6. The southern segment approaches the spine of Corso Vittorio Emanuele II, where the urban fabric shifts to higher-end residential and professional services.

This heterogeneity makes the Phase I corridor an analytically demanding test case precisely because the net suitability surface must disentangle multiple overlapping gradients of amenity access, institutional nuisance, and acoustic load — a task for which the WLC-based raster model is purpose-built.

7.2.3 Policy and Planning Framework

Metro Line 2 is classified as a strategic infrastructure project under the *Piano Urbano della Mobilità Sostenibile* (PUMS) of the Città di Torino and is consistent with the mobility targets of Italy’s *Piano Nazionale di Ripresa e Resilienza* (PNRR), which allocates significant funding to urban rapid transit in cities above a threshold population. From a planning-law standpoint, the land development implications of the project are governed by the *Piano Regolatore Generale* (PRG) and the *Variante 200* zoning revision, which designated several *Aree di*

Trasformazione along the corridors most likely to experience value uplift — providing the legal substrate for the LVC analysis in Section 7.7.

7.3 Net Suitability Model — Phase I Results

7.3.1 Model Configuration and Inputs

The net suitability model for UC2 is a raster-based WLC pipeline executed in EPSG:3003 at 5x5 m resolution. Its structure is identical to the UC1 composite index described in Chapter 3 but is spatially constrained to the Phase I 800 m corridor mask; all pixels outside this mask are assigned NaN and excluded from normalization.

The input amenity layers, scoring logic, and weights follow those documented in Table 3.2 of Chapter 3, with the metro station layer being the dominant criterion (weight $w_{\text{metro}} = 0.40$). The two-step normalization pipeline is applied identically: raw positive scores are normalized to $[0, 100]$ before acoustic penalties are subtracted, and the residual net scores are subsequently re-normalized to $[0, 100]$ within the corridor mask.

School proximity is scored using a differentiated piecewise model calibrated by school typology, as specified in Chapter 3 (Section 3.4.3). *Scuole d’Infanzia e Primarie* apply a 100 m detractor zone reflecting parent vehicular drop-off congestion (Owusu-Edusei Jr et al., 2007; Sah et al., 2016), followed by a booster zone extending from 100 m to 400 m. *Scuole Secondarie di I e II grado* apply a narrower 50 m detractor zone (student congregation noise) and a wider booster zone extending from 50 m to 500 m, reflecting the greater independent mobility of secondary students (Muller-Judex et al., 2025). This differentiation directly shapes the suitability surface in the 0–500 m school proximity band: pixels in the immediate school vicinity receive a lower score than the approach based on simple distance decay would assign, while the booster peak is displaced outward relative to the school location. The practical consequence within the Phase I corridor is most visible in the Rebaudengo and Nizza station catchments, where dense primary school provision creates localized low-score patches in the 0–100 m ring that are visible in the final suitability raster as inversions in an otherwise radially declining score field.

The acoustic disamenity surfaces applied in Step C consist of three components:

1. **Road noise penalty** (max -15 pts): dynamic buffer derived from TGM traffic counts via CNOSSOS-EU, with buffer distance $d = 10^{(L'_{W,\text{total}} - 65)/10}$ m (target threshold 65 dB to reflect an Italian Class III mixed-use standard).
2. **Tram line penalty** (max -8 pts): static 50 m linear buffer from GTT tram line geometries, capturing flange squeal and passing-train vibration of the legacy Series 2800 fleet.
3. **Tram stop penalty** (max -12 pts): static 100 m radial buffer from GTT tram stop points, capturing pneumatic braking, acceleration peaks, and social congregation noise.

All three penalty surfaces decay linearly from their maximum value at the geometry boundary to zero at the outer buffer edge, consistent with the cylindrical geometric divergence model underlying CNOSSOS-EU.

7.3.2 Spatial Pattern of Phase I Net Suitability

The Phase I net suitability surface (7.2) exhibits a structured spatial pattern that reflects the interaction of three overlapping gradients: station proximity, civic amenity density, and acoustic load.

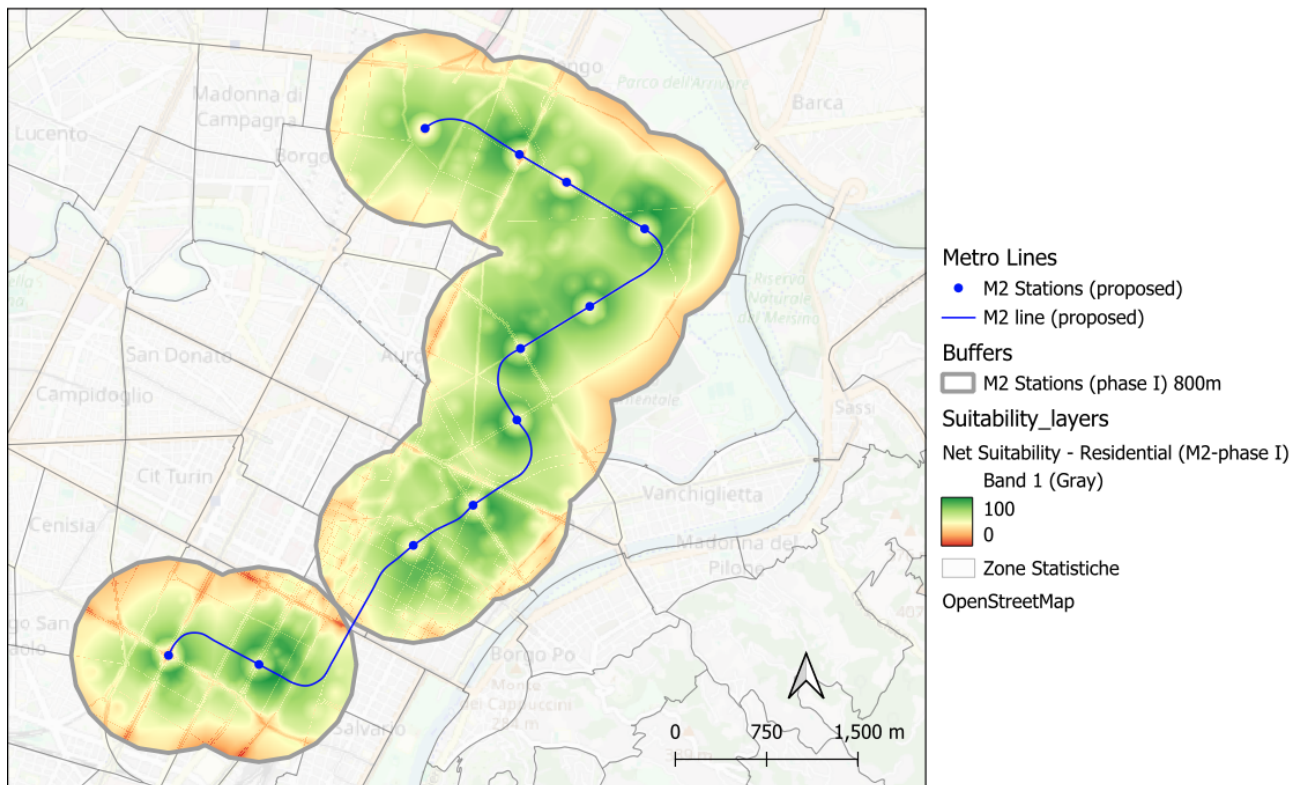


Figure 7.2: Net Suitability - Residential Properties - Line 2 Phase I

The disamenity donut. As predicted by the theoretical framework reviewed in Section 2.3.2, the lowest net suitability scores within the 800m corridor occur in the 0–150 m annulus immediately surrounding each Phase I station. Within this annulus, the metro station score function is at its minimum (the station acts as a pure detractor at $d < 150$ m), and the raster pixels are simultaneously exposed to the highest road noise penalties from the major *corsi* on which stations are typically located. In the northern stations (Rebaudengo, Barriera di Milano), this low-score annulus overlaps with the 300 m hospital detractor buffer from *Ospedale Maria Vittoria*, compounding the disamenity load.

The sweet-spot ring. Peak net suitability scores cluster in the 200–500 m band from each station. At this intermediate distance, the station score function is near its maximum (accessibility premium dominates), road noise attenuation is substantial (TGM buffers rarely exceed 120 m on secondary streets), and the piecewise scoring functions for schools, markets, and security facilities are in their booster zones.

In the central segment of the Phase I corridor, this ring intersects a dense mosaic of neighbourhood commercial services and primary schools, generating some of the highest composite scores in the city-wide analysis.

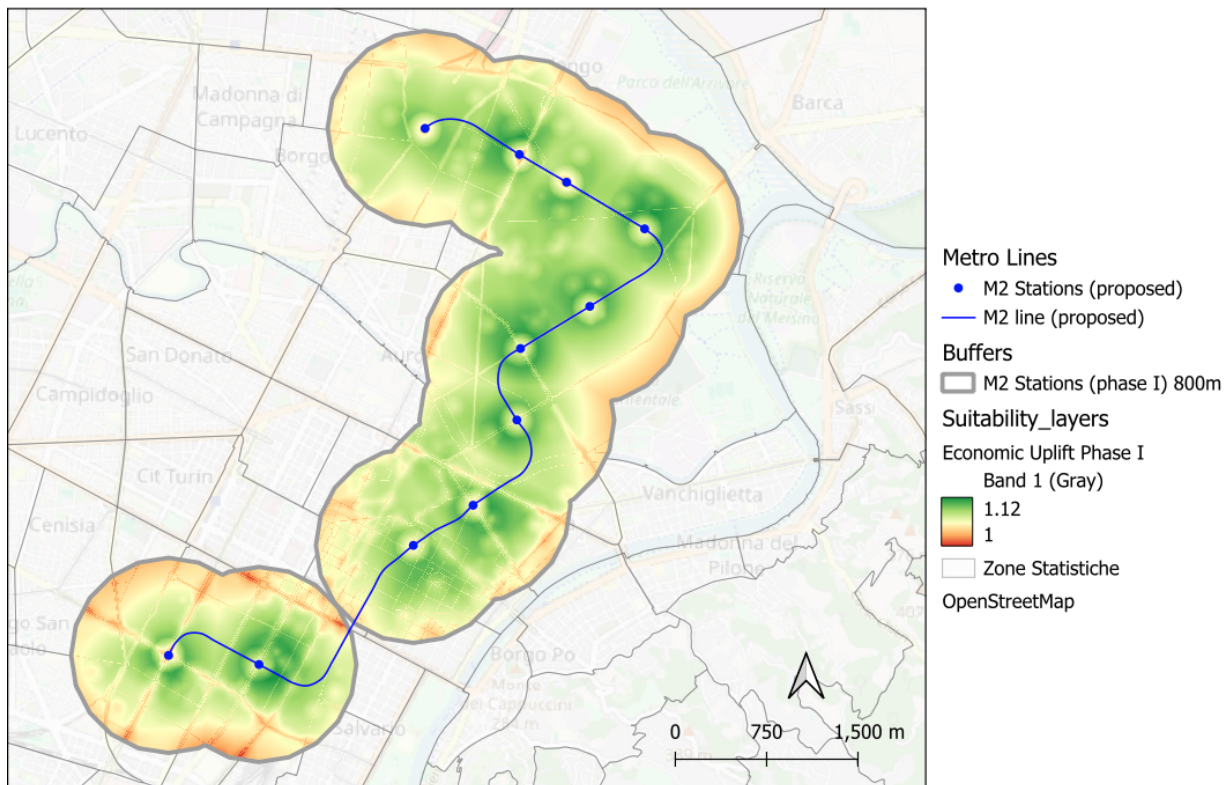


Figure 7.3: Price Uplift - Residential Properties - Line 2 Phase I

Residential price uplift around the new line 2 stations is expected to be on average between 5 and 12%, with the highest increases located in the "sweet-spot ring", as seen in 7.3, assuming there are no other detractors in the area.

7.4 Net Suitability Model — All Phases Results

7.4.1 Corridor Extension and Coverage

The All Phases scenario extends the Phase I corridor southwards and south-eastwards, incorporating the Lingotto, Millefonti, and Mirafiori stations planned for subsequent construction lots. The aggregate 800m catchment of All Phases covers an estimated 42 km² of the municipal territory, representing approximately 30% of the Comune di Torino's built-up area.

This extended corridor presents a qualitatively different suitability landscape from Phase I. The southern stations are located in urban sectors characterized by:

- Lower civic amenity density relative to the historic centre, reducing the booster contributions of secondary criteria (schools, markets, security facilities);
- Proximity to large-format infrastructure — in particular the *Lingotto* complex and the former *FIAT Mirafiori* industrial estate — whose spatial footprint introduces large-block detractor zones that suppress inner-ring suitability scores;

- Significantly lower baseline road noise loads on the secondary street network south of Corso Orbassano, where TGM counts are lower, generating wider acoustic shadow zones.

7.4.2 Comparative Phase Differencing

A methodologically important output of the UC2 analysis is the *phase differencing raster*: the pixel-wise difference between the All Phases and Phase I net suitability surfaces. This layer identifies the marginal contribution of the southern phases to corridor-wide suitability, controlling for the Phase I infrastructure that will in any case be built. Positive values in the differencing raster indicate pixels that gain suitability as new stations enter their 800 m catchment; negative values (which should be rare, given that the All Phases mask is a superset of Phase I) would indicate artifacts of the normalization re-scaling under the expanded corridor.

Because the second normalization (Step D) rescales scores relative to the within-corridor minimum and maximum, expanding the corridor to All Phases can alter the normalization anchors. This is an intentional methodological choice: it ensures that the reported net suitability score always represents the relative quality of a given pixel within the actual accessible catchment, rather than against an abstract city-wide benchmark.

7.4.3 Priority Uplift Zones - All Phases

Cross-referencing the All Phases net suitability surface with the OMI 2024–25 property price grid reveals a set of high-upside zones: statistical zones that currently trade at low-to-moderate OMI valuations but record high net suitability scores in the All Phases model. These zones are analytically distinct from the “Dual Dividend” zones identified in UC1 (Chapter 6, Section 7.7.6) — which were defined as the intersection of social deprivation and low sustainability scores — though there is partial spatial overlap in the northern corridor.

The All Phases priority uplift zones depicted in 7.4, represent parcels where:

1. Current OMI valuations are suppressed relative to the city median, suggesting market under-pricing of future accessibility gains;
2. Net suitability scores are in the upper tercile of the All Phases corridor distribution, indicating that the acoustic and civic disamenity load is relatively low despite proximity to a future station;
3. The parcel falls within a designated *Area di Trasformazione* under the PRG, meaning that development potential is formally recognized in the planning framework.

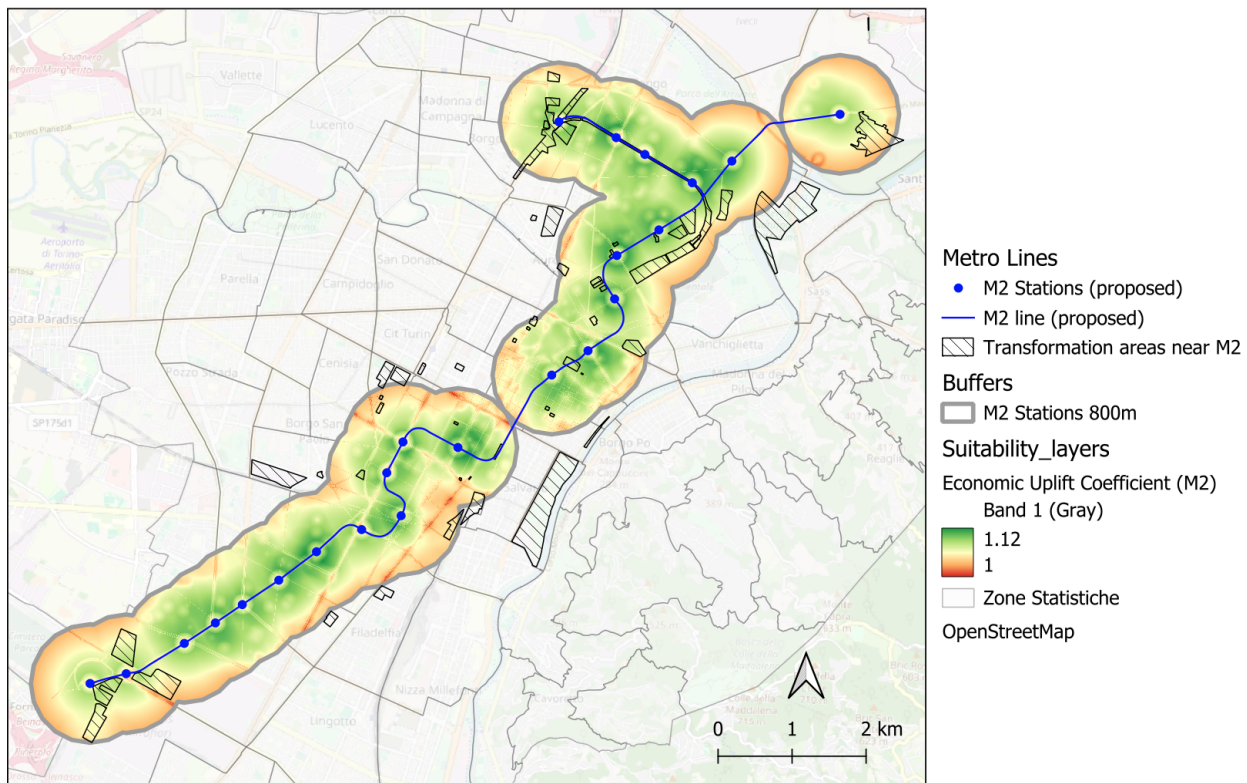


Figure 7.4: Economic Uplift - Residential Properties - Line 2 all phases

These zones could represent primary targets for LVC extraction through the *Contributo Straordinario* mechanism analyzed in Section 7.7.

7.5 Economic Uplift Model

7.5.1 Theoretical Grounding

The capitalization of rapid transit accessibility into residential property values is one of the best-documented relationships in urban economics. The meta-analysis by [Mohammad et al. \(2013\)](#) — reviewing 102 empirical studies across North America, Europe, and Asia — finds a central tendency of +8% to +12% within the primary catchment zone of a new heavy rail or automated metro station, with the effect concentrated in the 200–800 m band consistent with the suitability sweet-spot ring identified in the previous section. For Italian contexts specifically, [Cascarano and Mocetti \(2022\)](#) document a 5–8% appreciation in the Rome Metro C corridor using a difference-in-differences hedonic model; [Errera \(2020\)](#) report premiums of 8–12% for the Milan M4 line; and [Bottero et al. \(2023\)](#) estimate GWR-derived coefficients for Turin that imply capitalization rates of 6–10% for transit accessibility improvements.

The review by [Higgins and Kanaroglou \(2016\)](#) provides the methodological justification for capping the premium at approximately 12% in mature, built-up European cities: as baseline accessibility levels are already relatively high in dense urban cores, the marginal accessibility gain from a new metro station is proportionally smaller than in greenfield or peri-urban settings. This ceiling of 1.12 is adopted for the present model.

7.5.2 Uplift Coefficient Specification

The translation from net suitability score to economic uplift coefficient follows the linear interpolation model introduced in Chapter 3 (Equation 3.2):

$$\text{Coeff}_i = 1.00 + \frac{s_i}{100} \times 0.12 \quad (7.1)$$

where $s_i \in [0, 100]$ is the Step D re-normalized net suitability score at pixel i . The coefficient ranges from 1.00 (zero suitability; no metro-driven appreciation above the baseline) to 1.12 (perfect suitability; maximum 12% appreciation).

The expected price change at pixel i is:

$$\Delta P_i (\text{€/m}^2) = P_{\text{OMI},i} \times (\text{Coeff}_i - 1.00) \quad (7.2)$$

where $P_{\text{OMI},i}$ is the mean residential OMI valuation (€/m²) for the relevant OMI microzone intersecting pixel i . The product ΔP_i represents the metro-attributable value increment *above and beyond* the prevailing market valuation, capturing only the infrastructure-induced appreciation. It does not include general market inflation or neighbourhood-level gentrification driven by non-metro factors.

Assumptions and limitations. The linear interpolation model embeds several simplifying assumptions that deserve explicit acknowledgement:

1. **Linearity:** the relationship between suitability score and capitalization is assumed to be linear across the $[0, 100]$ range. Empirical evidence suggests an approximately linear relationship within the sweet-spot band (Debrezion et al., 2007), though some studies document non-linearities at the extreme ends.
2. **Stationarity:** the model assumes that the uplift coefficient structure calibrated on ex-post studies of comparable lines (Milan M4/M5, Turin Line 1) is transferable to Metro Line 2. This assumption is plausible given the comparable urban density and market maturity, but cannot be verified until post-construction hedonic analysis becomes feasible.
3. **No announcement effects:** the model does not account for the anticipatory capitalization that Cascarano and Mocetti (2022) document for Rome Metro C. In practice, some portion of the projected uplift may already be reflected in 2024–25 OMI values if market participants have discounted the infrastructure approval.
4. **Symmetric treatment of nuisances:** the model assumes that the acoustic disamenity penalties captured in the net suitability score map one-to-one onto property value reductions, consistent with the hedonic evidence reviewed in Chapter 2 (Section 2.4.4).

7.5.3 Uplift Surface Results

The estimates presented in this section are scenario-based forecasts calibrated to the Italian hedonic pricing literature and should not be interpreted as causal econometric predictions of realized market outcomes. They are derived from ex-post capitalization coefficients estimated for comparable metro projects (Cascarano and Mocetti, 2022; Errera, 2020), and are subject to the uncertainty inherent in any prospective model applied to infrastructure not yet in service.

Applying Equation 7.1 to the Phase I net suitability raster and Equation 7.2 to the OMI 2024–25 price grid yields a continuous *economic uplift surface* at 5×5m resolution. This surface is exported as `Economic_Uplift_Coefficient.tif` and `Economic_Uplift_EuroPerSqm.tif`.

Table 7.1: Expected uplift coefficient and price increment ranges for Phase I, by station proximity band. OMI reference values are approximate medians for the relevant microzones (source: Agenzia delle Entrate OMI 2024–25).

Zone	Coeff range	OMI baseline (€/m ²)		ΔP range (€/m ²)
		Low	High	
Rebaudengo / Barriera	1.00–1.06	900	1 400	0–84
Nizza / central corridor	1.04–1.09	1 500	2 200	60–198
Porta Nuova environs	1.06–1.12	2 000	3 200	120–384
All Phases corridor (overall)	1.00–1.12	900	3 200	0–384

Table 7.1 reveals the structural asymmetry in metro-attributable value creation. Although the northern stations (Rebaudengo, Barriera di Milano) serve the highest-deprivation neighbourhoods — where the equity rationale for the investment is strongest — the absolute *monetary* uplift they generate is comparatively modest, precisely because OMI baseline prices are low. Conversely, the central and southern high-value zones generate substantially larger absolute increments while commanding higher baseline prices. This distributional finding has direct implications for LVC design: a *Contributo Straordinario* rate calibrated as a fixed percentage of the uplift will structurally transfer more revenue from already-expensive areas, while providing a smaller absolute subsidy cross to the equity-priority northern zones unless explicitly counter-weighted.

7.5.4 Aggregate Uplift Estimation

To compute an order-of-magnitude estimate of aggregate metro-attributable value creation across the Phase I corridor, let $\mathcal{R}$ denote the set of residential raster pixels within the corridor mask, and let $A_{\text{pixel}} = 25 \text{ m}^2$ be the pixel area. The aggregate uplift $\Sigma\Delta V$ (€) is:

$$\Sigma\Delta V = A_{\text{pixel}} \times \sum_{i \in \mathcal{R}} \Delta P_i \times k_{\text{res},i} \quad (7.3)$$

where $k_{\text{res},i}$ is the residential land-use coefficient at pixel i , masking out non-residential pixels (industrial, commercial, public uses). Equation 7.3 is computed on the rasterized residential footprint derived from the ISTAT 2021 surface area dataset used in UC1.

This aggregate figure provides the numerator for the LVC efficiency ratio introduced in Section 7.7: the share of infrastructure-attributable value creation that is captured through planning obligations relative to total projected uplift.

7.5.5 Sensitivity of Uplift Estimates to Capitalization Ceiling Assumptions

The uplift coefficient model adopted in this thesis is calibrated to a central capitalization ceiling of 12%, consistent with the upper bound of the GWR-derived coefficients reported for Turin by [Cascarano and Mocetti \(2022\)](#) and the upper range of the Italian HPM meta-analysis literature reviewed in Chapter 2. Because the ceiling parameter directly scales all uplift estimates, the aggregate LVC potential is proportionally sensitive to this assumption. Table 7.2 presents a qualitative sensitivity assessment under three alternative ceiling scenarios, derived by rescaling the central-case uplift surface proportionally.

Table 7.2: Qualitative sensitivity of Phase I uplift estimates to capitalization ceiling assumption. Directional magnitudes relative to the central case (12% ceiling).

Scenario	Cap. ceiling	Pixel range	uplift	Aggregate LVC potential	Key assumption
Conservative	6%	$\approx 50\%$ of central case		Substantially lower	Reflects lower-end HPM estimates; appropriate if announcement effects have already partially capitalized
Central (adopted)	12%	€0–84/m ² (north); €120–384/m ² (south)		Central estimate	Consistent with GWR coefficients and Italian HPM meta-analysis upper range
Optimistic	15%	$\approx 125\%$ of central case		Moderately higher	Appropriate only if post-construction survey data confirm full capitalization without displacement effects

Note: Pixel uplift ranges and aggregate figures for the Conservative and Optimistic scenarios are qualitative extrapolations from the central case. Precise values require re-running the full pipeline with modified ceiling parameters. The 9% intermediate scenario (midpoint between Conservative and Central) would yield uplift estimates approximately 25% below the central case.

The sensitivity analysis confirms that the directional conclusion, that Phase I generates substantially higher absolute uplift in the already-expensive southern corridor relative to the equity-priority northern segment, is robust across all three ceiling scenarios, since the spatial distribution of net suitability scores does not change with the ceiling parameter. What changes is the absolute magnitude of projected price increments and aggregate LVC revenue, both of which scale proportionally with the ceiling assumption. Planning applications should therefore treat the aggregate LVC figure as an order-of-magnitude ceiling rather than a precise revenue forecast, and sensitivity to the capitalization rate assumption should be disclosed when the figures are used in policy or financial analysis.

7.6 Compound Disamenity and Acoustic Shadow Analysis

7.6.1 Conceptual Framework

A key analytical contribution of UC2 is the systematic identification of *compound disamenity zones*: spatial configurations in which multiple distinct noise or nuisance sources simultaneously penalize the same raster pixels, producing a cumulative drag on net suitability that exceeds what any single source would generate alone. The raster map algebra structure of the model makes this analysis tractable: because each penalty surface is computed and stored as an independent GeoTIFF layer before summation in Step C, it is straightforward to compute pixel-wise overlap counts and aggregate penalty magnitudes.

Three compound configurations are of particular analytical interest in the Phase I corridor:

1. **Major Corso plus Metro Station vicinity:** Pixels in the 0–150 m annulus of a station that also fall within the dynamic CNOSSOS-EU road noise buffer of a high-traffic *corso*. This configuration generates a penalty of up to $-15 - 0$ (station detractor is score zero, not an additional subtracted penalty) from road

noise alone, compounded by the station’s “disamenity donut” effect.

2. **Tram line plus Tram stop overlap:** Within a 50 m band of a tram line that also falls within 100 m of a tram stop, both the −8 pt line penalty and the −12 pt stop penalty apply simultaneously. These pixels represent the highest acoustic load attributable to legacy surface transit, with a combined maximum of −20 pts before road noise is added.
3. **Hospital zone plus Road noise:** The 300 m detractor annulus of a hospital or major healthcare facility that simultaneously overlaps with a TGM-derived road noise buffer. Within this zone, the siren-and-ambulance traffic externality is compounded by the background road noise from the access *via*, generating a compound detractor configuration that suppresses suitability even in otherwise well-served neighbourhoods.

7.6.2 The “Movida” Externality

Research indicates that properties exposed to nocturnal noise exceeding ambient thresholds in these districts experience a price discount of approximately 0.33% per additional dB, with properties in high-noise zones trading at 10–20% below comparably located units two blocks away (Ottoz et al., 2023).

The spatial footprint of this externality overlaps with the Phase I corridor in the Nizza station catchment zone, where the 150–250 m Movida buffer intersects with the metro station sweet-spot ring. The present model does not include a Movida penalty layer — this is identified as a limitation in Section 7.6.3 below, but the analysis of compound configurations at this station should be read with the understanding that reported suitability scores may be optimistic for pixels exposed to nocturnal noise concentrations.

7.6.3 Spatial Pattern of Compound Disamenity

The compound disamenity map derived from pixel-wise overlap counting reveals a non-random spatial structure. High-compound zones cluster along three linear features:

- **Corso Giulio Cesare** (northern segment): where elevated TGM road noise buffers overlap with the Rebaudengo and Barriera station proximity detractors and with the tram route 4 corridor.
- **Corso Vittorio Emanuele II / Corso Massimo d’Azeglio** (central–southern segment): where road noise from one of Turin’s highest-volume arterials interacts with tram routes 16 and 10 and the Porta Nuova station disamenity donut.
- **Via Nizza** (southern segment, leading towards Lingotto): a corridor characterized by tram route 18 noise, moderate road traffic, and limited acoustic shielding due to the relatively open urban morphology of this area.

Conversely, acoustic shadow zones — where building fabric provides passive shielding from linear noise sources — are most pronounced in the historic urban blocks between Corso Re Umberto and Corso Galileo Ferraris, in the inner courts of the *isolati* of the Crocetta district. These locations combine metro sweet-spot accessibility, low road noise (interior streets carry low TGM), and minimal tram infrastructure, yielding some of the highest net suitability scores in the Phase I corridor.

The acoustic shadow geography has a direct implication for investment decision-making: the units with the highest predicted net suitability — and consequently the highest uplift coefficients — are not the units immediately fronting the transit infrastructure but rather those occupying the interior fabric of well-connected residential blocks. This “second-row premium” (Errera, 2020) is explicitly encoded in the raster model and should be visible in the spatial distribution of `Economic_Uplift_Coefficient.tif`.

7.6.4 Sensitivity Analysis: Tram Network Retirement Scenario

A policy-relevant scenario embedded in the UC2 model concerns the partial retirement of legacy tram routes once Metro Line 2 enters service. If, as has been discussed in GTT operational planning documents, the routes most directly paralleled by the new metro alignment (routes 4 and 10 on the northern and central segments) were reduced in frequency or re-routed, the tram line and tram stop penalty surfaces would be proportionally reduced.

To operationalize this scenario, the model can be re-run with the tram penalty layers set to zero for the affected routes, holding all other inputs constant. The expected outcome is a measurable increase in net suitability scores, and consequently uplift coefficients, in the compound disamenity zones identified above. This scenario analysis directly quantifies the *complementarity* between the new metro infrastructure and the reform of the legacy surface network: the two interventions together generate non-additive suitability gains that neither would produce independently.

7.7 Land Value Capture Implications

7.7.1 The Italian LVC Framework

Land Value Capture (LVC) refers to the policy instruments through which public authorities recover a share of the value uplift that public infrastructure investment creates in land and property markets, using the captured revenue to finance the infrastructure itself or associated social goods (Giannakis and Bruzzo, 2023). In the Italian planning law context, the primary LVC instrument is the *Contributo Straordinario*, established under Article 16 of D.P.R. 380/2001 (the *Testo Unico dell’Edilizia*).

The Contributo Straordinario applies when a rezoning, variance, or planning permission “extraordinary” to the general plan generates a measurable increase in the economic value of the affected land parcel. The competent municipality may require the landowner or developer to transfer to the public authority a contribution not exceeding 66% of the value increment thus created — with the precise rate to be determined by the municipal council within this ceiling. For a project of the scale and infrastructure-attribution clarity of Metro Line 2, the legal basis for applying the Contributo Straordinario to *Aree di Trasformazione* within the 800 m corridor is well-established in Italian administrative jurisprudence.

7.7.2 Aree di Trasformazione as Primary LVC Targets

The PRG Variante 200 designates a set of *Aree di Trasformazione* along the Phase I and All Phases corridors. These are parcels whose existing use is deemed incompatible with the long-term plan and which are formally earmarked for redevelopment, subject to an approved *Piano Esecutivo Convenzionato* (PEC) or *Accordo di Programma*. The Variante 200 designation makes these parcels the most legally tractable LVC targets: the change in planning status from, e.g., industrial use (*D2*) to residential/mixed use (*R*), combined with the metro-attributable suitability uplift, constitutes the value increment on which the Contributo Straordinario is assessed.

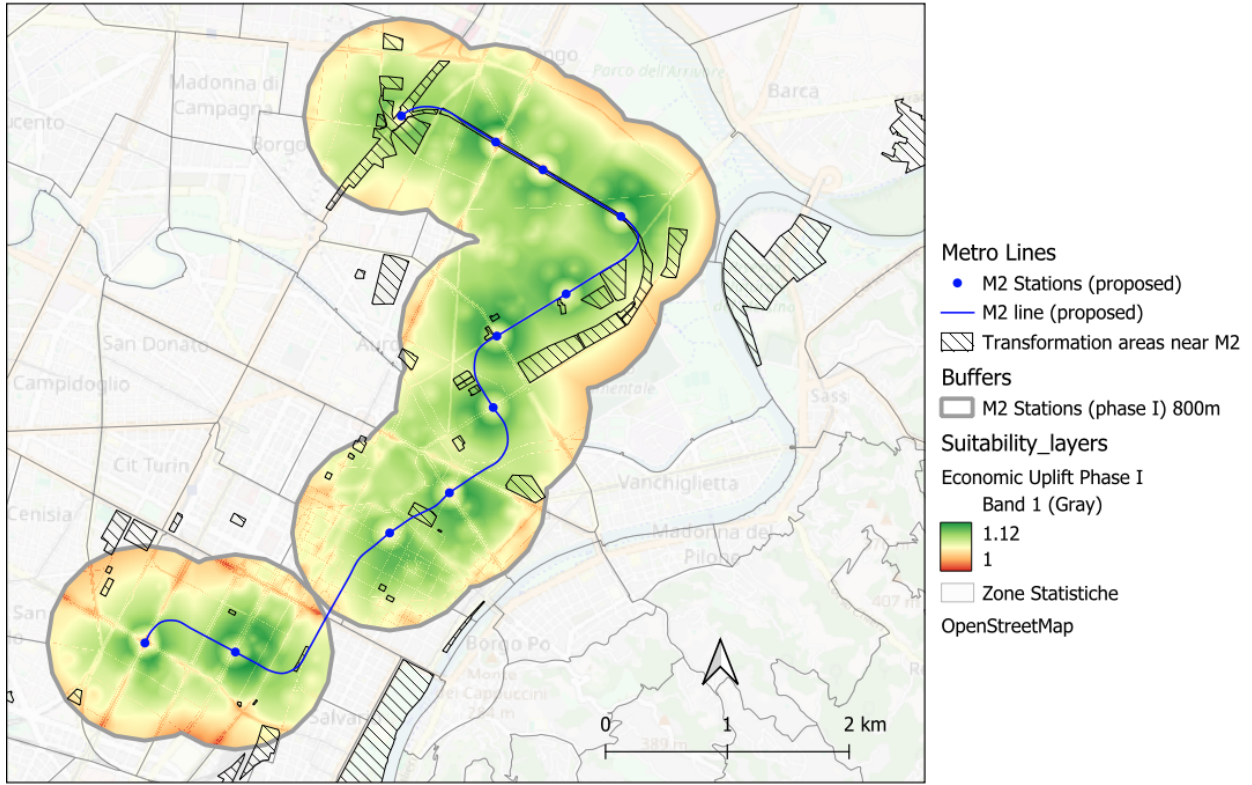


Figure 7.5: Transformation Areas within Line 2 - Phase I catchment area

Within the Phase I corridor, the most significant Aree di Trasformazione include former industrial sites in the Aurora and Barriera di Milano districts (northern segment), where conversion from $D2/D3$ to residential use is already underway in adjacent parcels.

7.7.3 LVC Calculation Methodology

The UC2 model produces the direct inputs required for a first-order LVC estimate. For each *Area di Trasformazione* parcel j intersecting the corridor mask, the metro-attributable value uplift is:

$$\Delta V_j = \sum_{i \in j} \Delta P_i \times A_{\text{pixel}} \times k_{\text{res},i} \quad (7.4)$$

where the summation is over all residential-classified pixels within parcel j . The maximum recoverable LVC contribution from parcel j under D.P.R. 380/2001 is then:

$$CS_j = \alpha_j \times \Delta V_j, \quad \alpha_j \leq 0.66 \quad (7.5)$$

where α_j is the capture rate set by municipal resolution. In French Grand Paris Express experience, capture rates of 15–30% have been applied for comparable transit projects (Ferm and Moore-Cherry, 2025); the Lombardy Regional Law 12/2005 (amended 2018) established precedent for rates of 20–40% in Milanese TOD zones (Micelli, 2018). A benchmark capture rate of $\alpha = 0.25$ (25%) is adopted for the illustrative calculations in this chapter, on the grounds that it balances LVC revenue generation with developer viability.

7.7.4 Aggregate LVC Potential — Phase I

Combining the aggregate uplift estimation (Equation 7.3) with the 25% capture rate benchmark:

$$CS_{\text{total}} = 0.25 \times \Sigma \Delta V \quad (7.6)$$

The resulting aggregate LVC potential from Phase I provides an order-of-magnitude ceiling on the revenue available through planning obligations. This should be interpreted as a *theoretical maximum* under the assumption that (a) all Aree di Trasformazione are fully redeveloped, (b) the metro project is the sole driver of value uplift (no concurrent market appreciation), and (c) all uplift is captured at the statutory ceiling. In practice, implementation frictions: negotiation with developers, market cycle timing, phased build-out, would reduce realized capture rates.

7.7.5 Policy Recommendations

The UC2 analysis generates four actionable policy recommendations for the Città di Torino:

- 1. Differentiated capture rates.** Given the distributional asymmetry documented in Section 7.5.3 — whereby absolute monetary uplifts are highest in already-expensive central zones and lowest in the equity-priority northern corridor — the municipality should consider applying higher capture rates ($\alpha \approx 0.40$) in the central and southern zones and lower rates ($\alpha \approx 0.15$) in the northern Barriera di Milano and Rebaudengo catchments. This would partially counteract the regressive spatial logic of a flat-rate LVC regime.
- 2. Early designation of Aree di Trasformazione.** Planning designation of transformation areas should precede the announcement of final station locations, to minimize anticipatory “announcement effect” capitalization that reduces the net uplift available for capture. The evidence from Rome Metro C (Cascarano and Mocetti, 2022) demonstrates that a significant share of total capitalization occurs in the announcement phase, before any physical construction.
- 3. Temporal staging of contribution obligations.** LVC obligations should be structured as *phased contributions* tied to construction milestones rather than lump-sum payments at permit issuance. This reduces developer viability risk and aligns the obligation timing with the actual delivery of the accessibility benefit.
- 4. Ring-fencing of captured revenue.** To maintain political legitimacy and community acceptance of LVC — a persistent challenge in Italian contexts (Giannakis and Bruzzo, 2023) — captured revenue should be formally ring-fenced for infrastructure maintenance, urban quality improvements, and affordable housing in the Phase I catchment, with mandatory annual public reporting on disbursements.

7.7.6 Relationship to the Dual Dividend Framework

The “Dual Dividend” concept introduced in UC1 — zones where simultaneous gains in sustainability and equity are achievable — takes on additional texture in the UC2 LVC context. In the northern Phase I corridor, the Dual Dividend zones identified in Chapter 6 coincide with areas of relatively modest absolute LVC potential but maximum equity benefit per euro of infrastructure investment. The UC2 model makes this trade-off explicit and spatially legible: policymakers and planners can visualize the precise geography of the “revenue vs. equity” dilemma and make transparent choices about capture rate calibration.

This is precisely the decision-support function that the dashboard architecture described in Chapter 8 is designed to facilitate: rendering complex, multi-criteria spatial trade-offs in formats accessible to planning officials, real estate professionals, and citizens simultaneously.

Chapter 8

The Dashboard: A Unified Decision-Support System

The computational outputs of Use Cases 1 and 2 constitute a rich analytical resource: composite sustainability indices across 94 *zone statistiche*, domain-by-domain score maps, net suitability rasters at 5 m×5 m resolution, and pixel-level economic uplift surfaces. Translating these outputs into urban governance outcomes, however, is not automatic. Research on planning information systems consistently identifies an implementation gap between the production of spatial intelligence and its uptake in decision-making: raw raster outputs or static choropleth maps are inaccessible to non-specialist actors and fail to communicate the conditional, scenario-dependent nature of the underlying analysis (Kitchin et al., 2015).

The decision-support system (DSS) described in this chapter is designed to close this gap. It operationalizes the analytical outputs of both use cases as an interactive, web-based interface that surfaces spatial information at the appropriate level of granularity for three structurally distinct user communities: city planning officials, real estate development professionals, and retail investors or citizens. This chapter describes both the system as implemented at the time of thesis submission and the target multi-user architecture towards which the prototype is designed to evolve.

8.1 From Analysis to Action: The DSS Rationale

Urban sustainability assessments and transit suitability models have limited policy impact when they remain in the form of academic outputs accessible only to their authors. The translation from analysis to decision requires an interface layer that adapts complex geospatial intelligence to the operational context of each user group. This is the fundamental rationale for integrating the two use cases of this thesis into a shared dashboard platform.

The approach is consistent with the communicative planning and Public Participation GIS (PPGIS) tradition, in which geospatial tools serve not merely as reporting systems but as boundary objects (Star and Griesemer, 1989): shared analytical artefacts that enable productive dialogue between communities of practice with different spatial knowledge and decision horizons. A planning official evaluating Priority Intervention Zones for the PRG revision, a real estate professional assessing Metro Line 2 corridor investment opportunities, and a prospective resident comparing neighbourhood sustainability profiles are engaged in fundamentally different decision processes, but they all benefit from access to the same underlying spatial dataset. The dashboard makes this shared access possible while adapting the presentation to each audience's needs.

8.2 Design Philosophy and Target Architecture

8.2.1 Guiding Principles

The dashboard was designed according to five principles derived from the literature on urban analytics platforms (Aminrad, 2024). These principles guided both the current prototype and the target multi-user architecture described in Section 8.5:

Principle 1 — Layered Complexity. The system exposes analytical depth progressively. In the current implementation, users can drill from the city-wide composite sustainability score down to individual domain scores, then to individual indicators, and finally to the raw data and score for a specific neighbourhood. The same layered approach is intended for the UC2 outputs: a pixel-level net suitability score accessible from a zone-level uplift summary.

Principle 2 — Transparent Methodology. Every metric displayed should be traceable to its source data and computation method. In the current prototype, indicator definitions, benchmark values, criterion types (HIB/LIB), and units are all visible in the Configure panel; users can inspect the normalization parameters for any indicator before interpreting the resulting scores. A full methodology card system (accessible through a toggle in the map popup) is planned for Phase II.

Principle 3 — Scenario Interactivity. Users should be able to modify model parameters and observe downstream effects. In the current implementation this is realized for UC1: indicator weights and benchmarks can be modified directly in the Configure panel, and the scoring engine recomputes all results on the next Generate call. Interactive recalculation of the UC2 net suitability raster within the browser environment is planned for Phase II.

Principle 4 — Equity Visibility. The Priority Intervention Zones and Dual Dividend areas identified in UC1 should be prominently co-displayed with the UC2 economic uplift surface, so that equity geography remains visible to all user types regardless of their primary analytical purpose. In the current prototype, both the UC1 sustainability choropleth and the UC2 raster overlays are accessible within the same Leaflet map canvas, enabling direct visual comparison.

Principle 5 — Open Standards and Reproducibility. All tabular outputs can be exported as CSV files with UTF-8 encoding compatible with Excel. All spatial layers are stored in PostGIS (EPSG:3003) and importable from standard GeoPackage files via a drag-and-drop interface. Export to INSPIRE-compliant WFS endpoints is planned for Phase II.

8.2.2 Target Three-Audience Architecture

The full target architecture of the DSS is organized around three user communities with structurally different needs:

Module 1 — City Planning Officials require neighbourhood-scale evidence for PRG revision, PUMS evaluation, and EU sustainability reporting. Their priority outputs are the composite and domain-level CSI maps, Priority Intervention Zone overlays, scenario comparison tools (weight sensitivity), and structured exports for planning documents.

Module 2 — Real Estate Development Professionals require parcel-level investment intelligence for site selection, due diligence, and Contributo Straordinario estimation. Their priority outputs are the net suitability surface, the economic uplift raster, and the identification of second-row premium parcels within the Aree di Trasformazione overlay.

Module 3 — Retail Investors and Citizens require accessible plain-language summaries of neighbourhood sustainability and transit impact at the specific address level. Their priority outputs are the neighbourhood report card, the metro proximity score, and a noise environment indicator, presented in a format accessible to users without GIS literacy.

The Phase I prototype described in Section 8.3 delivers the core functionality required by Module 1 in full, provides read-only access to the UC2 outputs required by Module 2, and supports Module 3 use through the neighbourhood profile page. The remaining Module 2 and Module 3 features are designated as Phase II development priorities in Section 8.6.

8.3 Phase I Implementation: The Urban Spatial Analysis Dashboard

8.3.1 Technical Architecture

The Phase I prototype is implemented as a decoupled web application comprising a Django 4.2 REST API backend and a static HTML/JavaScript frontend, connected via an open CORS (Cross-Origin Resource Sharing) interface. The two components run as independent processes: the backend serves JSON data through the API, and the frontend is opened directly in a browser as a static HTML file. This decoupled design simplifies deployment and allows the frontend to be served from any static file host without server-side rendering.

Backend. The backend is a Django 4.2 application with GeoDjango and the Django REST Framework (DRF). Spatial data is stored in a PostgreSQL database with the PostGIS extension, using EPSG:3003 (Monte Mario / Italy zone 1) as the coordinate reference system throughout. GeoPackage files are imported to PostGIS using `ogr2ogr`, which promotes geometry types to their multi-variants and creates a GIST spatial index on the geometry column. The scoring engine, spatial analysis, and CSV data processing are implemented as service classes in `spatial_engine/services.py`. All API responses are JSON. The local development version operates on a private research server without enforced authentication, which is appropriate for the single-user research context in which it was developed and tested; the production-ready cloud version with full authentication is described in Section 8.6.

Frontend. The frontend consists of three static files: `index.html` (the main dashboard), `neighbourhood_profile.html` (the detail page), `app.js` (2,500 lines of ES2021 JavaScript), and `style.css` (a dark-theme CSS file). The interactive map is powered by Leaflet.js 1.9.4, centred on Turin at the EPSG:4326 coordinates [45.0703, 7.6869]. Large vector layers (above 10,000 features) are rendered via Mapbox Vector Tiles using the Leaflet.VectorGrid plugin; smaller layers use a single GeoJSON request for faster interactivity. No build step or package manager is required: the frontend is fully self-contained and loads its dependencies from CDN links.

Database models. The system maintains six persistent models: *SpatialLayer* (registry of imported GeoPackage layers), *AnalysisScenario* (saved spatial analysis configurations and results), *Framework* (indicator evaluation framework, three instances pre-seeded), *Issue* (thematic group within a framework), *IndicatorDefinition* (indicator with benchmarks and scoring parameters), and *IndicatorData* (raw values uploaded via CSV, one row per spatial unit). All primary keys are UUIDs.

8.3.2 Spatial Layer Management and Analysis Module

Layer management. The Layers tab provides a drag-and-drop or click-to-upload interface for `.gpkg` files up to 500 MB. On upload, the backend inspects all layers using `fiona` (without loading geometry) and imports each to PostGIS via `ogr2ogr`, creating a dynamically named table. The layer catalog displays each imported layer with its name, geometry type, feature count, and EPSG code. Layers can be toggled onto the Leaflet map (using the hybrid GeoJSON/MVT rendering strategy described above), renamed, inspected via a stats modal showing the full attribute schema, and deleted (which also drops the PostGIS table).

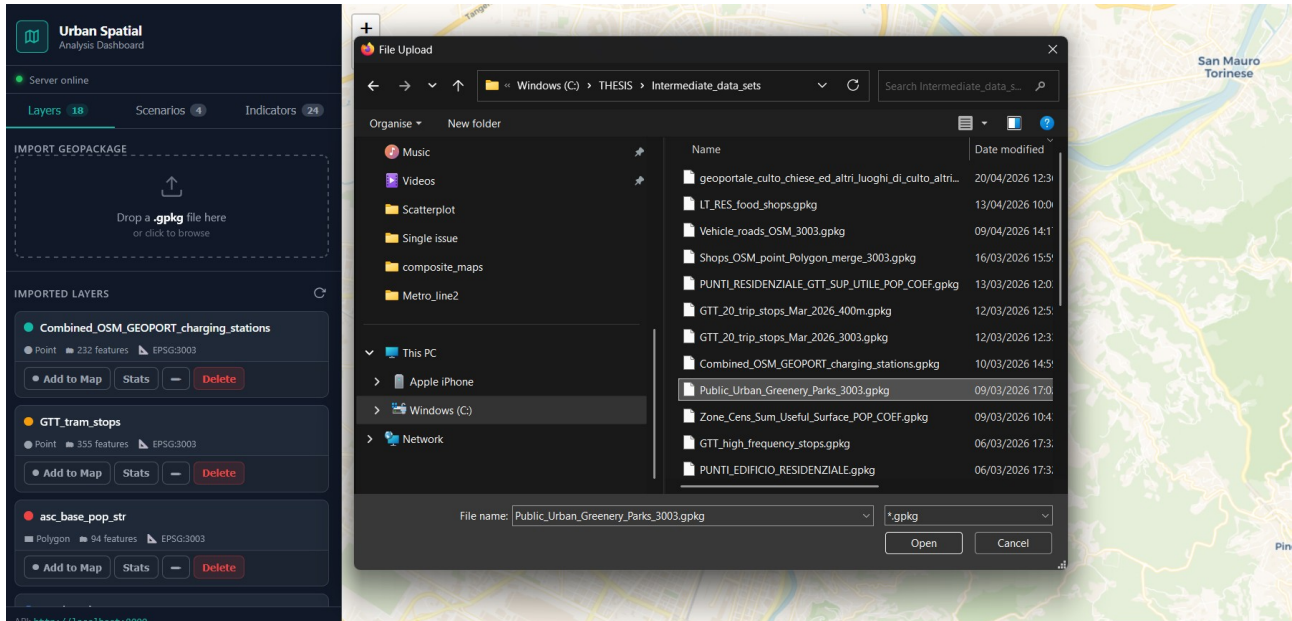


Figure 8.1: Dashboard layer management interface

Spatial analysis scenarios. The Scenarios tab allows users to define and run buffer-distance spatial join scenarios. A scenario specifies a base layer (typically a point layer such as a transit stop or school location), a join layer (typically a polygon or point layer to intersect), and a buffer radius in metres (maximum 2,000 m). On execution, the backend computes three GeoJSON FeatureCollections: all base-layer features, the dissolved buffer polygons, and all join-layer features within the buffer distance, each annotated with the minimum distance to the nearest base feature (`__min_dist_m`).

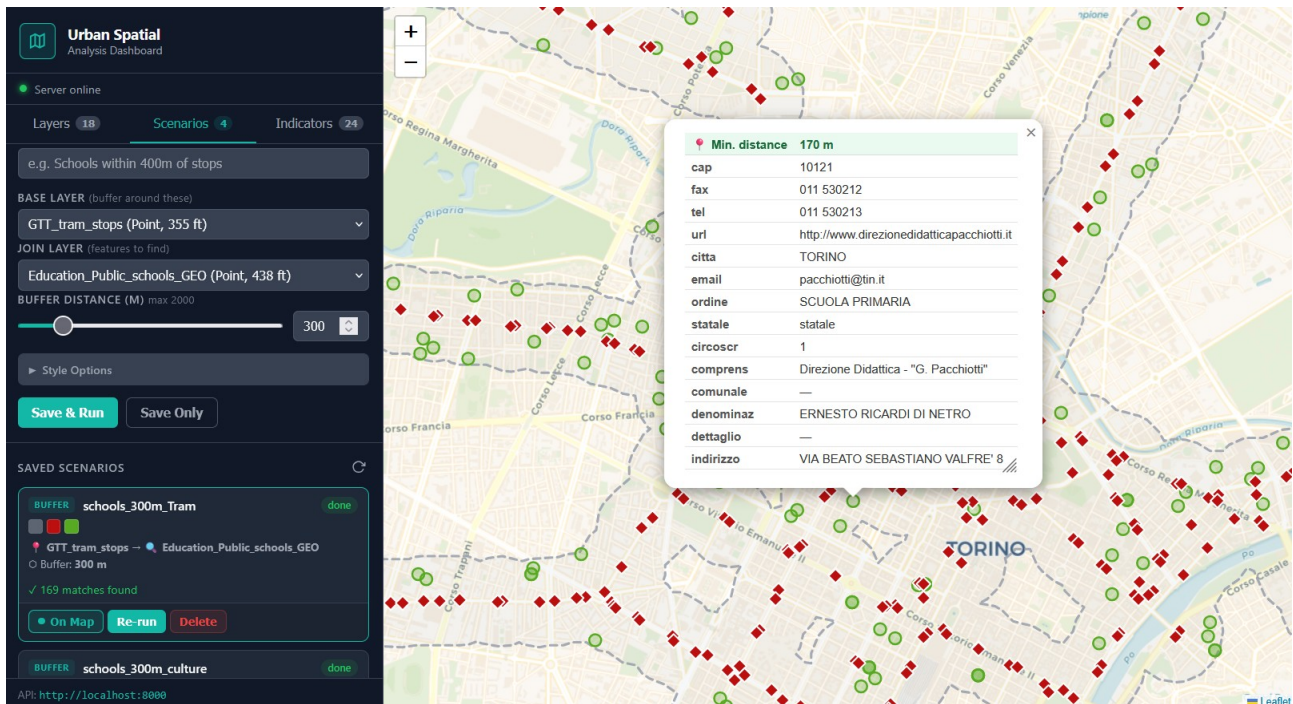


Figure 8.2: Dashboard spatial analysis interface

Results are displayed as three independent Leaflet layers on the map, each with configurable colours and marker shapes. Additional scenario types (heatmap, nearest facility, count-points-in-polygon) are listed in the UI as disabled placeholder options for Phase II.

8.3.3 Use Case 1: Indicator Framework Management and Visualization

The Indicators tab is the primary interface for Use Case 1 and is organized into three sub-tabs: Configure, Visualize Indicators, and Visualize Spatial Units.

Configure Sub-Tab

The Configure sub-tab provides a full-width panel (the map is hidden during configuration) for setting up the indicator framework. At thesis submission, three frameworks are pre-seeded in the database: *SBE_SNTool* (fully configurable), *UN_GUMF* (labelled “coming soon”, disabled), and *UN_U4SSC* (labelled “coming soon”, disabled). The GUMF and U4SSC stubs ensure that extending the tool to these frameworks in Phase II requires only configuration and data upload rather than structural code changes.

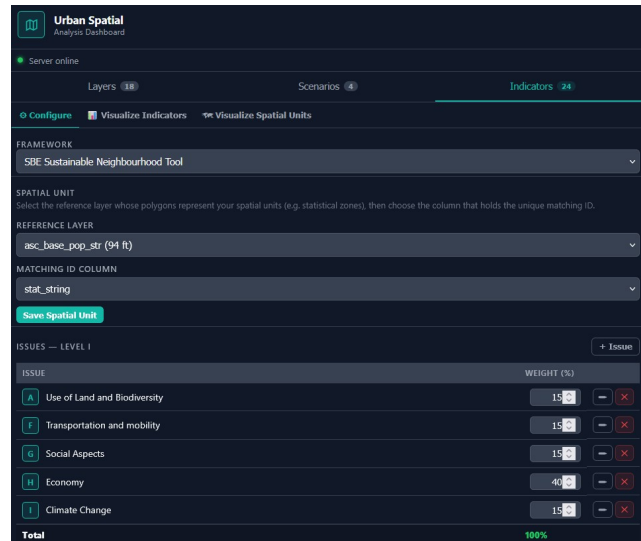


Figure 8.3: Dashboard indicator configuration interface

For the SNTTool MED framework, the Configure panel supports:

- **Spatial unit assignment:** The user selects which imported GeoPackage layer represents the spatial units (for this thesis, the ISTAT 2021 *Zona Statistica* layer with 94 zones) and specifies the attribute column that provides unique matching identifiers linking the spatial layer to the CSV indicator data.
- **Issue management:** Issues (lettered A–J) can be created, renamed, and deleted (deletion is blocked when indicators exist under the issue). Each issue has an editable weight percentage; the UI displays a live running total with a warning when weights do not sum to 100.
- **Indicator management:** Selecting an issue reveals its indicator table. Each indicator has a code suffix (e.g., 1.1 – Population Density), a weight percentage, a measurement unit, a criterion type (HIB or LIB), and two benchmark values (benchmark_0 maps to score 0; benchmark_5 maps to score 5). Indicators can be added, edited, and deleted through a modal dialog.
- **CSV data upload:** Each indicator supports a two-step CSV upload: the user uploads a csv file, selects the matching-ID column and the value column from the file header, and confirms. On confirmation, all existing data for that indicator are deleted and replaced. Rows with unparseable numeric values are skipped; rows with empty values are imported with a null raw value. The indicator row in the table shows a checkmark once data has been successfully uploaded.

Visualize Indicators Sub-Tab

The Visualize Indicators sub-tab displays a sidebar panel alongside the Leaflet map. The user selects a framework and presses **Generate**, which fires two parallel requests: one to the `/api/frameworks/{id}/scores/` endpoint (which returns all indicator and composite scores for all spatial units) and one to `/api/layers/{id}/geojson/` (which returns the spatial unit geometry as GeoJSON). On completion, the map renders a choropleth layer coloured on a red–orange–yellow–green ramp from 0 to 100 on the WLC scale (where $WLC = (score + 1) / 6 \times 100$ converts the -1 to $+5$ SNTTool scale to a 0–100 range).

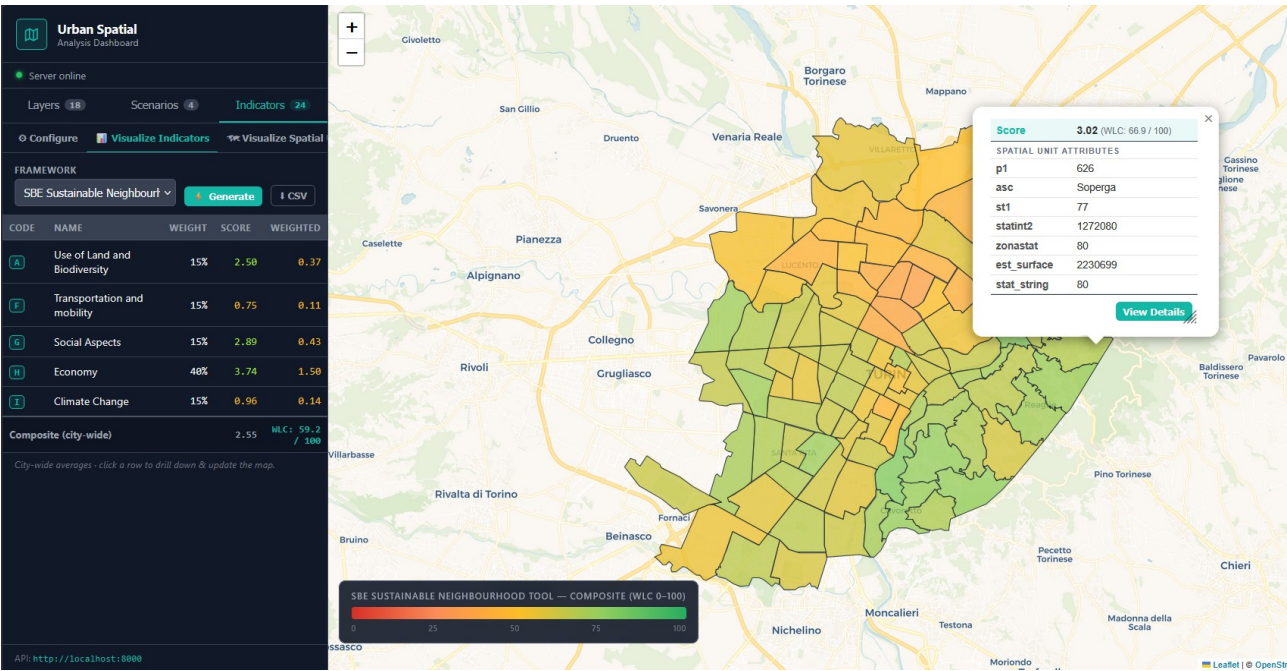


Figure 8.4: Dashboard visualize indicators

The score table shows one row per Issue by default (composite view), with columns for code, name, weight, mean score, and mean weighted score. Clicking a row drills into that issue, showing one row per indicator. A breadcrumb navigation bar tracks the current drill context (*All Issues > A — Land Use and Biodiversity > A1.1 - Population Density*). At each drill level, the choropleth updates to reflect the score of the selected issue or indicator, with grey polygons for spatial units that have no data at that level. Hovering over a polygon highlights it in cyan; clicking opens a popup with the score, WLC value, and raw indicator value (at indicator drill level), plus spatial unit attributes (neighbourhood name, population, surface area). A **View Details** button in the popup navigates to the neighbourhood profile page.

A **Download CSV** button exports the current drill context as a UTF-8 BOM-encoded CSV file, with columns for the spatial unit ID, neighbourhood name, all raw indicator values, and all scores. Files are named `scores_composite.csv`, `scores_{letter}.csv`, or `scores_{code}.csv` depending on the current drill level.

Visualize Spatial Units Sub-Tab

The Visualize Spatial Units sub-tab provides a complementary view focused on comparing spatial units by their composite score. After generating scores, the sidebar displays a ranked table of all 94 *zone statistiche* sorted by composite score (highest first), with colour-coded score badges (red < 33, amber 33–66, green > 66 on the WLC scale) and a detail button linking to the neighbourhood profile page.

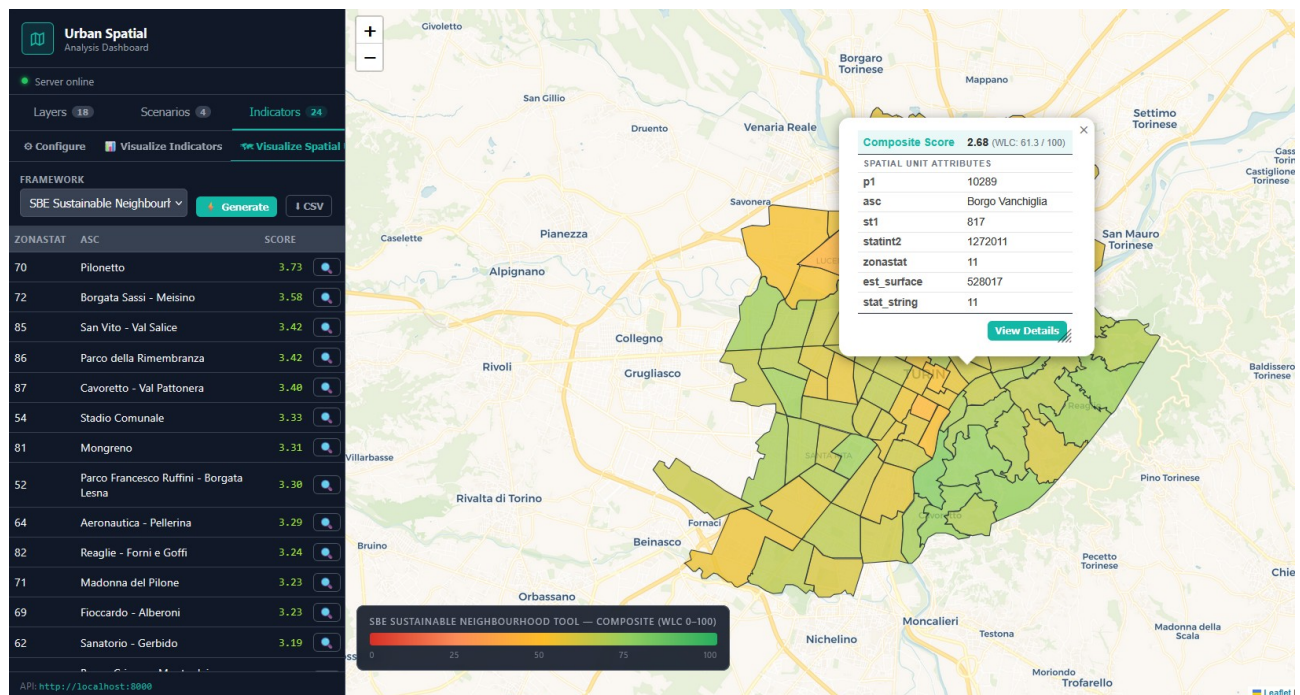


Figure 8.5: Visualize Spatial Units

The map choropleth in this sub-tab always shows the composite score regardless of the drill context in the Visualize Indicators tab.

Neighbourhood Profile Page

The neighbourhood profile page (`neighbourhood_profile.html`) is a standalone dark-themed HTML page navigated to from the detail button in either the ranked table or the map popup. It calls the `/api/frameworks/{fw_id}/neighbourhood/{matching_id}/` endpoint, which runs the full scoring computation and extracts the per-unit data in a single response.

The page layout consists of:

- A **hero section** displaying the neighbourhood name (the *asc* field from the statistical zone layer), the composite score on the -1 to $+5$ scale, and the neighbourhood's city-wide rank (e.g., *#12 of 94*).
- A **statistics row** showing total population, the number of foreign residents, and the zone's surface area in km^2 .
- An **issues accordion** in which each SNTTool MED issue is a collapsible section displaying a table of its indicators. Each indicator row shows the code, name, weight, raw value (with unit), and score (with colour coding). If the user arrived from a specific indicator drill context, that indicator's row is highlighted and the parent issue section is auto-expanded, and the page smooth-scrolls to the highlighted row.

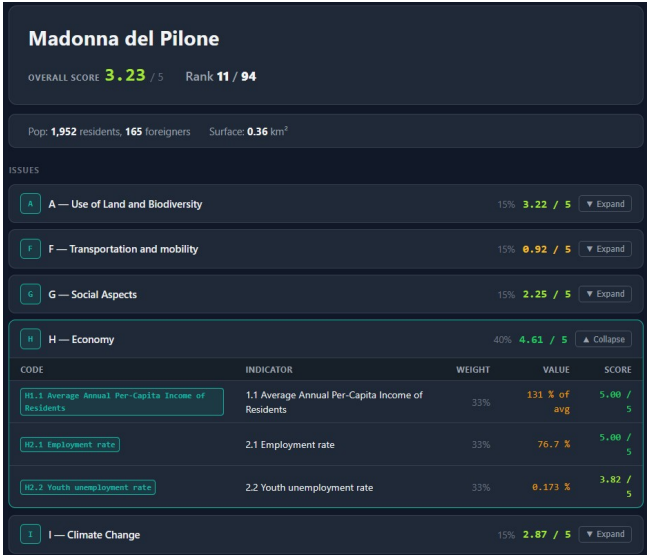


Figure 8.6: Neighbourhood Profile View

The profile page provides the deepest level of the layered complexity principle: a user who identifies a low-performing zone on the composite choropleth can drill to the specific indicators responsible for the deficit without leaving the browser environment.

8.3.4 Use Case 2: Raster Map Integration

The net suitability and economic uplift outputs of Use Case 2 were computed entirely outside the dashboard, using the Python geoprocessing pipeline described in Chapter 3 (Section 3.4) and QGIS for cartographic post-processing. For the thesis submission, the resulting GeoTIFF rasters are integrated into the dashboard as interactive map overlays using the `georaster-layer-for-leaflet` plugin, which renders single-band and multi-band GeoTIFF files as Leaflet tile layers directly in the browser, without requiring a tile server.

The following raster layers are available as overlays within the dashboard map canvas:

- **Net Suitability Score — Phase I:** the Step D re-normalized suitability surface (0–100 scale) for the 800 m Metro Line 2 Phase I corridor catchment.
- **Net Suitability Score — All Phases:** the corresponding surface for the full Metro Line 2 alignment.
- **Economic Uplift Coefficient:** the pixel-level uplift coefficient surface (range 1.00–1.12) derived from the Phase I net suitability raster.
- **Economic Uplift (€/m²):** the projected residential price increment above the OMI 2024–25 baseline, at 5 m×5 m resolution.
- **Aree di Trasformazione within Phase I catchment:** the PRG-designated transformation zone polygons overlaid on the uplift surface to identify the principal LVC target parcels.

Each raster layer can be toggled independently via the Layers panel, with adjustable opacity. Hovering over the net suitability or uplift rasters returns the pixel value in a tooltip. The rasters are displayed in read-only mode: no parameter adjustments or recalculations are possible within the current dashboard version. This constraint is the most significant limitation of the Phase I prototype for Module 2 (real estate professional) users, and is the primary priority for Phase II development.

8.4 Scoring Methodology

The scoring engine is implemented in `spatial_engine/services.py` as the `ScoringService` class. All arithmetic is performed in Python after a single database query that loads all `IndicatorData` rows for the framework; no per-unit database queries are issued during scoring.

Indicator score. A raw value is mapped to the SNTTool MED -1 to $+5$ scale according to the criterion type:

HIB (Higher Is Better) : $\text{raw} < B_0 \rightarrow -1$; $B_0 \leq \text{raw} \leq B_5 \rightarrow (\text{raw} - B_0)/(B_5 - B_0) \times 5$; $\text{raw} > B_5 \rightarrow 5$.
Requires $B_0 < B_5$.

LIB (Lower Is Better) : $\text{raw} \leq B_5 \rightarrow 5$; $B_5 < \text{raw} \leq B_0 \rightarrow (B_0 - \text{raw})/(B_0 - B_5) \times 5$; $\text{raw} > B_0 \rightarrow -1$.
Requires $B_5 < B_0$.

The function returns `None` if the raw value is null, if either benchmark is null, or if $B_0 = B_5$.

Issue and composite scores. The issue score is the weighted average of available indicator scores within that issue. When some indicators return `None` for a given spatial unit, their weights are excluded from the denominator and the remaining weights are renormalized (“Option B” renormalization). The composite score applies the same logic across issues. A spatial unit receives a null composite score only when every indicator in every issue is null.

WLC transformation. The SNTTool-scale score is converted to a 0–100 WLC value by $\text{WLC} = (\text{score} + 1)/6 \times 100$. This maps $-1 \rightarrow 0$, $0 \rightarrow 16.7$, and $+5 \rightarrow 100$. The choropleth colour ramp ranges from red (0) through orange, yellow, and yellow-green to green (100). City-wide averages are computed as the mean of all non-null unit scores, reported alongside the per-unit results in the API response.

This scoring implementation faithfully reproduces the methodology described in Chapter 3 (Section 3.3.2), with the WLC transformation providing the 0–100 scale used for choropleth colouring and CSV exports while the native -1 to $+5$ SNTTool score is retained in the neighbourhood profile display.

8.5 Towards Three-Audience Architecture: Design Target and Implementation Gap

The Phase I prototype described above delivers the core functionality required by the three user communities to substantially different degrees. Understanding this gap is important both for evaluating the current prototype and for prioritizing Phase II development.

Module 1 (City Planning Officials). The current implementation fully supports the primary planning workflow: configuring the SNTTool MED indicator set, uploading indicator data, computing composite and domain-level CSI scores, visualizing them as a choropleth across the 94 *zone statistiche*, drilling from composite to issue to indicator level, and exporting results as CSV for inclusion in PRG planning documents and EU sustainability reports. The buffer-distance scenario tool supports spatial analysis of service provision (e.g., identifying statistical zones within 400 m of a transit stop, as required by the F1.1 indicator verification). The neighbourhood profile page provides the parcel-level drill-down required for targeted PRG area assessments. The UC2 raster overlays allow planning officials to visually overlay the sustainability choropleth with the net suitability and uplift surfaces, supporting the Dual Dividend spatial analysis. What remains for Phase II in this module is the Priority Intervention Zone delineation tool (an automated export of bottom-quartile zones), formal INSPIRE WFS data endpoint, and structured one-page PDF summary cards for individual zones.

Module 2 (Real Estate Development Professionals). The current implementation provides read-only access to the UC2 raster layers as Leaflet overlays, which is sufficient for visual inspection of the net suitability

and economic uplift surfaces and for identifying the second-row premium band and Aree di Trasformazione overlay. What is absent for this audience is the investment screening panel (multi-criteria filter for parcels by suitability score, OMI range, planning designation), the risk flagging system (disamenity donut, high acoustic load, LVC obligation markers), and the interactive uplift coefficient recalculation that would allow professionals to test sensitivity to penalty parameter assumptions. These features require Phase II development of the UC2 computation API and a purpose-built investment interface.

Module 3 (Retail Investors and Citizens). The neighbourhood profile page provides a foundation for Module 3 use: a prospective resident who knows the *Zona Statistica* code for an area of interest can access a domain-by-domain breakdown of that zone’s sustainability score and its city-wide rank. However, the address lookup and geocoding flow (enter a specific street address, receive a score), the plain-language “report card” summary, the Metro Line 2 proximity indicator (distance to nearest planned station, pixel-level net suitability score), and the side-by-side address comparison tool are all Phase II features not yet implemented.

8.6 Phase II: Planned Enhancements

The Phase II development roadmap, whose detailed specification is beyond the scope of the current thesis, encompasses the following priorities organized by the component they extend:

UC2 interactivity. The most analytically significant Phase II enhancement is the integration of the UC2 net suitability computation as a recalculable module within the dashboard. This requires exposing the Python raster pipeline as a REST endpoint (e.g., via a FastAPI microservice) that accepts modified penalty parameters (noise thresholds, school buffer radii, amenity weights) and returns updated GeoTIFF outputs. Once this endpoint is available, the dashboard can expose sliders for penalty parameters and re-render the raster overlay without reloading the page, enabling the scenario interactivity described in Design Principle 3 for Use Case 2.

Framework extensibility. The GUMF and U4SSC framework stubs already seeded in the database can be activated once their indicator definitions and benchmark values are configured. This requires no structural changes to the data model or the scoring engine. However, the neighbourhood profile page currently hard-codes the spatial attribute columns from the SNTTool MED statistical zone layer (population, foreign residents, surface area); extending it to other frameworks with different spatial units would require a configurable attribute display system.

Investment screening interface. The Module 2 investment screening panel requires a new frontend component and an API endpoint that accepts multi-criteria filter parameters and returns a GeoJSON feature collection of qualifying parcels ranked by net suitability score. The Aree di Trasformazione layer and the Contributo Straordinario reference values would be served from this endpoint.

Address lookup and citizen report card. The Module 3 address lookup requires a geocoding service (e.g., the Geoportale della Città di Torino’s geocoding API or OpenStreetMap Nominatim), a point-in-polygon query against the *Zona Statistica* layer, a pixel-level value extraction from the UC2 rasters, and a plain-language summary rendering. This is the most user-facing enhancement and the one with the greatest equity impact, given that it transfers professional-grade spatial intelligence to individual housing market participants.

Additional scenario types and live data integration. The buffer-distance scenario module can be extended to support heatmap generation, nearest-facility analysis, and count-points-in-polygon operations. The F1.1 transit frequency indicator benefits from connection to GTT’s live GTFS-RT feed rather than the static March 2026 snapshot. OMI price data can be automatically refreshed from the Agenzia delle Entrate open data portal’s semi-annual releases.

Production cloud deployment. In parallel with the Phase II feature roadmap above, a production-ready cloud version of the dashboard has been fully implemented and is currently undergoing pre-deployment validation.

The cloud architecture is built on Docker Compose with four services: a Django 4.2/Gunicorn application server (**web**), a PostGIS database container (**db**), an Nginx reverse proxy handling HTTP-to-HTTPS redirection and static file serving (**nginx**), and a Redis service placeholder for future caching and task-queue integration (**redis**). The cloud version enforces JWT authentication globally on all write endpoints, with a three-tier role-based access control model: *admin* users (full configuration and user management access), *analyst* users (data upload, analysis execution, and result viewing), and *viewer* users (read-only map and score access). A GitHub Actions CI pipeline runs automatically on every push to the main branch, executing a Django system check, migration validation, and the full test suite before any deployment proceeds. The target deployment environment is a Hetzner CX31 VPS with Certbot SSL certificates and automated daily database backups. The outstanding tasks before the platform transitions from research prototype to operational municipal tool are: a formal cybersecurity assessment, structured user acceptance testing with representative users from each of the three target audiences, and final production deployment including DNS configuration and HTTPS activation. These steps, rather than any remaining code development, constitute the primary barrier to public release.

8.7 Dashboard as DSS: Capabilities and Limitations

8.7.1 What the Phase I Prototype Enables

Synthesizing the functional architecture described above, the Phase I prototype delivers three core DSS capabilities that would not be achievable with static analytical outputs alone:

1. **Configurable composite indicator computation.** The dashboard eliminates the need to re-run the Python geoprocessing pipeline when indicator weights or benchmarks are revised. A planning official can change the weight of Domain F to simulate a transport-prioritized PRG scenario and regenerate the full CSI map in seconds, without any programming knowledge. This makes the weight sensitivity analysis described in Chapter 6 (Section 6.3.2) operationally accessible to non-technical stakeholders for the first time.
2. **Neighbourhood-level drill-down and profiling.** The combination of the Visualize Indicators choropleth, the issue-level drill-down, and the neighbourhood profile page creates a seamless analytical pathway from city-wide pattern recognition to neighbourhood-specific diagnosis. A planner identifying the bottom-quartile zones in the composite map can navigate to any of those zones' profile pages and identify which specific indicators are driving the deficit, without cross-referencing separate spreadsheets or GIS layers.
3. **Integrated UC1 and UC2 visualization.** The simultaneous display of the UC1 sustainability choropleth and the UC2 raster overlays within the same Leaflet map canvas makes the Dual Dividend spatial coincidence visually explicit: the zones of lowest sustainability score in the northern corridor (visible as red in the CSI choropleth) are co-located with the zones of highest projected uplift potential (visible in the net suitability raster overlay), supporting the integrated argument for equity-oriented Metro Line 2 investment that is central to this thesis.

8.7.2 Current Limitations

Three categories of limitation qualify the current prototype's operational utility:

UC2 read-only constraint. The most significant functional gap is that the UC2 raster outputs are view-only. A real estate professional or planning official cannot adjust noise penalty parameters, school buffer radii, or

amenity weights within the dashboard and observe the effect on the net suitability surface. This constrains the dashboard's role for UC2 to visualization and communication rather than decision exploration. The Phase II UC2 interactivity enhancement addresses this directly.

Single-framework operability. Only the SNTTool MED framework is currently configurable. The GUMF and U4SSC stubs are visible in the UI but non-functional. This means the dashboard cannot yet serve as a cross-framework comparison tool for the three indicator frameworks reviewed in Chapter 3, limiting its utility for EU-level sustainability reporting workflows that require GUMF-aligned indicator outputs.

No Module 3 citizen interface. The neighbourhood profile page provides zone-level data to any user who knows the *Zona Statistica* identifier for their area of interest, but the address lookup flow that would make this information accessible to a non-specialist audience has not been implemented. The citizen democratization of property and sustainability intelligence described in the design principles therefore remains a target rather than a delivered capability.

Static data snapshots. The indicator data uploaded during the thesis workflow reflect a specific analytical moment: GTFS March 2026, OMI 2024–25, ISTAT 2021 Census, LCP2023 land cover. Changes in the urban environment are not reflected until the pipeline is re-executed and the CSV data re-uploaded through the Configure interface. Phase II live data integration mitigates this by connecting to API-accessible data sources, but does not eliminate the inherent latency between real-world change and dashboard update.

No authentication or multi-tenancy. The current implementation has no user authentication, role-based access control, or multi-user session management. It is designed for single-user research use on a local development server. Production deployment as a shared planning tool would require an authentication layer distinguishing public citizen access from authenticated professional tiers, and a production server configuration (HTTPS, WSGI server, reverse proxy) that is outside the scope of the current prototype.

Absence of formal usability evaluation. The Phase I prototype was presented to city planning officials during a demonstration meeting, allowing for an initial stakeholder review of the interface and analytical outputs. However, no structured independent user testing has been conducted: no usability protocol, task-completion metrics, or System Usability Scale (SUS) evaluation has been administered to representative users from any of the three target communities. The demonstration confirmed that the dashboard's core workflow is comprehensible to a planning professional audience, but it does not constitute evidence of usability in the formal HCI sense. A structured usability evaluation involving representative users from Modules 1, 2, and 3, applying standard usability testing protocols, is identified as a priority for Phase II development and is a prerequisite before the dashboard can be claimed to meet the communicative planning and PPGIS design standards cited in Section 8.1.

Chapter 9

Discussion

The empirical work presented in Chapters 6 through 8 constitutes a multifaceted investigation of urban sustainability at the neighbourhood scale, using Turin as both a substantive case study and a methodological proving ground. This chapter synthesizes the principal findings across both use cases, addresses the three research questions that structured the thesis, evaluates the methodological contributions in relation to the broader literature, and identifies the boundary conditions and limitations that qualify the results. It concludes with a discussion of practical implications for urban planners, real estate professionals, and policy designers, and a structured comparison with comparable European studies.

9.1 Revisiting the Research Questions

9.1.1 RQ1: Operationalizing Sustainability Indicators for Turin

The first research question asked which indicators from the SNTTool MED framework are most suitable for neighbourhood-level sustainability comparison in Turin, and how they can be operationalized from open geospatial data. The answer developed in Chapters 4 and 5 is both affirmative and nuanced: a substantive multi-domain indicator set can be operationalized for Turin’s 94 *zone statistiche* using publicly available data, but the process demands careful curation to address spatial resolution mismatches, data vintage heterogeneity, and definitional divergences across frameworks. Of the 24 indicators successfully calculated across all 94 zones, 18 were retained in the final Composite Sustainability Index (CSI); the remaining six were excluded following a post-calculation discrimination test, as detailed below.

The cross-framework harmonization described in Chapter 4 identified the SNTTool MED’s available criteria across the five selected Issues (A, F, G, H, I), of which 24 were selected as calculable at the *zona statistica* scale within the thesis timeline. The selection process exposed a consistent pattern: the indicators most readily operationalized are those that rely on geometric or network-based computation from open cadastral and transport data, while those that depend on administrative microdata (income, employment, fiscal records) require more complex data integration and carry spatial resolution constraints. The ISTAT IDISE 2021 dataset proved particularly valuable in this regard: its sub-comune employment and NEET rate tabulations, not widely exploited in prior Turin neighbourhood analyses, enabled the calculation of the H2.1 employment rate indicator (adults aged 25–64) and the H2.2 youth NEET rate indicator (individuals aged 15–29 not in employment, education, or training) at a resolution commensurate with the *zona statistica* spatial unit. The use of IDISE 2021 as a primary source represents a methodological contribution in its own right, as most comparable Italian urban sustainability assessments at neighbourhood scale have used only municipal-level IRPEF declarations for the economic domain (Bottero et al., 2023; Zini et al., 2024).

Two indicators initially scoped within the framework were excluded from the final set of 24: F3.4 (Traffic Fatalities, which requires geocoded accident records for the full 2021–2025 period from the Polizia Municipale di

Torino, not yet released at the required spatial resolution) and I1.2 (GHG Emissions from Residential Buildings, which requires the consolidation of Attestato di Prestazione Energetica (APE) data at the *zona statistica* level, a process not yet complete for all 94 zones). Their exclusion does not materially undermine the analytic conclusions: F3.4 can be inferred directionally from the F-domain transport pattern, and I1.2 is expected to reinforce the north–south energy inequality gradient already visible in the I3.3 land permeability results. Both are identified as priorities for future data-collection and indicator-extension work.

The spatial resolution analysis reveals three distinct tiers of indicator reliability. First, indicators derived from geometric computation (A1.2 urban compactness, F4.2 street connectivity, I3.3 permeability) achieve the highest spatial precision, as their resolution is limited only by the granularity of the cadastral and land cover inputs. Second, indicators derived from administrative point-feature data (G3.1–G3.5 service proximity, F1.1 public transport frequency) achieve reliable *zona statistica*-level resolution through spatial aggregation and buffering. Third, indicators dependent on aggregated administrative tabular data (H1.1 income from IRPEF at CAP zone level, H2.1 and H2.2 from IDISE at sub-comune level) carry a spatial imprecision stemming from the mismatch between their reporting unit and the analysis unit. The income data (CAP zones) in particular introduce a lumping artefact, where a single CAP zone may span multiple *zone statistiche* of substantially different socioeconomic character. This limitation is acknowledged in the data uncertainty band of the CSI results and is discussed further in Section 9.3.

Following the initial calculation of all 24 indicators across the 94 zones, a post-calculation discrimination test identified six indicators that failed to meet the minimum threshold of meaningful within-city variation required for inclusion in the composite index (Table 9.1). Three transport indicators (F2.2 EV infrastructure, F2.3 bicycle network, and F3.3 bicycle lane safety) exhibited city-wide underperformance below the SNTool MED benchmark, with all 94 zones scoring at or near the lowest evaluation level and no meaningful differentiation between neighbourhoods. Two further indicators (A1.1 population density and A3.2 biodiversity in green zones) were excluded due to insufficient spatial contrast within the urban fabric and severe data limitations respectively, while F4.1 cyclomatic complexity was excluded on methodological grounds as insufficiently interpretable for PRG monitoring purposes.

Code	Name	Rationale for exclusion
A1.1	Population density	Relative population density homogeneity
A3.2	Biodiversity in green zones	Lack of data (tree species only)
F2.2	Electric-Vehicle Infrastructure (Charging Station)	All zones equally underperformed (no meaningful differences)
F2.3	Bicycle Network	All zones equally underperformed (no meaningful differences)
F3.3	Safety of bicycle lanes	All zones equally underperformed (no meaningful differences)
F4.1	Cyclomatic Complexity of the Street Network	Not meaningful for PRG monitoring

Table 9.1: Indicators excluded after post-calculation discrimination test

Sensitivity analysis: impact of the six-indicator exclusion on CSI scores. To assess the sensitivity of the composite index to this exclusion decision, the CSI was computed independently under both the 24-indicator and the 18-indicator equal-weight configurations and the resulting scores were compared zone by zone across all 94 *zone statistiche*. The comparison provides empirical evidence that the exclusion was both justified and consequential.

The most salient finding is a near-universal upward shift in composite scores when moving from the 24-indicator to the 18-indicator version. Under the 24-indicator configuration, the city-wide mean composite score

is 2.16 on the WLC scale (equivalent to 52.7 on the normalised 0–100 scale); under the 18-indicator configuration the mean rises to 3.06 (67.6 on the normalised scale), a mean increase of +0.90 WLC points (+14.9 percentage points). This upward shift reflects the removal of the three cycling and EV infrastructure indicators (F2.2, F2.3, F3.3), all of which contributed uniformly negative values to every zone’s composite score, introducing a city-wide floor that depressed scores without differentiating between neighbourhoods. The remaining variation in the magnitude of the per-zone shift reveals a more nuanced spatial pattern, illustrated in Table 9.2 for the zones most and least affected by the exclusion.

Zone	Name	24-ind.	18-ind.	Δ
<i>Five largest gainers — compact inner-urban zones</i>				
51	Pozzo Strada	2.27	3.81	+1.54
17bis	—	2.02	3.55	+1.53
23	Borgo Rossini	2.13	3.59	+1.46
35	Polo Nord	2.22	3.66	+1.44
53	Santa Rita Da Cascia	2.11	3.55	+1.44
<i>Five peri-urban hill zones with marginal score decrease</i>				
82	Reaglie – Forni e Goffi	2.69	2.67	−0.03
73	Strada di Soperga	2.54	2.49	−0.04
74	Barriera di Chieri – Valpiana – Val San Martino	2.57	2.52	−0.05
84	Strada di Pecetto – Eremo	2.41	2.30	−0.11
81	Mongreno	2.75	2.63	−0.12

Table 9.2: Impact of the six-indicator exclusion on equal-weight CSI scores for the five zones most positively affected (compact inner-urban) and the five zones marginally negatively affected (peri-urban hill zones). Scores are on the WLC scale (−1 to 5); the normalized 0–100 value is given by $(s + 1)/6 \times 100$.

The five zones recording the largest score increases (Pozzo Strada, Polo Nord, Borgo Rossini, Santa Rita Da Cascia, and zone 17bis) are all compact, transit-connected inner-urban neighbourhoods whose overall sustainability profile in the social, economic, and transport domains was being suppressed in the 24-indicator version by the uniformly low cycling and EV infrastructure scores. Conversely, five peri-urban hill zones on Turin’s eastern fringe (Mongreno, Strada di Pecetto, Barriera di Chieri, Strada di Soperga, and Reaglie) score marginally *lower* under the 18-indicator configuration ($|\Delta| < 0.13$), indicating that the excluded biodiversity indicator (A3.2, limited to the municipal tree cadastre) and the population density indicator (A1.1) had provided a slight scoring advantage to these low-density, tree-rich zones. This advantage is itself a form of measurement bias: higher tree counts in hill zones reflect the presence of hillside green space and private gardens rather than the quality of publicly accessible green urban infrastructure that A3.2 is designed to capture.

Figure 9.1 maps the spatial distribution of the score changes across all 94 *zone statistiche*, showing the redistribution of upper-tier scores from the peri-urban fringe to compact inner-urban neighbourhoods that results from the exclusion.

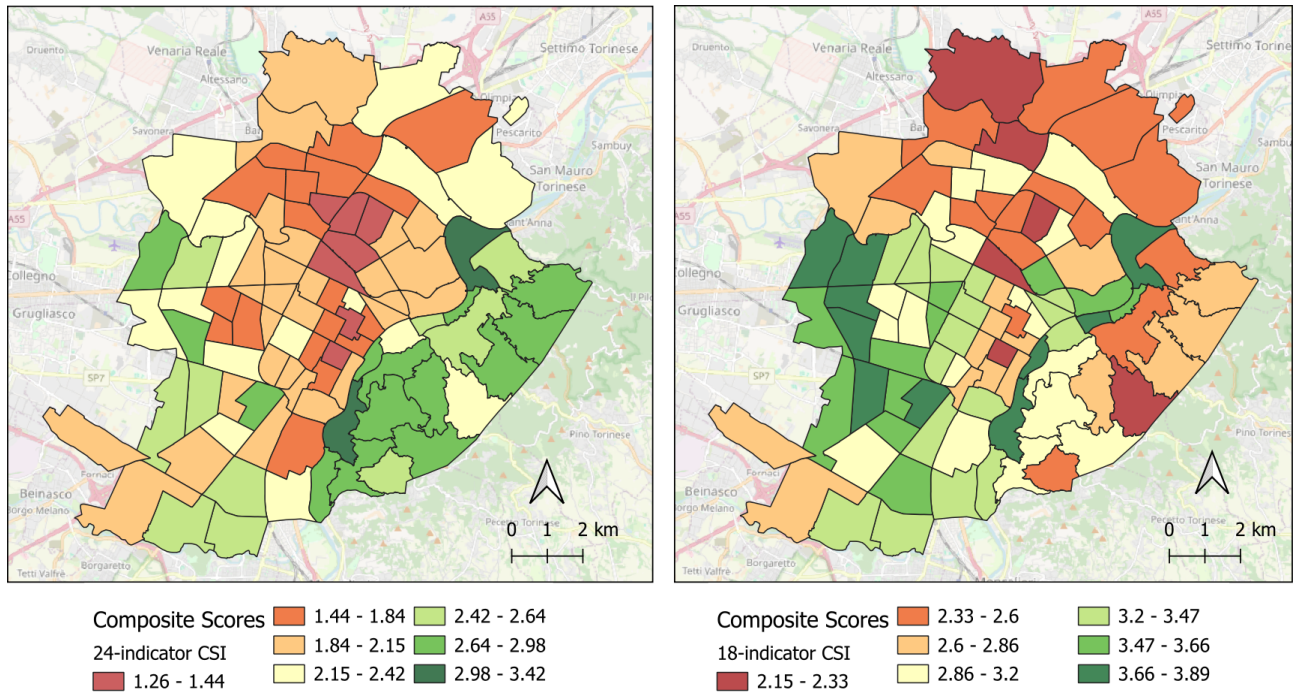


Figure 9.1: Comparison of equal-weight composite sustainability scores across the 94 *zone statistiche* under the 24-indicator (left) and 18-indicator (right) configurations. The redistribution of upper-tier scores from peri-urban hill zones to compact inner-urban neighbourhoods is visible in the colour shift across the eastern fringe.

The Spearman rank correlation between the two composite orderings is moderate and statistically significant ($\rho = 0.517$, $p < 0.001$, $n = 94$; Figure 9.2), confirming that while zones at the extremes of the distribution retain their relative positions, the removal of the six indicators produces substantial rank reshuffling in the mid-to-upper tier.

The LOWESS fit illustrates the moderate positive monotonic relationship between the two composites, with the greatest dispersion in the upper tier reflecting the rank reshuffling caused by removing the cycling, EV, biodiversity, density, and cyclomatic complexity indicators. Zones at the bottom of the distribution remain consistently low across both configurations, confirming that the exclusion does not alter the identification of priority intervention areas.

This pattern is consistent with the mechanism identified above: the zones most heavily penalized in the 24-indicator version are compact urban neighbourhoods whose true sustainability profile is only fully revealed once the non-discriminating indicators are removed.

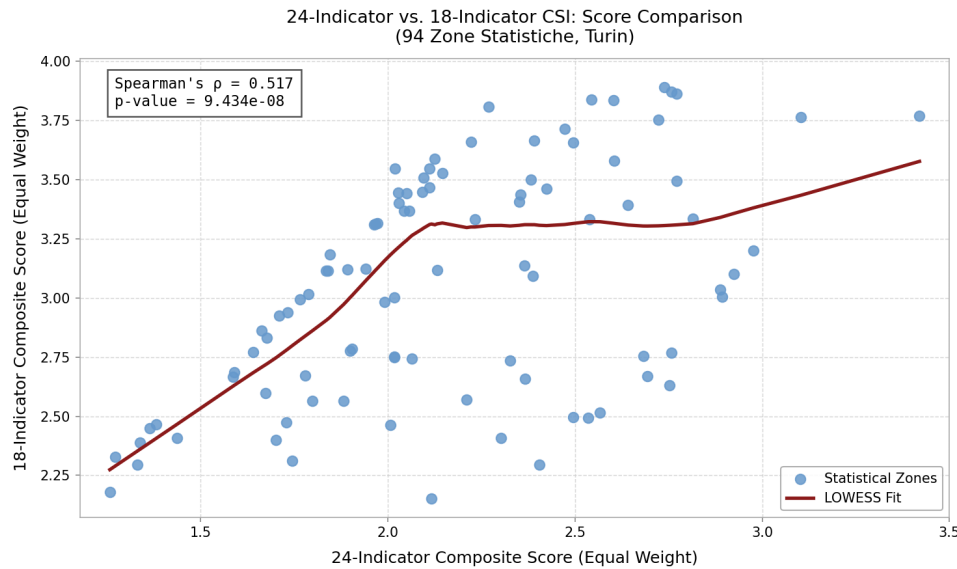


Figure 9.2: Scatter plot of 24-indicator versus 18-indicator equal-weight CSI scores for the 94 *zone statistiche* of Turin.

In other European or Mediterranean urban contexts where cycling modal share is substantially higher—for example, Dutch or Danish cities—the F2.2, F2.3, and F3.3 indicators would exhibit far greater spatial variation and would merit inclusion in the CSI. Similarly, in cities with denser biodiversity monitoring infrastructure (multi-taxon surveys rather than single-species tree cadastres), A3.2 could provide meaningful discrimination between neighbourhoods. The exclusion of these six indicators is therefore a context-specific methodological decision rather than a structural limitation of the SNTTool MED framework, and the dashboard’s FrameworkSpatialUnit (FSU) architecture explicitly allows them to be reactivated without any modification to the data model as the corresponding spatial datasets improve in coverage and resolution.

The remaining 18 indicators, listed in Table 9.3, span the five retained domains (A, F, G, H, I) and collectively produce a composite index with sufficient within-city discrimination to support the neighbourhood-level planning comparisons addressed in Use Case 1.

Code	Name	Rationale for inclusion
A1.2	Urban compactness	Representative of density of the urban environment
A2.1	Availability of green urban areas	Aligns with PRG priorities
A2.2	Green Areas in Relation to the Neighborhood Population	Aligns with PRG priorities
A2.3	Green Area Accessibility	Aligns with PRG priorities
F1.1	Performance of the Public Transport System	Key Performance Indicator
F4.2	Connectivity of the Street Network	Underscores service and amenity accessibility
G2.1	Affordability of Housing Property	Aligns with PRG priorities
G2.2	Affordability of Housing Rental	Aligns with PRG priorities
G2.3	Vacant Residential Units in the Neighborhood	Reveals touristification and gentrification issues
G3.1	Availability and Proximity of Key Services	Aligns with PRG priorities
G3.2	Availability and Proximity of a Public Primary School	Aligns with PRG priorities
G3.3	Availability and Proximity to a Public Secondary School	Aligns with PRG priorities
G3.4	Availability & Proximity to Children's Play Facilities	Aligns with PRG priorities
G3.5	Outdoor Public Spaces	Aligns with PRG priorities
H1.1	Average Annual Per-Capita Income of Residents	Key metric for economic well-being
H2.1	Employment rate	Key metric for economic well-being
H2.2	Youth unemployment rate	Indicator of broader social issues
I3.3	Permeability of Land	Key Performance Indicator

Table 9.3: Final set of 18 indicators used in the Composite Sustainability Index

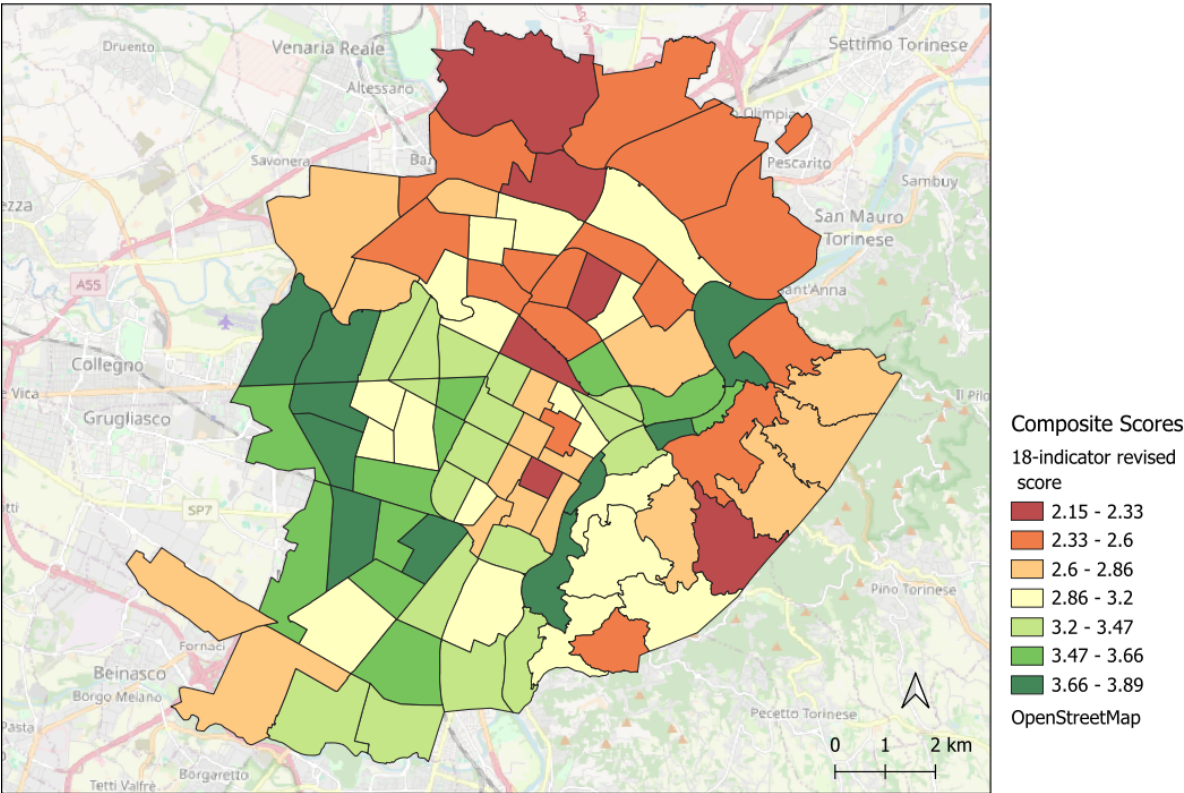


Figure 9.3: 18-indicator equal-weight Composite Sustainability Index across Turin's 94 *zone statistiche*.

By focusing on the 18 retained indicators, the composite map reveals a more meaningful and internally consistent picture of neighbourhood sustainability across Turin's statistical zones. The results confirm lower scores in the northern and north-eastern sub-municipalities, consistent with the historical infrastructure and social services deficits documented in those areas (see Figure 9.3). The 15 statistical zones with the highest composite scores are listed in Table 9.4.

Zone	Statistical Area Name (ASC)	Score
52	Parco Francesco Ruffini - Borgata Lesna	3.89
15	Borgo Crimea - Monte dei Cappuccini	3.87
54	Stadio Comunale	3.86
50	Borgata Parella - Lionetto	3.84
14	Motovelodromo	3.84
51	Pozzo Strada	3.81
70	Pilonetto	3.77
72	Borgata Sassi - Meisino	3.76
64	Aeronautica - Pellerina	3.75
59	Barriera di Orbassano	3.72
55	Ospizio di Carità	3.66
35	Polo Nord	3.66
61	Lingotto - Ex Ippodromo	3.66
23	Borgo Rossini	3.59
62	Sanatorio - Gerbido	3.58

Table 9.4: Top 15 highest-scoring statistical areas under the 18-indicator equal-weight CSI

The 15 statistical areas with the lowest composite scores are listed in Table 9.5. It is notable that two of these zones—Strada di Soperga (73) and Strada di Pecetto-Eremo (84)—scored above the 24-indicator city mean in the full configuration, but fall to the bottom quintile of the 18-indicator ranking because the biodiversity and density indicators that had previously boosted their scores were removed. Their appearance here reflects a genuine characteristic of the 18-indicator CSI: these low-density hill-fringe zones are poorly served by public transport, social facilities, and economic infrastructure relative to the broader urban fabric, and the 18-indicator version correctly surfaces this disadvantage once the non-discriminating environmental indicators are no longer masking it.

Zone	Statistical Area Name (ASC)	Score
76	Villaretto	2.15
9	Piazza Madama Cristina (Borgo San Salvario)	2.18
84	Strada di Pecetto - Eremo	2.30
12	Borgo Dora - Valdocco	2.30
67	Basse di Stura - Nuovo Poligono	2.31
38	Borgata Monterosa	2.33
39	Borgata Montebianco	2.39
44	Officine Savigliano - Acciaierie Fiat	2.40
3	Palazzo Carignano - Vecchio Ospedale (Borgo Nuovo)	2.41
77	Falchera	2.41
24	Borgata Aurora	2.45
66	Stradale di Lanzo	2.46
42	Borgata Vittoria	2.47
48	Borgata Lucento	2.47
73	Strada di Soperga	2.49

Table 9.5: Bottom 15 lowest-scoring statistical areas under the 18-indicator equal-weight CSI

9.1.2 RQ2: Spatial Patterns, PRG Monitoring, and Residential Market Conditions

The second research question asked what spatial patterns of urban sustainability and acoustic noise exposure emerge across Turin’s neighbourhoods, and what the implications are for the PRG monitoring framework and

residential property market conditions. The results in Chapter 6 confirm, and provide quantitative specificity to, the north–south inequality gradient that qualitative analyses of Turin’s urban structure have long identified (Bottero et al., 2023; Politecnico di Torino, 2016).

The domain-level results reveal important nuances within this overall gradient. Domain A (Land Use and Biodiversity) reflects the concentration of major public parks in the southern and central areas as well as the high concentration of natural green areas in the eastern hills. This finding is consistent with the broader ecological urbanism literature’s distinction between green area quantity and biodiversity quality (Dawodu et al., 2022), and carries a specific PRG implication: urban greening requirements should specify ecological quality standards for new green infrastructure, not merely area thresholds.

Domain F (Transport and Mobility) exhibits the sharpest north–south contrast of all five domains, with the PT service frequency indicator (F1.1), updated by daily trip frequency, reproduces the asymmetric accessibility structure documented in the GTFS-based analysis of Zini et al. (2024). Some of the lowest-scoring zones outside the suburban eastern hills are concentrated precisely in the Phase I Metro Line 2 corridor (Falchera, Rebaudengo, Barriera di Milano), a spatial coincidence that provides a direct, quantified basis for the “Dual Dividend” hypothesis explored in Section 6.5: the zones that stand to gain the most from Metro Line 2 transit accessibility are also those with the lowest current composite sustainability scores, suggesting that transit investment would yield compounded sustainability improvements across multiple domains simultaneously.

Domain G (Social Equity) reveals the “affordability trap” dynamic described in Section 6.2.3: some of the lowest-income northern zones achieve relatively good rental affordability scores (G2.2) precisely because OMI rental prices in those areas reflect low neighbourhood desirability and transit inaccessibility rather than active affordability policy. This dynamic has a critical implication for PRG planning: any intervention that improves sustainability scores in these zones (through transit investment, green infrastructure, or service facility provision) risks triggering rental price inflation that displaces the households whose welfare motivated the investment in the first place. The CSI results therefore implicitly make an argument for anti-displacement provisions in the PRG revision, including social housing set-aside requirements and rent stabilization mechanisms in Priority Intervention Zones designated for Metro Line 2 infrastructure improvements.

Domain H (Economy) confirms the multi-dimensional character of economic disadvantage in Turin’s post-industrial northern districts: the zones recording the lowest H1.1 income scores also record the lowest H2.1 employment rates and the highest H2.2 youth NEET proportions, producing a convergent picture of labour market exclusion that is spatially concentrated and self-reinforcing. The inclusion of H2.1 and H2.2 data from IDISE 2021 (rather than the cruder proxy of IRPEF declarations alone) adds analytical granularity to the economic domain: the NEET indicator in particular is sensitive to the youth demographic composition of northern zones, where the population of residents aged 15–29 is proportionally higher due to the lower average age of immigrant-origin communities in Barriera di Milano and Aurora.

Domain I (Climate and Energy) is currently represented solely by I3.3 (Land Permeability), whose spatial pattern reflects the impervious surface concentration of the dense northern and central districts. The results indicate that the zones scoring lowest on land permeability are largely congruent with the zones scoring lowest in Domains F and H, reinforcing the multi-dimensional disadvantage pattern.

The acoustic noise assessment (Section 2.4.4) adds an environmental quality dimension that partially decouples from the north–south sustainability gradient. Road traffic noise (computed using the CNOSSOS-EU dynamic buffer methodology from TGM annual average daily traffic data) affects both northern peripheral zones, through the major arterials of Corso Giulio Cesare and Corso Vercelli, and central zones, through the high-volume Corso Vittorio Emanuele II corridor. Tram network noise (static 50 m and 100 m buffers from GTT GTFS tram line geometry) overlays this pattern along the legacy tram routes, with the Series 2800 rolling stock profile producing the highest noise estimates in the central historic grid where track curvature and stop density are greatest.

The cross-analysis between the sustainability index, acoustic noise exposure, and property values (Section 6.5.1) reveals a more complex urban dynamic than a simple noise–property-value discount. Three findings merit particular discussion.

First, the noise exposure score is strongly positively correlated with the equal-weight CSI (Spearman’s $\rho = 0.623$, $p < 0.001$): because the noise score is inverted (higher = quieter), this means that the highest-scoring neighbourhoods are also the quietest, a “Green Oasis” effect in which sustainability features such as tree canopies, pedestrianized zones, and active mobility infrastructure function as acoustic buffers. This synergistic relationship provides additional justification for integrated green infrastructure investment: the same interventions that improve sustainability domain scores also attenuate noise exposure.

Second, the bivariate relationship between noise exposure and OMI property values is weakly negative (Spearman’s $\rho = -0.280$, $p = 0.006$), meaning that quieter areas command *lower* average prices. This counterintuitive finding reflects the urban accessibility premium: the noisiest zones are concentrated in the city centre and along major arterials that command high residential prices because of their centrality, retail density, and transit access. The private market, in other words, prices accessibility above acoustic quality in the aggregate cross-sectional analysis.

Third, a multivariable OLS regression explores these competing effects. An extended three-predictor model was estimated on the 93 *zone statistiche* for which OMI residential price data is available (zone 09bis, Parco del Valentino, is excluded as no residential OMI price data exists for that zone). The model includes the economy-prioritized CSI, the noise exposure score, and the log-transformed count of commercial establishments as independent variables, and is associated with approximately 38.3% of the observed spatial variance in property prices ($R^2 = 0.383$, adjusted $R^2 = 0.362$, $F_{3,89} = 18.40$, $p < 0.001$). The regression provides correlative evidence consistent with the LVC argument: holding noise and commercial concentration constant, a one-unit increase in the economy-prioritized CSI is associated with an increase of approximately €479.82/m² in average OMI prices ($p < 0.001$). Holding economic score and commercial count constant, a one-unit increase in the quietness score is associated with a decrease of approximately €115.61/m² ($p < 0.001$), indicating that the market tends to price accessibility and commercial animation above acoustic quality at the zone-average scale. The log-transformed commercial establishment count is not independently significant once noise and CSI are controlled for ($p = 0.287$), a result that is itself analytically informative: it indicates that the noise exposure variable is already proxying commercial concentration (Spearman $\rho = -0.581$ between log-commercial count and noise score, $p < 0.001$), consistent with the urban vitality interpretation advanced in Section 6.5.1. These associations are consistent with the broader hedonic literature on the interaction between noise and urban amenity density (Seo et al., 2014), but should be read as exploratory correlations rather than causal estimates, given the cross-sectional and zone-averaged nature of the data. VIF and Breusch-Pagan diagnostics reported in Section 6.5.1 confirm the absence of multicollinearity and heteroscedasticity in this model.

In summary, RQ2 is answered through a convergence of findings across five domains: the north–south sustainability gradient in Turin is statistically robust, spatially clustered, and multi-dimensional, encompassing transport inaccessibility, green space deficit, social deprivation, labour market exclusion, and impervious surface concentration simultaneously. This convergence strengthens the case for integrated, place-based intervention in the northern sub-municipalities, targeted at the Priority Intervention Zones identified in Section 6.5. The acoustic noise findings add a transversal disamenity layer that affects both northern and central zones and provides the direct analytical bridge to Use Case 2.

9.1.3 RQ3: Net Suitability, Property Value Uplift, and Land Value Capture

The third research question asked how a GIS-based net suitability model combining transit accessibility premiums with integrated acoustic disamenity penalties could predict the spatial distribution of residential property value uplift from the proposed Metro Line 2, and what the implications are for land value capture policy and Contributo Straordinario calculations for Aree di Trasformazione. The results in Chapter 7 demonstrate that the two-step normalization pipeline is both technically feasible at 5x5 metre raster resolution and analytically meaningful in its capacity to differentiate between locations whose headline accessibility premium is substantially reduced or enhanced by their acoustic environment.

The net suitability surface for the Phase I corridor exhibits the “disamenity donut” geometry anticipated in the suitability model design: a ring of reduced net scores in the 0–150 m annulus immediately surrounding each metro station, attributable to the concentration of road and tram noise sources at interchange points. This donut geometry is surrounded by a “second-row premium band” in the 200–500 m range from each station entrance, where the accessibility benefit is realized in full without the proximate noise penalty; the upper bound of this band varies by station depending on local acoustic conditions (see 9.4). The donut geometry is consistent with the pattern reported by [Debrezion et al. \(2007\)](#) for a range of European rapid transit openings and with the Milan M4/M5 analysis of [Errera \(2020\)](#), who identify a similar non-monotonic distance-decay profile in the Milanese data. The contribution of this thesis relative to those prior studies is the explicit modelling of the donut through a penalty-based raster pipeline rather than a statistical inversion of HPM residuals, which enables prospective prediction rather than retrospective identification.

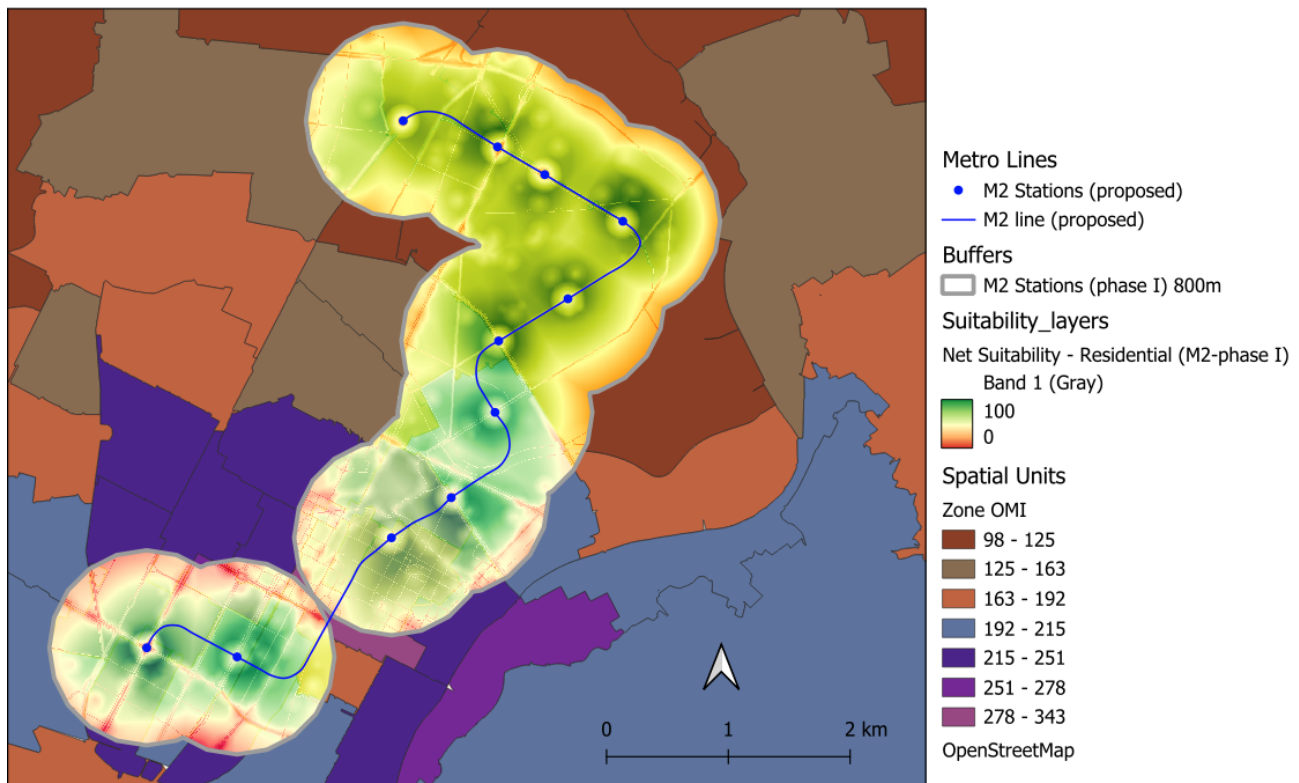


Figure 9.4: Net Residential Suitability around metro line 2 proposed stations, overlaid on OMI zones categorized by mean property value (thousand €).

The most analytically significant asymmetry in the Phase I corridor results is the contrast between the northern low-OMI zone and the central and southern higher-OMI zone. In the northern corridor (Rebaudengo–Barriera di Milano segment), OMI residential baseline values range from approximately €900 to €1,400/m², and the net suitability uplift coefficient produces an absolute projected price increment in the range of €0–84/m². In the central segment (Nizza–Porta Nuova), baseline values range from €1,500 to €2,200/m², generating increments of €60–198/m², while in the Porta Nuova environs the combination of high OMI baseline (€2,000–3,200/m²) and high net suitability scores yields increments of up to €384/m². This distributional asymmetry has material implications for LVC design: a uniform Contributo Straordinario rate applied to all Aree di Trasformazione in the corridor would capture disproportionately larger amounts in the already-higher-value southern zones, potentially creating a subsidy from lower-income northern communities to the public infrastructure budgets funded by southern developer contributions. A differentiated rate structure, with higher capture rates in the higher-OMI southern corridor and reinvestment obligations in the lower-OMI northern corridor, would be more equitable and is discussed further in Section 9.3.5.

The “Dual Dividend” hypothesis introduced in Chapter 1 is supported by the joint analysis of Use Cases 1 and 2. Many of the statistical zones with the lowest CSI scores under the equal-weight baseline (the Priority Intervention Zones identified in Section 6.5) are spatially congruent with the Phase I corridor zones exhibiting the largest net suitability score gains relative to the pre-metro accessibility baseline.

This congruence suggests that Metro Line 2 would not merely generate property value uplift in already-advantaged areas (the gentrification concern) but would systematically redistribute accessibility quality towards the zones where it is most deficient. The magnitude of this redistribution effect, which would be measured as the change in CSI score attributable to the F1.1 PT frequency indicator improvement under the Phase I scenario, is quantifiable by re-running the composite index after substituting a post-metro GTFS feed for the March 2026 baseline; this scenario analysis is identified as a direct operational use of the dashboard’s Configure panel and is designated as a priority for future work. Whether the CSI improvement is sufficient to trigger residential displacement depends on the speed and magnitude of the OMI uplift response, and this threshold sensitivity is discussed under the planning limitations in Section 9.3.

The Land Value Capture analysis for Aree di Trasformazione (Section 7.7) maps the PRG-designated transformation parcels within the Phase I 800 m corridor catchment. The aggregate projected residential uplift across these parcels is computed via pixel-wise summation of the ΔP_i surface masked to residential land use, as formalized in Equation 7.4. Applying the illustrative Contributo Straordinario capture rate of 25% to this aggregate gives an order-of-magnitude ceiling on the planning-obligation revenue potentially available to co-finance Metro Line 2 Phase I infrastructure costs. This figure should be interpreted as a theoretical maximum under full redevelopment of all designated transformation areas; practical realization depends on market cycle timing, developer viability negotiations, and phased build-out over the decade separating planning approval from line opening. The capture fraction is consistent with LVC efficiency estimates reported for comparable Italian urban transit projects (Bottero et al., 2023), where development obligations typically capture a smaller absolute share than the headline legal ceiling suggests.

The DSS dashboard (Chapter 8) provides the operational interface through which these RQ3 results are made actionable. In the Phase I prototype, the net suitability and economic uplift rasters are integrated as read-only Leaflet overlays that can be co-displayed with the UC1 sustainability choropleth, enabling visual identification of the Dual Dividend zones and second-row premium geography without requiring a standalone GIS installation. Planning officials can additionally modify UC1 indicator weights through the Configure panel and immediately regenerate the composite sustainability map, enabling rapid sensitivity analysis. The full three-audience architecture (planning module, investment screening module, citizen address lookup) is designated as Phase II development work, as described in Chapter 8 (Section 8.6). The delivered prototype’s capabilities

and its distance from the target architecture are evaluated in Section 9.2.3.

9.2 Methodological Contributions

This thesis advances the state of the practice in three methodological areas that are each distinct in their technical content but are unified by the common objective of increasing the precision and applicability of urban sustainability and transit impact assessment.

9.2.1 SNTTool MED Indicator Operationalization at the Neighbourhood Scale

The operationalization of SNTTool MED indicators at the *zona statistica* level in Chapter 4 extends the neighbourhood sustainability assessment literature in two directions. First, it operates at a finer spatial scale than most prior composite assessments for Italian cities: neighbourhood-level *zone statistiche* rather than municipal or provincial aggregates. This change in scale introduces data procurement challenges that are invisible at coarser resolutions, and the solutions developed here (notably the use of IDISE 2021 sub-comune tabulations for employment indicators, and LCP2023 for I3.3 permeability) constitute replicable methodological contributions for other cities engaged in SNTTool MED application.

Second, the harmonization framework explicitly treats indicator data sources as interchangeable within a defined specification, provided they satisfy the spatial resolution, temporal coverage, and definitional consistency criteria established in the selection protocol. This “source agnosticism” within a fixed indicator definition is important for replicability: a city that lacks LCP2023 but has Copernicus Urban Atlas 2018 coverage can substitute the latter for I3.3 without modifying the indicator definition, accepting only the reduced accuracy from the older vintage. The INSPIRE-compliant metadata documentation produced in Chapter 5 (Tables 5.1 and 5.2) formalizes this substitutability by recording the provenance, resolution, and uncertainty band for each of the 42 GeoPackage files in the analysis, enabling downstream users to assess the impact of data substitutions on indicator reliability.

In the context of the broader composite index literature, the selection protocol applied here is consistent with the OECD Handbook on Constructing Composite Indicators ([Organisation for Economic Co-operation and Development, nd](#)) recommendation to apply expert review, correlation analysis, and sensitivity testing as iterative quality controls. The weight sensitivity analysis performed in Section 6.3 is the sensitivity testing component of this process, and the results confirm that the north–south gradient is robust across all tested weight scenarios, with rank reversals occurring only among zones that are close in CSI score rather than at the extremes of the distribution.

9.2.2 Two-Step Normalization Pipeline with Proportional Acoustic Penalty

The two-step normalization pipeline introduced in Chapter 3 and applied in Chapter 7 is the most technically novel contribution of this thesis. The key design decision, applying the acoustic penalty after normalization but before the second-pass rescaling, ensures that the noise discount is proportional to each location’s own accessibility quality rather than an absolute deduction from a common scale. This design choice is motivated by the hedonic pricing literature’s finding that acoustic disamenity interacts multiplicatively with transit accessibility rather than additively ([Debrezion et al., 2007](#); [Seo et al., 2014](#)): a 60 dB(A) noise exposure suppresses property values by a larger absolute amount in a high-accessibility location (where the base value being discounted is higher) than in a low-accessibility location, even if the percentage discount is similar.

Prior GIS-based transit suitability models for Italian cities have typically applied noise as a simple negative weight in a WLC framework (for example, the Rome Metro C analysis of [Cascarano and Mocetti 2022](#), and

the multi-criteria suitability models reviewed by [Bottero et al. 2023](#)), treating it as one criterion among many rather than as a multiplicative post-normalization discount. The methodological consequence of the conventional approach is that it systematically underestimates the net suitability of high-accessibility but quiet locations and overestimates the net suitability of high-accessibility but noisy locations, because the noise penalty is diluted by the equal weighting of all criteria including those unrelated to acoustic quality. The two-step pipeline eliminates this dilution by applying the penalty directly to the normalized score before aggregation, ensuring that the acoustic environment has a first-order effect on the net suitability outcome wherever it is material.

The pipeline is implemented in Python 3.10 using the GeoPandas/Rasterio/NumPy stack described in Chapter 5, and all steps are fully reproducible from the GeoPackage inputs. The computational efficiency of the raster approach (5×5 m cells over the Phase I corridor mask) enables iterative scenario testing that would be impractical with a vector-based HPM model requiring each scenario to be re-estimated econometrically.

9.2.3 Integrated Multi-User DSS Dashboard

The dashboard described in Chapter 8 addresses a design challenge that the decision-support systems literature identifies as a persistent barrier to the adoption of academic sustainability assessments by professional users: the mismatch between the analytical richness of multi-criteria models and the operational simplicity required by non-specialist end-users ([Jankowski, 2009](#); [Malczewski, 1999](#)). The Phase I prototype makes a substantive contribution to this challenge in the UC1 domain: a planning professional with no Python or GIS expertise can modify indicator weights, upload updated CSV data, and regenerate the full composite sustainability map through a browser interface, without touching the underlying geoprocessing pipeline. The layered drill-down from composite to domain to indicator to neighbourhood profile operationalizes the “boundary object” framing proposed by [Star and Griesemer \(1989\)](#): the composite index serves as a shared analytical reference point while the detail layers allow each user to probe the specific dimensions most relevant to their decision context.

The most significant gap between the prototype’s delivered capabilities and the target multi-user architecture is the absence of UC2 interactivity. In the current implementation, the net suitability and economic uplift rasters are view-only overlays, meaning that real estate professionals cannot adjust noise penalty parameters or amenity weights within the dashboard and observe the effect on the suitability surface. This constrains the tool’s utility for the investment module use case: the second-row premium band geometry and Contributo Straordinario reference values must be read from the pre-computed rasters rather than explored interactively. The Phase II UC2 computation API described in Section 8.6 addresses this gap directly.

A notable design tension that persists into Phase II is the tradeoff between model transparency and communicative accessibility. The current Configure panel exposes the full indicator breakdown and weight parameters, which is appropriate for expert users but inaccessible to citizens unfamiliar with composite index methodology. Future work should explore a progressive disclosure design, in which a simplified default view conceals the parameter detail while providing an optional drill-down for users who need it, consistent with the layered complexity principle that motivated the original design.

9.3 Limitations and Boundary Conditions

A rigorous assessment of the thesis’s limitations is necessary not only for intellectual honesty but also to define the conditions under which the results can be transferred to other contexts, extended with new data, or improved through methodological refinements.

9.3.1 Data Vintage and Coverage

The most significant data limitation is the cross-vintage heterogeneity of the indicator inputs. The ISTAT 2021 Census is the primary population and housing data source, but income data (H1.1) are drawn from IRPEF 2021 declarations at CAP zone level, which may not perfectly align with the 2021 Census *zona statistica* boundaries. The GTT GTFS feed used for transport indicators reflects the March 2026 service schedule, which postdates the Census by five years. The Land Cover Piemonte 2023 (LCP2023) dataset used for I3.3 permeability has a 2023 vintage that is more recent than the population data. The OMI property value microzone boundaries used for the G2.x and UC2 uplift calculations are drawn from the 2024 Agenzia delle Entrate update. This combination of vintage misalignments means that the composite index does not represent a single consistent point in time but rather a synthetic cross-section that approximates “current conditions” without fully resolving their temporal heterogeneity. In practice, this is unavoidable for any neighbourhood-level composite index that relies on administrative data with different collection cycles, and it is consistent with standard practice in the European Urban Audit composite indicators that face the same challenge. Future annual updates to the index should aim to standardize the reference year as datasets from a common period become available.

The spatial resolution mismatch between indicator reporting units and the *zona statistica* analysis unit is a related but distinct issue. Income data at CAP zone level and employment data at sub-comune level are aggregated units that may each span multiple *zone statistiche*. The aggregation introduces a smoothing effect that underestimates within-zone variation for the H-domain indicators. The magnitude of this smoothing is difficult to quantify without access to individual-level microdata (ISTAT tax records or administrative registry files at the fiscal code level), which are restricted under GDPR and Italian data protection law. Future work that gains access to these data through formal research data access agreements with ISTAT would materially improve the H-domain resolution.

9.3.2 Model Structure and Analytical Assumptions

The Weighted Linear Combination approach to composite index construction is a pragmatic choice that has well-understood limitations: it assumes additive separability among indicator scores, linear substitutability between domain performance, and sensitivity to the ordinal ranking of weight scenarios ([Organisation for Economic Co-operation and Development, nd](#)). These assumptions are unlikely to hold precisely in an urban sustainability context where complementarities and synergies among indicators are known to exist (for example, green space provision and social cohesion, or transport accessibility and employment outcomes). Multiplicative aggregation, ordered weighted averaging, or fuzzy inference methods could capture these non-linearities, but at the cost of interpretability and the risk of over-parameterization given the final indicator sample size of 18 in 94 spatial units.

The equal spatial weighting within *zone statistiche* (each pixel within a zone contributes equally to the zone score regardless of land use) is a simplification that masks intra-zone variation. In a large northern peripheral zone that contains both dense residential blocks and industrial brownfield land, the composite score reflects an area-weighted average that may not accurately represent the sustainability conditions experienced by residents, who are concentrated in the residential portions. This limitation could be partially addressed by a population-weighted aggregation that weights indicator values by population density rather than by area, but this approach requires a reliable 100 m or 25 m population grid (such as GHS-POP R2023A or ISTAT 2021 grid) and has not been applied in the current analysis. The sensitivity of the CSI results to population weighting is identified as a priority for future work.

The net suitability model for UC2 assumes a linear relationship between the net suitability score and the OMI property value uplift coefficient, modelled as a fixed percentage premium per suitability score unit. This linearity

assumption simplifies the hedonic relationship, which in reality is likely non-linear and threshold-dependent (with a floor below which suitability scores cease to influence property decisions, and a ceiling above which additional suitability gains yield diminishing price increments). The non-linear specification of [Debrezion et al. \(2007\)](#) and the threshold detection approach of [Higgins and Kanaroglou \(2016\)](#) suggest that the linear approximation may overstate value uplift in the tails of the suitability distribution. Future work should estimate the non-linear uplift function directly from repeat-sales or hedonic price data using Turin’s OMI microzone time series.

The multivariable OLS regression linking the economy-prioritized CSI, quietness score, and log-transformed commercial establishment count to OMI property values ($R^2 = 0.383$, $n = 93$, $p < 0.001$) provides correlative evidence of the directional relationships discussed in Section 6.5.1, but several diagnostic caveats apply. Two standard diagnostics have been applied: the Variance Inflation Factor (VIF), which confirms that multicollinearity is not a material concern across all three predictors (VIF values of 1.22, 1.60, and 1.74 respectively, all well below the threshold of 5); and the Breusch-Pagan test, which fails to reject the null hypothesis of homoscedastic residuals ($LM = 3.33$, $p = 0.344$), validating the use of standard OLS standard errors. The outstanding unresolved diagnostic is spatial autocorrelation of the residuals (Moran’s I). Spatial dependence in the error term is expected in any city-level hedonic model given the strong spatial clustering of both property prices and neighbourhood sustainability quality documented by [Barreca et al. \(2017\)](#), and its presence would indicate that the OLS assumption of independently distributed errors is violated at the *zona statistica* scale. Until Moran’s I is computed and, if necessary, a spatial lag or spatial error model is estimated, the coefficient estimates should be treated as directional associations rather than precise hedonic price signals. This remains the most important outstanding diagnostic step for this model and is identified as a priority for follow-on work.

9.3.3 Acoustic Modelling Simplifications

The CNOSSOS-EU implementation applied in this thesis is a simplified adaptation of the full strategic noise mapping methodology, using TGM annual average daily traffic data and standard European road surface coefficients rather than vehicle-category-disaggregated traffic matrices and site-specific surface attenuation parameters. Several specific simplifications carry material uncertainty:

First, the TGM data used for road noise calculation is the most recently available annual average traffic count, but it does not reflect temporal variation within the day (peak versus off-peak), which is relevant for residential property valuation studies where night-time noise is weighted more heavily than daytime noise in standard L_{den} calculations. A full L_{night} analysis would require time-of-day traffic matrices that are not currently available from the TGM geoportal.

Second, façade-level acoustic attenuation (building geometry, insulation specifications, courtyard shielding) is not modelled at the individual building scale. The buffer-based approach applies a uniform distance-decay function to all properties within the noise zone regardless of their orientation, floor level, or building type, which is a material oversimplification in Turin’s dense historic districts where interior courtyard geometry provides substantial noise attenuation relative to street-facing facades.

Third, the “Movida” disamenity from nighttime entertainment concentrations in the Piazza della Repubblica and San Salvario areas, while documented in the Phase I corridor analysis (Section 7.6), is modelled through a static disamenity radius rather than a noise level estimate grounded in measurement data. The magnitude of the Movida penalty is therefore uncertain, and the analysis treats it as a qualitative flag rather than a precisely quantified discount.

Fourth, tram noise is modelled using the Series 2800 acoustic profile as the worst-case representative fleet, consistent with the GTT fleet data available at the time of analysis. However, GTT has announced a fleet renewal programme that will phase out Series 2800 rolling stock on some routes during the 2026–2032 planning

horizon. If the fleet renewal programme proceeds on schedule, the tram noise profile assumed in this thesis will overstate the disamenity experienced by residents in the 2032–2033 period when Metro Line 2 Phase I is expected to open (Comune di Torino, 2024). This conservatism in the tram noise assumption slightly understates the net suitability scores in zones where tram and metro routes overlap.

9.3.4 Scope Restrictions: Residential Focus and Static Analysis

The analysis is restricted to the residential property market, and the suitability model and LVC calculations do not address commercial, retail, or hospitality property. This restriction is appropriate given the thesis’s focus on residential sustainability and housing affordability, but it excludes a potentially significant component of value uplift in the Piazza della Repubblica and Porta Palazzo commercial corridors, where Metro Line 2 accessibility gains would benefit retail and hospitality investors as well as residents. An extension of the UC2 model to commercial property, using the OMI commercial value tables for the relevant microzones, would provide a more complete picture of the total corridor value uplift available for LVC.

The analysis is also static rather than dynamic: it models the post-opening accessibility equilibrium rather than the trajectory of value uplift between the announcement period (circa 2022–2024, when the Phase I alignment and station programme were publicly confirmed) and the opening date (end of 2032 or early 2033). Research on announcement effects in European transit projects (Higgins and Kanaroglou, 2016; Mohammad et al., 2013) consistently finds that a substantial fraction of the total accessibility-driven uplift is capitalized into property prices at or shortly after the announcement date rather than at opening. A dynamic model incorporating announcement-period price data from the OMI time series would enable estimation of the announcement effect and would separate the already-capitalized uplift from the residual uplift attributable to opening-period accessibility improvements, with direct implications for the timing of LVC capture.

9.3.5 Planning Law and LVC Feasibility

The LVC projections in Chapter 7 are theoretical estimates grounded in the legal framework of DPR 380/2001 and the PRG Contributo Straordinario mechanism. Their practical realization depends on several factors that are outside the scope of this analysis. First, the PRG revision required to formally designate the Aree di Trasformazione along the Metro Line 2 corridor has not been completed at the time of writing; the ZUT designations used in the LVC analysis are drawn from the existing Variante 200 zoning rather than a purpose-designed transit corridor overlay zone. Second, the Contributo Straordinario negotiation is a bilateral process between the Comune di Torino and individual developers; in practice, contributions are often reduced through viability assessments that demonstrate infrastructure costs and profit constraints, meaning the capture rate may be substantially below the 50% legal maximum. Third, the political feasibility of LVC depends on the willingness of successive municipal administrations to maintain a consistent capture policy over the ten-year horizon between Phase I planning approval and project completion. Historical precedent from Italian urban transit projects suggests that LVC revenues frequently fall below projections due to implementation lags and policy discontinuities (Bottero et al., 2023).

9.4 Implications for Practice

The findings of this thesis carry actionable implications for three distinct professional communities: urban planners and municipal policymakers engaged with the PRG revision, real estate development professionals assessing the Metro Line 2 corridor, and public finance officers responsible for designing LVC instruments.

9.4.1 For Municipal Planners: PRG Monitoring and Priority Allocation

The Composite Sustainability Index produced by this thesis is designed to serve as a neighbourhood baseline for Turin’s PRG revision cycle. Its most direct practical application is the identification and quantification of Priority Intervention Zones: the bottom quintile of CSI scores, concentrated in the northern sub-municipalities, provides a spatially explicit and multi-dimensionally justified evidence base for designating areas of concentrated planning investment. The spatial overlap between the lowest-CSI zones and the Phase I Metro Line 2 corridor (the “Dual Dividend” areas identified in Section 6.5) provides a further argument for concentrating PRG green infrastructure, social facility, and housing affordability provisions in these zones, exploiting the transit investment as a catalyst for broader sustainability improvements.

For the Piano Urbano della Mobilità Sostenibile (PUMS) evaluation process, the F-domain indicators (particularly F1.1 PT service frequency and F4.2 street connectivity) provide a pre-investment transport equity baseline against which the Phase I accessibility improvement can be measured once Metro Line 2 enters service. The dashboard’s Configure panel enables planners to upload a post-metro GTFS-derived CSV for the F1.1 indicator and re-compute the CSI for all affected zones without rerunning the Python geoprocessing pipeline, supporting the PUMS monitoring protocol through the standard CSV data-upload workflow already implemented in the Phase I prototype.

The acoustic noise assessment provides a complementary evidence layer for the PRG’s environmental provisions, specifically the road-noise-buffer mapping for rezoning decisions along the major arterials (Corso Giulio Cesare, Corso Vercelli, Corso Vittorio Emanuele II) and the tram-noise mapping for brownfield redevelopment sites along legacy tram routes. The CNOSSOS-EU buffer output, provided as GeoPackage files in EPSG:3003, is directly compatible with the Comune di Torino’s GIS platform and requires no conversion for use in PRG map overlays.

9.4.2 For Real Estate Professionals: Investment Screening and Due Diligence

For real estate development professionals, the most operationally valuable outputs of this thesis are the net suitability raster and the second-row premium band geometry derived from the donut geometry analysis. The second-row premium band identifies the spatial range from metro station entrances within which the full accessibility premium is realized without the proximate acoustic and congestion disamenity: typically from approximately 200 m to 500 m from the station entrance in the Phase I corridor, with significant variation depending on the local acoustic environment and the presence of competing disamenities (Movid noise in the Piazza della Repubblica segment, industrial land uses in the Rebaudengo segment).

In the Phase I prototype, development professionals can access the net suitability and economic uplift rasters as interactive Leaflet overlays co-displayed with the Aree di Trasformazione polygon layer, enabling visual identification of the highest-uplift parcels within the Phase I corridor. The investment screening panel (multi-criteria filter by suitability score, OMI range, and planning designation) and the Contributo Straordinario reference value export are designated as Phase II features whose implementation is informed by the analytical outputs of this thesis.

For retail investors and prospective residential purchasers, the neighbourhood profile page provides a form of property intelligence not otherwise synthesized for a general audience in the Turin market: domain-level sustainability scores, city-wide rank, and key socioeconomic attributes for any of the 94 *zone statistiche*. The full address-level net suitability score and noise exposure profile, which would transfer professional-grade spatial intelligence to individual housing market participants, is a Phase II deliverable. The democratization of this information is identified as one of the most significant social equity contributions of the DSS design, precisely because the information advantage it addresses is currently held by institutional actors who can commission bespoke HPM analyses unavailable to individual purchasers.

9.4.3 For Land Value Capture Policy

The LVC analysis in Chapter 7 suggests that a flat-rate Contributo Straordinario applied uniformly across all Aree di Trasformazione in the Phase I corridor would be both inefficient and inequitable. It would be inefficient because it fails to capture the full uplift premium in high-OMI southern segments where the absolute value gain exceeds the capture obligation, and it would be inequitable because it imposes equal obligations on developers in the northern low-OMI segment where the absolute uplift is smaller but where the planning imperative for affordable housing provision is greatest.

A differentiated LVC framework would instead apply a rate schedule that increases with baseline OMI value, reserving a higher capture rate (up to the 50% legal maximum) for the highest-value southern corridor segments and a lower rate (perhaps 20–30%) for the northern corridor segments, with a corresponding requirement that the lower-rate concession in the north be matched by a minimum affordable housing set-aside percentage. This structure would replicate the logic of the Grand Paris Express LVC framework (Ferm and Moore-Cherry, 2025), which applies differentiated capture rates across corridor segments based on property market maturity, and would partially address the gentrification risk identified in the RQ2 discussion.

The timing of LVC capture is also material. Given the evidence of announcement-period price effects in comparable Italian transit projects, a supplementary LVC instrument based on betterment levies applied at the planning permission stage (rather than at the development completion stage) would capture a portion of the uplift that has already been incorporated into land prices since the Phase I alignment was publicly confirmed. The legal basis for such a levy exists under the Contributo di Costruzione framework, but has rarely been applied prospectively for transit projects in Italy. This gap between legal possibility and planning practice is identified as a research priority for future work on Italian transit LVC.

9.5 Comparison with Comparable European Studies

Situating the findings of this thesis within the European transit and sustainability assessment literature provides both external validation and a basis for identifying the relative contribution of the methodology developed here.

9.5.1 Rome Metro C: Cascarano and Mocetti (2022)

The most directly comparable Italian study is Cascarano and Mocetti (2022), which estimates the property value capitalization of Rome’s Metro C opening using a difference-in-differences (DID) design with repeat-sales data from the Agenzia delle Entrate OMI archive. Cascarano and Mocetti report a residential value premium of approximately 3–5% within an 800 m catchment of Metro C stations, with the premium strongest in zones where baseline accessibility was lowest (analogous to the northern low-OMI corridor in this thesis) and weakest in zones with pre-existing bus and tram access.

The comparison with this thesis’s UC2 results is instructive at the methodological level. Cascarano and Mocetti’s DID approach provides a causal estimate of the realized value premium from an operational metro line, using the pre-opening period as a control. The prospective raster model applied in this thesis cannot replicate the causal identification strategy, since Metro Line 2 has not yet opened. However, the raster approach provides spatial granularity (5x5 m versus OMI microzone averages) and scenario flexibility (multiple weight and penalty parameter scenarios) that are unavailable in the HPM framework. The two approaches are therefore complementary: the Cascarano and Mocetti premium estimates (adjusted for the scale and corridor characteristics of the Metro Line 2 Phase I alignment) serve as external calibration benchmarks for the uplift coefficient assumptions in the UC2 model, while the raster model provides the within-corridor spatial distribution that the HPM cannot resolve.

A notable methodological difference is the treatment of acoustic disamenity. Cascarano and Mocetti include noise zone classifications as a covariate in their hedonic specification but do not explicitly model the disamenity donut geometry; their station proximity variable is monotonically positive, suggesting that the donut's proximate penalty is masked by the aggregation at microzone level. The two-step pipeline applied in this thesis resolves this masking at the pixel level, producing a non-monotonic accessibility surface that the microzone-based HPM cannot generate.

9.5.2 Milan M4 and M5: Errera (2020) and Related Literature

Errera (2020) provides a transit-oriented development analysis of the Milan Metro M5 opening, documenting a residential price premium of 2–4% within 500 m of new M5 stations and identifying the second-row premium band (300–700 m from station entrance) as the segment that captures the largest absolute price increment relative to the pre-metro baseline. The second-row premium geography reported by Errera is consistent with the net suitability donut geometry generated by the UC2 model for the Phase I corridor: both analyses identify the proximate zone (within approximately 200–300 m) as acoustically penalized, while the zone beyond 300 m realizes the full accessibility premium.

The M5 analysis is particularly relevant because the M5 corridor (Garibaldi–Bignami) traverses a comparable post-industrial regeneration context to the Phase I Metro Line 2 northern segment, with similar challenges of low baseline OMI values, high social vulnerability, and elevated displacement risk. Errera's finding that the M5 opening triggered a measured acceleration in rental price growth in the first-ring zones (300–500 m from stations) in the lower-OMI Maciachini–Zara segment is a cautionary precedent for the Metro Line 2 corridor's northern Barriera di Milano segment, reinforcing the anti-displacement provisions argument made in Section 9.1.2.

9.5.3 Grand Paris Express: LVC Benchmark

The Grand Paris Express (GPE) project provides the most comprehensive contemporary European reference for LVC design in a major urban transit corridor. The *Société du Grand Paris* reports that developer contributions, inclusive of differentiated Taxe d'Aménagement and ZAC-based development obligations, are projected to fund approximately 10–15% of the total GPE construction cost of €36 billion, with capture rates varying from 8% in peripheral low-OMI segments to 25% in the central high-OMI segments (Ferm and Moore-Cherry, 2025). These figures are useful reference points for the Metro Line 2 LVC projections, suggesting that the indicative capture rate of 25% applied in Section 9.1.3 is within the plausible range for a corridor with the Phase I OMI profile, though the absolute amounts are substantially smaller given the scale difference between the GPE and Metro Line 2.

The GPE experience also highlights the importance of the institutional framework for LVC delivery. The *Société du Grand Paris*'s ability to negotiate development obligations along the corridor was underpinned by a dedicated statutory framework (*Contrat de développement territorial*), which gave the agency negotiating authority that Italian municipalities typically lack under the current PRG and DPR 380/2001 framework. The creation of a purpose-designed LVC authority for Italian metro corridors, analogous to a Società di Trasformazione Urbana (STU) with enhanced LVC mandates, is identified as a key institutional design recommendation emerging from this analysis.

9.5.4 Smart City and DSS Positioning

In the urban DSS and smart city literature, the dashboard described in Chapter 8 occupies a middle position between high-complexity machine-learning-based neighbourhood analytics platforms (Bibri, 2022) and the simpler

indicator dashboards typified by the UN-Habitat City Prosperity Index online tool. Its design aspiration is most closely aligned with the communicative planning and PPGIS frameworks discussed by [Jankowski \(2009\)](#): a tool designed to mediate between technical analysts and diverse stakeholder communities, using the composite index as a shared analytical language. The Phase I prototype realises this aspiration for the planning professional audience, delivering a fully operational indicator management and visualization workflow. Extension to the real estate professional and citizen audiences remains a Phase II target.

The integration of UC2 raster outputs within the same Leaflet map canvas as the UC1 sustainability choropleth is, to the author's knowledge, novel in the Italian planning DSS literature. Most comparable Italian tools treat sustainability monitoring and property market analysis as separate analytical streams. The co-display in this thesis reflects the theoretical argument that sustainability and property market outcomes are causally linked through transit accessibility (the Dual Dividend hypothesis), and that a DSS designed to support integrated PRG and LVC decision-making must present both streams in a common analytical environment, even at the Phase I stage where UC2 interactivity is still pending.

The structured comparison conducted in this chapter establishes the principal European benchmarks against which the methodological contributions of this thesis can be evaluated. The chapter that follows draws the analytical threads of both use cases into a consolidated account of findings, contributions to knowledge, and directions for future investigation.

Chapter 10

Conclusions

10.1 Summary of Findings

This chapter draws the analytical threads of both use cases into a consolidated account of what the thesis has established, the knowledge it contributes, and the directions along which the research can be extended. The three research questions that structured the investigation each receive a concise answer below, followed by an integrative statement linking the two use cases.

RQ1: Operationalizing Sustainability Indicators for Turin

The first research question asked which indicators from the SNTool MED framework are most suitable for neighbourhood-level sustainability comparison in Turin, and how they can be operationalized from open geospatial data. The analysis in Chapters 4 and 5 confirms that a credible, data-grounded neighbourhood sustainability index can be constructed for a major Italian city using predominantly open data and a reproducible Python geoprocessing pipeline. Twenty-four indicators spanning five issues (A, F, G, H, I) were fully calculated for Turin's 94 *zone statistiche*, with the selection process governed by explicit criteria of data availability, spatial computability, theoretical grounding, discriminatory power, and non-redundancy. A post-calculation review, conducted in Chapter 9, identified that six of the initial 24 indicators failed to meet the discriminatory power criterion in the Turin context: the bicycle network, EV infrastructure, and bicycle lane safety indicators where all zones underperformed the minimum benchmark without differentiation; the population density indicator where relative homogeneity limited spatial contrast; the biodiversity indicator where data limitations restricted the analysis to catalogued trees; and the cyclomatic complexity indicator where the measure proved insufficiently meaningful for PRG monitoring. The operative composite index therefore relies on 18 indicators whose spatial results are consistent with independent qualitative assessments of Turin's urban inequality while adding quantitative granularity at the neighbourhood scale. The methodological decisions made in the selection process, particularly the use of ISTAT IDISE 2021 sub-comune tabulations for employment indicators and Land Cover Piemonte 2023 for the land permeability indicator, are replicable in other Italian cities and represent a contribution to the broader SNTool MED application literature.

RQ2: Spatial Patterns, PRG Monitoring, and Residential Market Conditions

The second research question asked what spatial patterns of urban sustainability and acoustic noise exposure emerge across Turin's neighbourhoods, and what the implications are for the PRG monitoring framework and residential property market conditions. The composite sustainability index confirms a statistically robust north-south inequality gradient across the 94 *zone statistiche*, encompassing transport inaccessibility, green space deficit, social deprivation, labour market exclusion, and impervious surface concentration simultaneously. This gradient is robust across all four weighting scenarios tested, with rank reversals confined to zones that are close

in composite score rather than at the extremes of the distribution. The acoustic noise cross-analysis reveals an important synergistic relationship: the strong positive correlation between the quietness score and the composite sustainability index (Spearman's $\rho = 0.623$, $p < 0.001$) demonstrates that sustainability investments which improve domain scores simultaneously attenuate noise exposure, a “Green Oasis” effect that provides additional justification for integrated green infrastructure investment. A three-predictor OLS regression ($n = 93$ *zone statistiche*, $R^2 = 0.383$, $p < 0.001$) provides correlative evidence linking economic sustainability, noise exposure, and commercial vitality to residential property prices. Holding noise and commercial concentration constant, a one-unit increase in the economy-prioritized CSI is associated with an increase of approximately €479.82/m² in average OMI prices. The addition of log-transformed commercial establishment count as a third predictor reveals that the count is not independently significant ($p = 0.287$) once noise is controlled for, indicating that the noise variable already proxies the commercial animation of central zones and that these two dimensions of urban vitality are not independently separable at the zone-average scale. Variance Inflation Factor diagnostics confirm the absence of multicollinearity across all three predictors (all VIF < 2), and the Breusch-Pagan test confirms homoscedastic residuals ($p = 0.344$). Spatial autocorrelation of the residuals, as assessed by Moran's I , remains untested and constitutes the main outstanding diagnostic for this model. All reported associations are correlative rather than causal, consistent with the cross-sectional and zone-level nature of the data. The most significant planning implication of RQ2 is the “affordability trap” dynamic in the low-income northern zones, where relatively favourable rental affordability scores reflect low neighbourhood desirability rather than active housing policy, meaning that any CSI-improving intervention risks triggering rental price inflation and residential displacement unless anti-displacement provisions are incorporated in the PRG revision.

RQ3: Net Suitability, Property Value Uplift, and Land Value Capture

The third research question asked how a GIS-based net suitability model combining transit accessibility premiums with integrated acoustic disamenity penalties could predict the spatial distribution of residential property value uplift from the proposed Metro Line 2, and what the implications are for land value capture policy. The two-step normalization pipeline produces a continuous net suitability surface at 5×5 m resolution that captures both the “disamenity donut” geometry, characterized by suppressed scores in the 0–150 m annulus immediately surrounding each station where road and tram noise loads are highest, and the “second-row premium band”, where peak scores are reached in the 200–500 m range and the accessibility benefit is fully realized without proximate acoustic penalty. The distributional asymmetry of the projected uplift surface has direct implications for LVC design: absolute price increments range from €0–84/m² in the northern Rebaudengo–Barriera di Milano corridor, where OMI baseline values are lowest, to €120–384/m² in the Porta Nuova environs, where the combination of high baseline prices and high net suitability scores produces the largest absolute increments. A flat-rate *Contributo Straordinario* applied uniformly across all *Aree di Trasformazione* in the Phase I corridor would therefore capture revenue disproportionately from already-higher-value southern segments while failing to cross-subsidize the equity-priority northern corridor, where the planning case for affordable housing set-aside is greatest.

The Dual Dividend: An Integrative Finding

The joint spatial analysis of Use Cases 1 and 2 provides strong evidence consistent with the Dual Dividend hypothesis that structured the thesis from the outset: the statistical zones with the lowest composite sustainability scores under the equal-weight baseline are spatially congruent with the Phase I corridor zones exhibiting the largest projected net suitability improvement relative to the pre-metro accessibility baseline. This congruence demonstrates that Metro Line 2 would not merely generate property value uplift in already-advantaged areas but would systematically direct its accessibility benefit towards the neighbourhoods where sustainability deficits

are deepest, providing a strong evidence base for the equity argument in favour of Phase I investment. The DSS dashboard described in Chapter 8 makes this spatial coincidence operationally visible, enabling planning professionals to co-display the UC1 sustainability choropleth and the UC2 net suitability raster within a single map canvas and to identify the Dual Dividend zones without requiring a standalone GIS installation.

10.2 Contribution to Knowledge

This thesis advances knowledge across four distinct but interconnected dimensions: empirical, methodological, applied, and operational.

1. Empirical contribution. The thesis produces what is, to the author’s knowledge, the first integrated WLC sustainability assessment for the Comune di Torino at the *zona statistica* scale, operationalizing the SNTTool MED framework with 24 fully calculated indicators drawn from Issues A, F, G, H, and I (of which 18 meet the discriminatory power criterion for composite scoring across Turin’s 94 neighbourhoods). Most prior neighbourhood-level composite assessments for Italian cities have operated at the municipal or sub-municipal level using a narrower indicator set, and none has applied the SNTTool MED framework at this spatial resolution with full INSPIRE-compliant metadata documentation for each dataset. The CSI results establish a replicable sustainability baseline against which the PRG revision cycle and future infrastructure investments can be monitored, and demonstrate that a meaningful multi-domain neighbourhood index can be produced from open Italian administrative and geospatial data without access to restricted microdata.

2. Methodological contribution. The two-step normalization pipeline, in which the dynamic CNOSSOS-EU acoustic penalty is applied as a proportional post-normalization discount rather than as an additive criterion weight, addresses a systematic limitation in conventional GIS-based WLC transit suitability models. Prior Italian transit suitability analyses, including the Rome Metro C and Milan M4 studies reviewed in Chapter 9, have treated acoustic disamenity as one criterion among many, diluting its effect through equal weighting with non-acoustic criteria. The two-step design ensures that the noise discount is proportional to each location’s own accessibility quality, consistent with the hedonic evidence that acoustic disamenity interacts multiplicatively with transit accessibility rather than additively. The pipeline is fully reproducible from the GeoPackage inputs using the Python 3.10 geoprocessing stack documented in Chapter 5, and is adaptable to any Italian city for which TGM annual average daily traffic data and equivalent GTFS feeds are available.

3. Applied contribution. The thesis produces what is, to the author’s knowledge, the first pixel-scale (5×5 m) economic uplift surface for the Metro Line 2 Phase I corridor, calibrated against the Italian HPM meta-analysis literature and incorporating the disamenity donut geometry prospectively rather than retrospectively. The uplift surface, together with the *Aree di Trasformazione* overlay and the aggregate LVC calculation formalized in Equations 7.4 and 7.5, provides direct inputs for *Contributo Straordinario* assessment by the Comune di Torino. The distributional asymmetry finding, that absolute monetary uplift is highest in already-expensive southern corridor segments and lowest in the equity-priority northern segments, contributes a spatial finance perspective to the Italian planning literature on transit LVC that has not previously been quantified at this resolution.

4. Operational contribution. The DSS dashboard described in Chapter 8 demonstrates that the analytical outputs of this thesis are not merely academic abstractions but operational planning tools. The Phase I prototype delivers the full Module 1 workflow for city planning officials: indicator framework configuration, CSV data upload, composite sustainability score computation, choropleth visualization, issue-level and indicator-level

drill-down, neighbourhood profile pages, and scenario weight sensitivity analysis, all through a browser interface requiring no Python or GIS expertise. The co-display of the UC1 sustainability choropleth and the UC2 raster outputs within a single Leaflet map canvas, and the fully specified Phase II roadmap for real estate professional and citizen-facing modules, constitute a three-audience DSS architecture whose design principles contribute to the urban analytics and communicative planning literature (Jankowski, 2009; Star and Griesemer, 1989). Beyond the immediate thesis scope, the dashboard is designed from the outset as the seed of a continuous urban monitoring platform: its modular framework architecture — with pre-seeded stubs for the GUMF and U4SSC frameworks alongside the operational SNTTool MED — and its production-ready cloud stack (Docker Compose, JWT role-based access, GitHub Actions CI) are explicitly built for extensibility and institutional adoption. The platform has already been presented to city planning officials at the Comune di Torino and is positioned to support the municipality’s ongoing planning obligations, including the PRG revision cycle and emerging accessibility monitoring requirements under the Piano di Eliminazione delle Barriere Architettoniche (PEBA).

10.3 Future Research Directions

Six research directions emerge from the limitations and boundary conditions identified in Chapter 9. They are organized into two clusters: methodological extensions to the analytical models developed in this thesis, and governance and scaling directions that address the transfer of the methodology to wider policy contexts.

10.3.1 Model Extensions

Non-linear capitalisation function. The linear interpolation model linking net suitability score to uplift coefficient (Equation 7.1) embeds a proportionality assumption that the hedonic pricing literature suggests does not hold uniformly across the suitability distribution: empirical studies document diminishing returns at very high accessibility levels and a floor effect at very low suitability scores (Debrezion et al., 2007; Higgins and Kanaroglou, 2016). Replacing the linear ceiling with a logistic or polynomial function, estimated directly from the Turin OMI microzone time series for the 2015–2025 period using a repeat-sales or panel hedonic model, would produce an empirically grounded non-linear capitalisation curve specific to the Turin market context and would reduce the risk of overestimating uplift at high suitability scores and underestimating it in low-suitability peripheral zones.

Temporal GTFS integration for the F1.1 indicator. The PT system performance indicator (F1.1) currently relies on the March 2026 GTT GTFS feed as a static snapshot. Integrating temporal GTFS data across successive annual releases would enable the construction of a dynamic transit accessibility time series, supporting a pre-to-post Metro Line 2 comparison once Phase I enters service in 2032–2033. The dashboard’s Configure panel is already designed to accept updated CSV uploads for any indicator without rerunning the geoprocessing pipeline, meaning that the F1.1 time series update can be implemented through the standard data-upload workflow and would constitute the most direct operational use of the dashboard for PUMS monitoring and PRG revision evaluation.

Validation against ARPA Piemonte measured noise data. The CNOSSOS-EU road noise buffers applied in this thesis are modelled from TGM traffic counts rather than validated against measured acoustic levels. ARPA Piemonte maintains continuous noise monitoring stations across Turin and publishes strategic noise maps compliant with the Environmental Noise Directive (European Parliament and Council, 2002). A systematic comparison of the modelled buffer outputs with the ARPA L_{den} maps for the corridors included in

this analysis would quantify the accuracy of the simplified CNOSSOS-EU implementation, identify the road segments where the modelled buffer diverges most from measured conditions, and provide a calibration basis for future applications of the pipeline in other Italian cities.

Incorporation of Movida and POI congestion disamenity layers. The Movida externality in the San Salvario and Piazza della Repubblica segments is currently treated as a qualitative flag in the compound disamenity analysis rather than modelled as a calibrated penalty surface. Incorporating geocoded night-time noise measurement data from the Comune di Torino’s environmental monitoring records and point-of-interest density from OpenStreetMap as a proxy for commercial congregation externalities would produce a more complete compound disamenity model for the central Phase I segment, where the Movida effect materially overlaps with the second-row premium band and its current omission may lead to an overestimate of net suitability scores in that zone.

10.3.2 Governance and Scaling

Post-construction hedonic validation. The prospective uplift estimates produced by the UC2 model cannot be causally validated until Metro Line 2 Phase I enters service. A difference-in-differences hedonic validation study, replicating the methodology of [Cascarano and Mocetti \(2022\)](#) using the Turin OMI microzone repeat-sales archive for the 2025–2035 period, would provide the definitive empirical test of whether the modelled uplift coefficients match the realized market response. This study is identified as the most methodologically rigorous form of future validation for the analytical framework developed here, and would contribute to the Italian transit HPM literature a post-construction calibration dataset for a fully automated metro project comparable in scale and urban context to the Milan M4.

Replication to other PNRR-funded transit corridors. The methodology developed in this thesis is designed to be replicable. Several Italian cities with PNRR-funded rapid transit investments currently under construction, including Palermo, Genova, and Bologna, present comparable open-data environments and planning contexts. Replication studies would test the generalizability of the indicator selection criteria and the two-step normalization pipeline in different morphological and demographic contexts, establish whether the discriminatory power thresholds applied in Turin are appropriate across the range of Italian urban densities, and potentially support a multi-city comparative neighbourhood sustainability database aligned with the SNTool MED’s original design intent as a Mediterranean urban monitoring instrument.

DSS as a nucleus for continuous urban monitoring. The most immediate development trajectory for the dashboard extends its role from a thesis output to a continuous municipal monitoring platform. The first concrete extension currently under active development is a dedicated accessibility monitoring module aligned with the requirements of the Piano di Eliminazione delle Barriere Architettoniche (PEBA). Phase I of this module will produce a neighbourhood-level accessibility index for Turin’s *quartieri* using existing open datasets, applying the same WLC methodology demonstrated in Use Case 1 to identify priority intervention areas for accessibility improvement. Phase II will incorporate field data collected through a mobile mapping system (MMS) — an instrumented survey vehicle integrating an IMU Ekinox inertial unit, a Riegl VZ400i terrestrial laser scanner, and digital cameras — which enables high-resolution, street-level accessibility surveys to be conducted and their outputs ingested directly into the indicator scoring pipeline, replacing open-data proxies with ground-truth field measurements for the indicators most sensitive to pavement and path conditions. Further planned developments include temporal comparison across monitoring cycles to track indicator evolution between PRG revision periods; automated data refreshes through integration with the Comune di Torino’s Open Data Torino portal; automated

reporting for plan documentation; and extension to additional thematic areas beyond the five SNTool MED issues currently operationalized, developed in collaboration with institutional stakeholders. Taken together, these extensions transform the dashboard from a static analytical snapshot into a living planning instrument capable of supporting the municipality’s evidence needs across successive policy cycles.

Geospatial foundation models and Urban Digital Twins. Looking further ahead, two research frontiers represent the natural evolution of the methodology developed in this thesis. First, large pre-trained foundation models for geospatial data — models trained on satellite imagery, street-level sequences, and point cloud data at continental scale — are beginning to enable zero-shot or few-shot land cover classification, green space mapping, and accessibility network extraction that could substantially automate and accelerate the indicator data preparation pipeline, reducing the barrier to replication in cities where open-data availability is lower than in Turin (Mai et al., 2023). upstream components of the WLC scoring engine would allow the analytical framework to scale to a Mediterranean network of cities without requiring bespoke supervised training for each urban context. Second, Urban Digital Twins — continuously updated, simulation-capable digital representations of the city that ingest live sensor feeds, administrative data, and open datasets — represent the logical evolution from the static DSS prototype described in this thesis towards a genuinely dynamic planning environment. The existing architecture (PostGIS spatial backend, modular REST API, Docker-ready cloud stack) provides a technically sound foundation from which this evolution can proceed: the MMS integration described above constitutes a first step in that direction, and future work connecting the scoring engine to real-time data streams would close the gap between the current research prototype and a fully operational Urban Digital Twin for neighbourhood sustainability monitoring.

10.4 Closing Reflection

This thesis began from a practical observation: Turin is a city undergoing two simultaneous transitions, one fiscal and one spatial. The PNRR has made a major infrastructure investment in Metro Line 2 possible, but the planning framework for capturing the value that investment will create, and for ensuring that neighbourhood improvements do not come at the cost of displacing the residents who need them most, remains underdeveloped. The analytical work presented in these pages was undertaken with the intention of making that planning framework more precise.

What emerged from the process was something more than a technical exercise. The composite sustainability index for Turin’s 94 *zone statistiche*, built from open data through a reproducible geoprocessing pipeline, makes spatial inequality legible in a way that qualitative urban analysis has long described but rarely measured at the neighbourhood scale with sufficient granularity for planning intervention. The finding that some of the zones scoring lowest on the composite index are also the zones standing to gain most from Metro Line 2 is not coincidental; it reflects the structural logic of post-industrial urban geography that both use cases, taken together, render visible and quantifiable.

I am also aware of what the work leaves open. Whether the LVC instruments available under Italian planning law are adequate to capture the corridor’s uplift potential, whether the DSS dashboard will find its way into actual planning workflows at the Comune di Torino, and whether Metro Line 2 will follow the Milan M5 precedent in triggering displacement in the northern corridor before adequate anti-displacement provisions are in place, are questions that only time and continued research can answer. The tools developed here are, at their best, a contribution to the planning and policy conversations in which those answers will be shaped. Whether those conversations happen, and whether the evidence changes their outcome, depends on the people and institutions who take them up.

Disclosure on the Use of LLMs and Artificial Intelligence Tools

- **Claude (Anthropic, version Claude Sonnet 4.6)** was used to assist in drafting and structuring the prose of all chapters of this thesis, working from methodology notes, working documents, and the thesis outline prepared by the author. The tool was also used to assist in organizing the $\text{\LaTeX}$ source structure and bibliography. All AI-generated text was reviewed, verified against primary sources, and substantially edited by the author. The analysis, methodological choices, geoprocessing workflows, indicator calculations, and interpretations are entirely the author's own.
- **Claude Code (Anthropic, version Claude Sonnet 4.6)** was used to create the architecture, back-end and front end of the DSS dashboard proof-of-concept used in this thesis.
- **Gemini (Google, version 3.1 Pro)** was used for cross-referencing selected citations and verifying bibliographic details, as well as assisting in generating Python code to perform specific calculations and transformations.

Bibliography

- Agenzia delle Entrate (n.d.). Quotazioni immobiliari. Technical report, Osservatorio del Mercato Immobiliare (OMI), Rome, Italy. Official database for Italian real estate market values provided by the Ministry of Economy and Finance.
- Alonso, W. (1964). *Location and Land Use: Toward a General Theory of Land Rent*. Harvard University Press, Cambridge, MA.
- Aminrad, Z. (2024). Urban sustainability dashboards as boundary objects: Evidence from Helsinki, Copenhagen, and Turin. *Urban Informatics*, 3(1):12.
- Andersson, H., Jonsson, L., and Ögren, M. (2021). A sound investment? traffic noise mitigation and property values. *Journal of Environmental Economics and Policy*, 11(1):32–53.
- Anselin, L. (1995). Local indicators of spatial association — LISA. *Geographical Analysis*, 27(2):93–115.
- Artmann, M., Kohler, M., Meinel, G., Gan, J., and Ioja, I.-C. (2019). How smart growth and green infrastructure can mutually support each other: A conceptual framework for compact and green cities. *Ecological Indicators*, 96(2):10–22.
- Barreca, A., Curto, R., and Rolando, D. (2017). Assessing social and territorial vulnerability on real estate submarkets. *Buildings*, 7(4):94.
- Barreca, A., Fregonara, E., and Rolando, D. (2021). Epc labels and building features: Spatial implications over housing prices. *Sustainability*, 13(5):2838.
- Beria, P., Grimaldi, R., and Laurino, A. (2025). Urban tramways, noise, and real estate: Evidence from Italian legacy networks. *Urban Science*, 9(3):327.
- Bibri, S. E. (2022). The social shaping of the metaverse as an alternative to the imaginaries of data-driven smart cities: A study in science, technology, and society. *Smart Cities*, 5(3):832–874.
- Bibri, S. E. and Krogstie, J. (2021). Data-driven smart sustainable cities of the future: Urban computing and intelligence for strategic, short-term, and joined-up planning. *Computational Urban Science*, 1(8):1–29.
- Bjørner, T. B. (2003). Planes, trains, and automobiles: The impact of traffic noise on house prices. *The Journal of Real Estate Finance and Economics*, 26(2–3):179–196.
- Bocher, E., Petit, G., Bernard, J., and Palominos, S. (2019). NoiseModelling: An open source GIS based tool to produce environmental noise maps. *ISPRS International Journal of Geo-Information*, 8(3):130.
- Bonini Baraldi, S., Governa, F., and Salone, C. (2019). “they tried to make me go to rehab. i said, no, no, no”. representations of ‘deprived’ urban spaces and urban regeneration in turin, italy. *Urban Research & Practice*, 14(3):286–306.

- Bornioli, A. and Parkhurst, G. (2024). Just around the corner: Accessibility by proximity in the 15-minute city. *Journal of Urban Mobility*, 5:100073.
- Bottero, M., Bravi, M., and Dell'Anna, F. (2023). The value of urban parks and infrastructure in the city of Turin: A GWR approach. *Sustainability*, 15(5):4136.
- Cascarano, M. and Mocetti, S. (2022). The value of accessibility: Evidence from a new metro line in Rome. *Temi di Discussione (Bank of Italy Working Papers)*, (1389).
- Cervero, R. (2013). Linking urban transport and land use in developing countries. *Journal of Transport and Land Use*, 6(1):7–24.
- Città di Torino (1995). Piano regolatore generale (prg) di Torino. Urban planning document, Comune di Torino, Direzione Urbanistica. Approved by Regional Council Decree No. 3-45091 on April 21, 1995; represents the main urban planning instrument for the city.
- Coluccia, B., Solazzo, G., Aquilino, M., et al. (2026). Modelling real-estate values around railway stations: Insights from an Italian case. *Sustainability*, 18(5):2304.
- Comune di Torino (2024). Linea 2 metro entro 2032: pre-esercizio primo lotto funzionale. Technical report, Città di Torino. Comunicato stampa ufficiale relativo al cronoprogramma della metropolitana.
- Dawodu, A., Cheshmehzangi, A., and Akinwolemiwa, B. (2022). The systematic selection of neighbourhood sustainability assessment tools and their application to the case of China: A review. *Sustainable Development*, 30(1):195–213.
- De Pieri, F. (2010). Eventfully preserved: Turin's historic heritage in the policies for urban regeneration of the last twenty years. *Rivista di Scienze del Turismo*, (2):167–181.
- Debrezion, G., Pels, E., and Rietveld, P. (2007). The impact of railway stations on residential and commercial property value: A meta-analysis. *The Journal of Real Estate Finance and Economics*, 35(2):161–180.
- Eastman, J. R. (1999). Multi-criteria evaluation and GIS. In Longley, P. A., Goodchild, M. F., Maguire, D. J., and Rhind, D. W., editors, *Geographical Information Systems*, volume 1, pages 493–502. John Wiley & Sons, New York.
- Errera, A. (2020). Transit infrastructure and property values in Milan: An analysis of the M4 metro line announcement and capitalisation effects. *Politecnico di Milano Working Paper*. Research paper, Department of Architecture and Urban Studies.
- European Commission (2019). The european green deal. Technical Report COM(2019) 640 final, European Commission.
- European Conference on Sustainable Cities & Towns (1994). Charter of european cities & towns towards sustainability (aalborg charter). Technical report, European Sustainable Cities Platform, Aalborg, Denmark. Approved by the participants at the first European Conference on Sustainable Cities & Towns.
- European Environment Agency (2024). Urban sustainability in Europe: Avenues for change. Technical Report EEA Report No 06/2024, EEA.
- European Ministers responsible for Urban Development (2007). Leipzig charter on sustainable european cities. Technical report, Council of the European Union. Adopted at the Informal Ministerial Meeting on Urban Development and Territorial Cohesion in Leipzig.

- European Parliament and Council (2002). Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. Technical Report L 189, Official Journal of the European Communities. Environmental Noise Directive (END).
- European Parliament and Council (2007). Directive 2007/2/EC of the European Parliament and of the Council establishing an infrastructure for spatial information in the European Community (INSPIRE). Technical Report L 108, Official Journal of the European Union.
- European Parliament and Council (2015). Commission Directive (EU) 2015/996 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council. Technical Report L 168, Official Journal of the European Union.
- Farhan, B. and Murray, A. T. (2008). Distance decay and coverage in facility location planning. *Annals of Operations Research*, 167(1):281–303.
- Ferm, J. and Moore-Cherry, N. (2025). The changing tracks of land value capture in constrained policy contexts: A comparison of London’s Crossrail and Grand Paris Express. *Land Use Policy*. Advance online publication.
- Fitzgerald, J. and Lenhart, J. (2016). Eco-districts: Can they accelerate urban climate planning? *Environment and Planning C: Government and Policy*, 34(2):364–380.
- Garau, C. and Annunziata, A. (2024). The 15-Minute City: An attempt to measure proximity to urban services in Rome. *Sustainability*, 16(21):9432.
- Giannakis, E. and Bruzzo, A. (2023). Planning regulation and land value capture in Italy between traditional approaches and new perspectives. *Land Use Policy*, 133:106852.
- Governo Italiano (2001). Decreto del presidente della Repubblica 6 giugno 2001, n. 380: Testo unico delle disposizioni legislative e regolamentari in materia edilizia. Technical Report GU n. 245 del 20-10-2001, Gazzetta Ufficiale della Repubblica Italiana.
- Governo Italiano (2017). Decreto legislativo 17 febbraio 2017, n. 42: Disposizioni in materia di armonizzazione della normativa nazionale in materia di inquinamento acustico. Technical Report GU n. 79 del 4-4-2017, Gazzetta Ufficiale della Repubblica Italiana.
- Governo Italiano (2021). Piano nazionale di ripresa e resilienza: Italia Domani. National policy plan, Presidenza del Consiglio dei Ministri. Presented to the European Commission as part of the NextGenerationEU recovery package.
- Gruppo Torinese Trasporti (2025). Carta della mobilità 2025. Service charter, GTT S.p.A., Torino, Italy. Official service charter outlining quality standards for public transport in the Turin metropolitan area.
- Gruppo Torinese Trasporti (n.d.). Metropolitana automatica di Torino. Accessed April 30, 2026.
- Habermas, J. (1984). *The Theory of Communicative Action*, volume 1. Beacon Press, Boston.
- Higgins, C. D. and Kanaroglou, P. S. (2016). Forty years of modelling rapid transit’s land value uplift in North America: Moving beyond the tip of the iceberg. *Transport Reviews*, 36(5):610–634.
- Hillier, B. and Hanson, J. (1984). *The Social Logic of Space*. Cambridge University Press, Cambridge.
- Idealista (2025). Quanti anni di stipendio servono per acquistare casa nelle grandi città italiane. News report on real estate affordability in Italian cities.

- idealista/news (2024). Solo il 38% delle case italiane potrebbe installare una colonnina di ricarica per auto elettriche. Accessed: 2026-06-04.
- idealista/news (2026). Italy housing costs: Renting takes 28% of income, buying 18%. idealista/news. Accessed May 7, 2026.
- Infra.To (n.d.). Metro linea 2. Technical report, Infra.To. Accessed April 30, 2026.
- International Organization for Standardization (2003). ISO 19115:2003 — geographic information — metadata. Technical report, ISO.
- International Telecommunication Union (2017). Collection methodology for key performance indicators for smart sustainable cities. Technical report, United for Smart Sustainable Cities (U4SSC), ITU.
- Istituto Nazionale di Statistica (2021). Annual report 2021: The state of the nation. Summary, ISTAT, Rome, Italy. English summary of the official Italian report.
- Istituto Nazionale di Statistica (2023a). Indice di disagio socio-economico di individui e famiglie a livello sub-comunale (IDISE) - Anno 2021. Report, ISTAT. Official statistical release on socio-economic hardship at the sub-municipal level in Italy.
- Istituto Nazionale di Statistica (2023b). Work and life balance. Report, Istat. Official statistical report on Italian labor and social indicators.
- Istituto Nazionale di Statistica (2026). Resident population by age, sex and marital status on 1st january 2026. Technical report, Istituto Nazionale di Statistica.
- Jabareen, Y. R. (2006). Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education and Research*, 26(1):38–52.
- Jacobs, J. (1992). *The death and life of great American cities*. Vintage.
- Jankowski, P. (2009). Towards participatory geographic information systems for community-based environmental decision making. *Journal of Environmental Management*, 90(6):1966–1971.
- Jiang, H., Shen, Q., Chen, X., et al. (2022). Which distance-decay function can improve the goodness of fit of the metro station ridership regression model? a case study of Beijing. *Buildings*, 12(10):1686.
- Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., and Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, 21(2):39.
- Kephalopoulos, S., Paviotti, M., and Anfosso-Ledee, F. (2012). Advances in the development of common noise assessment methods in Europe: The CNOSSOS-EU framework for strategic environmental noise mapping. *Science of the Total Environment*, 482–483:400–410.
- Kissling, W. D., Walls, R., Brunger, A., Huijbregts, M., et al. (2022). Quantifying and visualizing the 15-Minute walkable city concept across Europe: A multicriteria approach. *Journal of Maps*, 18(5):1–11.
- Kitchin, R., Lauriault, T. P., and McArdle, G. (2015). Knowing and governing cities through urban indicators, city benchmarking and real-time dashboards. *Regional Studies, Regional Science*, 2(1):6–28.

- Kounadi, O. et al. (2023). Does noise affect housing prices? a case study in the urban area of Thessaloniki. *EPJ Data Science*, 12(1):47.
- Kubetskaya, L. and Kudryavtseva, N. (2023). Ensembles of turin squares and the urban planning code of city development. In *4th International Conference on Architecture: Heritage, Traditions and Innovations (AHTI 2022)*, pages 307–315. Athena Publishing.
- Mai, G., Huang, W., Sun, J., Song, S., Mishra, D., Liu, N., Gao, S., Liu, T., Cong, G., Hu, Y., et al. (2023). On the opportunities and challenges of foundation models for geospatial artificial intelligence. *arXiv preprint arXiv:2304.06798*.
- Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis*. John Wiley & Sons, New York.
- Marzolla, F., Casolaro, L., and Mocetti, S. (2025). Urban transit and real estate values: Quasi-experimental evidence from the Rome Metro C. *Journal of Urban Economics*. Advance online publication.
- Mattern, S. (2015). Mission control: A history of the urban dashboard. *Places Journal*.
- Mawarni, M. and Machdi, I. (2016). Dynamic nearest neighbours for generating spatial weight matrix. In *2016 International Conference on Advanced Computer Science and Information Systems (ICACSIS)*, pages 257–262. IEEE.
- Micelli, E. (2018). Land value capture by urban development agreements: The case of Lombardy region (Italy). In Bisello, A., Vettorato, D., Laconte, P., and Costa, S., editors, *Smart and Sustainable Planning for Cities and Regions*, pages 493–505. Springer, Cham.
- Ministero della Sanità (1975). Decreto ministeriale 5 luglio 1975: Modificazioni alle istruzioni ministeriali 20 giugno 1896, relativamente all'altezza minima ed ai requisiti igienico-sanitari principali dei locali di abitazione. Ministerial Decree G.U. n. 190 del 18 luglio 1975, Ministero della Sanità, Rome, Italy. Published in the Official Gazette of the Italian Republic on July 18, 1975.
- Mohammad, S. I., Graham, D. J., Melo, P. C., and Anderson, R. J. (2013). A meta-analysis of the impact of rail projects on land and property values. *Transportation Research Part A: Policy and Practice*, 50:158–170.
- Moreno, C., Allam, Z., Chabaud, D., Gall, C., and Pratlong, F. (2021). Introducing the “15-Minute City”: Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities*, 4(1):93–111.
- Moro, A., Bazzan, E., Balaras, C. A., and Droutsas, P. (2023). SNTTool MED: Sustainable neighbourhood tool — integrated tool and assessment methodology for sustainable neighbourhoods in MED cities. Technical report, iiSBE Italia R&D, Sustainable MED Cities Project, ENI CBC MED Programme. Version 2023-A.
- Muller-Judex, L., Dietl, V., Just, T., and Eisner, A. (2025). The value of school renovations: Effects on real estate prices in berlin. ERES eres2025 215, European Real Estate Society (ERES).
- Museimpresa (n.d.). Turin, industrial capital. <https://museimpresa.com/en/itinerari/turin-industrial-capital/>.
- Organisation for Economic Co-operation and Development (n.d.). OECD programme on a territorial approach to the SDGs.
- Ottoz, E., Pavese, P., and Sella, L. (2023). The effect of movida on residential property prices: up or down? *Applied Economics*, 55(55):6504–6519.

- Owusu-Edusei Jr, K., Espey, M., and Lin, H. (2007). Does close count? school proximity, school quality, and residential property values. *Journal of Agricultural and Applied Economics*, 39(1):211–221.
- Pellerey, V. and Torabi Moghadam, S. (2025). A place-based framework for assessing the effectiveness of inclusive climate actions for nature-based solutions in cities. *Journal of Cleaner Production*, 486:144566.
- Pettit, C., Lieske, S. N., and Leao, S. Z. (2019). Geospatial dashboards for monitoring smart city performance. *Sustainability*, 11(20):5648.
- Politecnico di Torino (2016). Quality of urban area, distance from city centre, and housing value. *IRIS Repository, Politecnico di Torino*.
- Provincia Autonoma di Trento (2024a). Giovani di 15-29 anni che non lavorano e non studiano (NEET). Technical report, Open Data Trento. Dataset on youth unemployment and education status (NEET) in the Trento region.
- Provincia Autonoma di Trento (2024b). Tasso di occupazione 25-64 anni. Dataset, Open Data Trentino. Official employment rate statistics for the 25-64 age demographic provided via the institutional Open Data portal.
- Pucher, J. and Buehler, R. (2017). Cycling towards a more sustainable transport future. *Transport Reviews*, 37(6):689–694.
- Regione Piemonte (2022). Legge regionale 28 marzo 2022, n. 4: Disposizioni in materia di addizionale regionale IRPEF di adeguamento all’articolo 1, commi 2 e 5, della legge 30 dicembre 2021, n. 234. Legge regionale n. 4, Consiglio Regionale del Piemonte. Published in Bollettino Ufficiale della Regione Piemonte n. 12/Sez. 3 on March 29, 2022.
- Sah, V., Conroy, S. J., and Narwold, A. (2016). Estimating school proximity effects on housing prices: The importance of robust spatial controls in hedonic estimations. *The Journal of Real Estate Finance and Economics*, 53(1):50–76.
- Seo, K., Golub, A., and Kuby, M. (2014). Combined impacts of highways and light rail transit on residential property values: A spatial hedonic price model for Phoenix, Arizona. *Journal of Transport Geography*, 41:53–62.
- Star, S. L. and Griesemer, J. R. (1989). Institutional ecology, “translations” and boundary objects: Amateurs and professionals in Berkeley’s Museum of Vertebrate Zoology, 1907–39. *Social Studies of Science*, 19(3):387–420.
- Steenmans, K., Robin, E., Acuto, M., Iwaszuk, E., and Garza, L. O. (2023). Governing the informed city: Examining local government strategies for information production, consumption and knowledge sharing across ten cities. *Urban Governance*, 3(4):243–251.
- Taddeo, R., Simboli, A., and Morgante, A. (2024). Green neighbourhood sustainability index: A measure of the balance between anthropogenic pressure and ecological relevance. *Ecological Indicators*, 160:111868.
- Tobler, W. R. (1970). A computer movie simulating urban growth in the Detroit region. *Economic Geography*, 46:234–240.
- Tram di Torino (2024). Tram Serie 2800: Evoluzione tecnica e storia. Webpage. Technical specifications and history of the Fiat/Stanga articulated tram series used by GTT Torino.
- Trojanek, R., Tanas, J., Raslanas, S., and Banaitis, A. (2017). The impact of aircraft noise on housing prices in poznan. *Sustainability*, 9(11):2088.

- UN-Habitat (2022). The global urban monitoring framework: A guide for urban monitoring of SDGs and NUA and other urban-related thematic or local, national and global frameworks. Technical report, United Nations Human Settlements Programme.
- United Nations (1992). Agenda 21: Programme of action for sustainable development. Technical report, United Nations. Adopted at the United Nations Conference on Environment and Development (UNCED), Rio de Janeiro, Brazil.
- United Nations (2015). Transforming our world: The 2030 agenda for sustainable development. Technical Report A/RES/70/1, United Nations.
- United Nations (2016). New urban agenda. Technical report, United Nations, Quito.
- Valenzuela-Levi, N. and Abreu, M. (2021). The income equality dividend in ‘green’infrastructure: Evidence from the transport and waste sectors in the oecd. *Journal of cleaner production*, 315:128088.
- Venerandi, A., Quattrone, G., and Capra, L. (2021). Exploring the 15-Minute neighbourhoods: An evaluation based on the walkability performance to public facilities. *Transportation Research Part D: Transport and Environment*, 101:103080.
- World Commission on Environment and Development (1987). *Our Common Future*. Oxford University Press, Oxford.
- World Health Organization (2016). Urban green spaces and health: A review of evidence. Technical report, WHO Regional Office for Europe, Copenhagen.
- Zar, J. H. (2005). Spearman rank correlation. *Encyclopedia of biostatistics*, 7.
- Zhao, Z. J., Das, K. V., and Larson, K. (2014). Land value capture to fund public transportation infrastructure: Examination of joint development projects’ revenue yield and stability. *Transport Policy*, 36:240–252.
- Zini, G., Vitetta, A., and Musolino, G. (2024). Accessibility and competitiveness of public transport in Turin and Rome: A gis-based indicator framework. *Smart Cities*, 7(1):327–349.

Appendices

Appendix A

INSPIRE-Compliant Metadata Catalogue

Full INSPIRE-compliant metadata records for all completed indicator datasets are documented here, conforming to ISO 19115:2003 and ISO 19139:2007 as required by Commission Regulation (EC) No 1205/2008. Each record includes: title, abstract, lineage (data sources and transformation steps), spatial resolution, temporal reference, conformity statement, access and use constraints, and point of contact.

Code	Indicator	GeoPackage(s)	INSPIRE Theme
A1.1	Population Density	ZONE_CENSIMENTO_POPULATION_DENSITY_IND.gpkg	Population distribution — Demography
A1.2	Urban Compactness	ASC_URBAN_COMPACTNESS_INDIC.gpkg	Buildings
A2.1	Availability of Green Urban Areas	ASC_AVAIL_GREEN_URBAN_AREA_INDIC.gpkg	Land use
A2.2	Green Areas in Relation to the Neighborhood Population	ASC_AVAIL_GREEN_URBAN_AREA_INDIC.gpkg	Population distribution — Demography
A2.3	Green Area Accessibility	ASC_GREEN_AREA_ACCESS_INDIC.gpkg	Land use
A3.2	Biodiversity in Green Zones	ASC_BIODIVERSITY_GREEN_ZONES.gpkg	Species distribution
F1.1	Performance of the Public Transport System	ASC_PER_PUBLIC_TRANSPORT_2026_IND.gpkg	Transport networks
F2.2	Electric Vehicle Infrastructure (Charging Stations)	ELE_CHAR_ST_INDIC.gpkg	Transport networks
F2.3	Bicycle Network	ASC_F2_3_Bicycle_Network.gpkg	Transport networks
F3.3	Safety of Bicycle Lanes	ASC_F3_3_Safety_of_bicycle_lanes.gpkg	Transport networks
F4.1	Cyclomatic Complexity of the Street Network	ASC_F4_1_Cyclomatic_Complexity_IND.gpkg	Transport networks
F4.2	Connectivity of the Street Network	ASC_F4_2_Connectivity_Street_Network_IND.gpkg	Transport networks
G2.1	Affordability of Housing Property	zone_OMI_G2_1_Property_Affordability_IND.gpkg	Statistical units
G2.2	Affordability of Housing Rental	zone_OMI_G2_2_Rental_Affordability_IND.gpkg	Statistical units
G2.3	Vacant Residential Units in the Neighborhood	G2.3_ZONE_CENS_VACANT_RES_UNIT_IND.gpkg	Buildings
G3.1	Availability and Proximity of Key Services	ASC_Availability and Proximity of Key Services.gpkg	Utility and governmental services
G3.2	Availability and Proximity of a Public Primary School	ASC_G3.2 Availability and Proximity of a Public Primary School.gpkg	Utility and governmental services
G3.3	Availability and Proximity to a Public Secondary School (I grado)	ASC_G3_3 Availability and Proximity to a Public Secondary School - I grado.gpkg	Utility and governmental services
G3.4	Availability & Proximity to Children's Play Facilities	ASC_G3.4_Availability & Proximity to Childrens Play Facilities.gpkg	Utility and governmental services
G3.5	Outdoor Public Spaces	ASC_G3_5_Outdoor_Public_Spaces_IND.gpkg	Land use
H1.1	Average Annual Per-Capita Income of Residents	ASC_H1_1_Avg_Annual_Income_IND.gpkg	Statistical units
H2.1	Employment Rate	ASC_H2_1_Employment_Rate_IND.gpkg	Statistical units
H2.2	Youth Unemployment Rate	ASC_H2_2_Youth_Unemployment_IND.gpkg	Statistical units
I3.3	Permeability of Land	ASC_permeable.gpkg	Land cover

Appendix B

Python Scripts and Reproducibility

Annotated Python scripts for all geoprocessing and modelling workflows described in Chapters 5 through 7 are provided in this appendix.

Script	Description
outdoor_public_area_dissolve	Consolidates public space layers, clipping and dissolving them by neighborhood to calculate the total surface area and percentage of built-up space.
soil_permeability	Intersects and clips permeable surface data by neighborhood boundaries, applying topological fixes to calculate total permeable square meters.
road_noise	Applies the CNOSSOS-EU methodology to create noise buffers around roads, tram lines and tram stops.
scatterplot_lowess	Calculates Spearman's rank correlation between property values and noise exposure, generating an annotated scatterplot with a LOWESS smoothing curve to visualize trends.
multivariable_OLS	Fits a multivariable OLS regression model predicting property prices based on economy and noise scores, outputting statistical summaries and partial regression plots.
weighted_average	Merges spatial score data with demographic datasets to calculate and export population-weighted averages for various urban domain scores across statistical zones.
radar_chart	Calculates population-weighted averages for domain scores, normalizes them to a 0–100 scale, and generates a radar chart comparing Turin's average against thresholds.
city_noise_only	Generates a 5 m city-wide noise exposure raster by applying dynamic CNOSSOS-EU logic for roads and static distance-decay penalties for transit, industry, and amenities.
City_wide_noise_and_suitability	Computes a city-wide net suitability raster by aggregating positive accessibility scores for urban amenities and the full metro network, minus calculated noise nuisance penalties.
Line1_suitability	Models localized net suitability around Metro Line 1, combining base amenity accessibility with station proximity bonuses, subtracting noise penalties, and masking beyond 800 m.
Suitability_normalized	Generates normalized suitability rasters for Metro Line 2 scenarios using purely positive accessibility metrics (amenities and transit) without integrating noise detractions.
Noise_and_amenities_normalized	Evaluates Metro Line 2 development scenarios, combining amenity suitability with new station proximity, deducting noise nuisances, and generating normalized 0–100 score rasters.
Price_uplift	Transforms a normalized suitability raster into an economic uplift coefficient map, applying a linear stretch to generate property value multipliers based on transit proximity.

Table B.1: List of Python scripts created for this thesis.