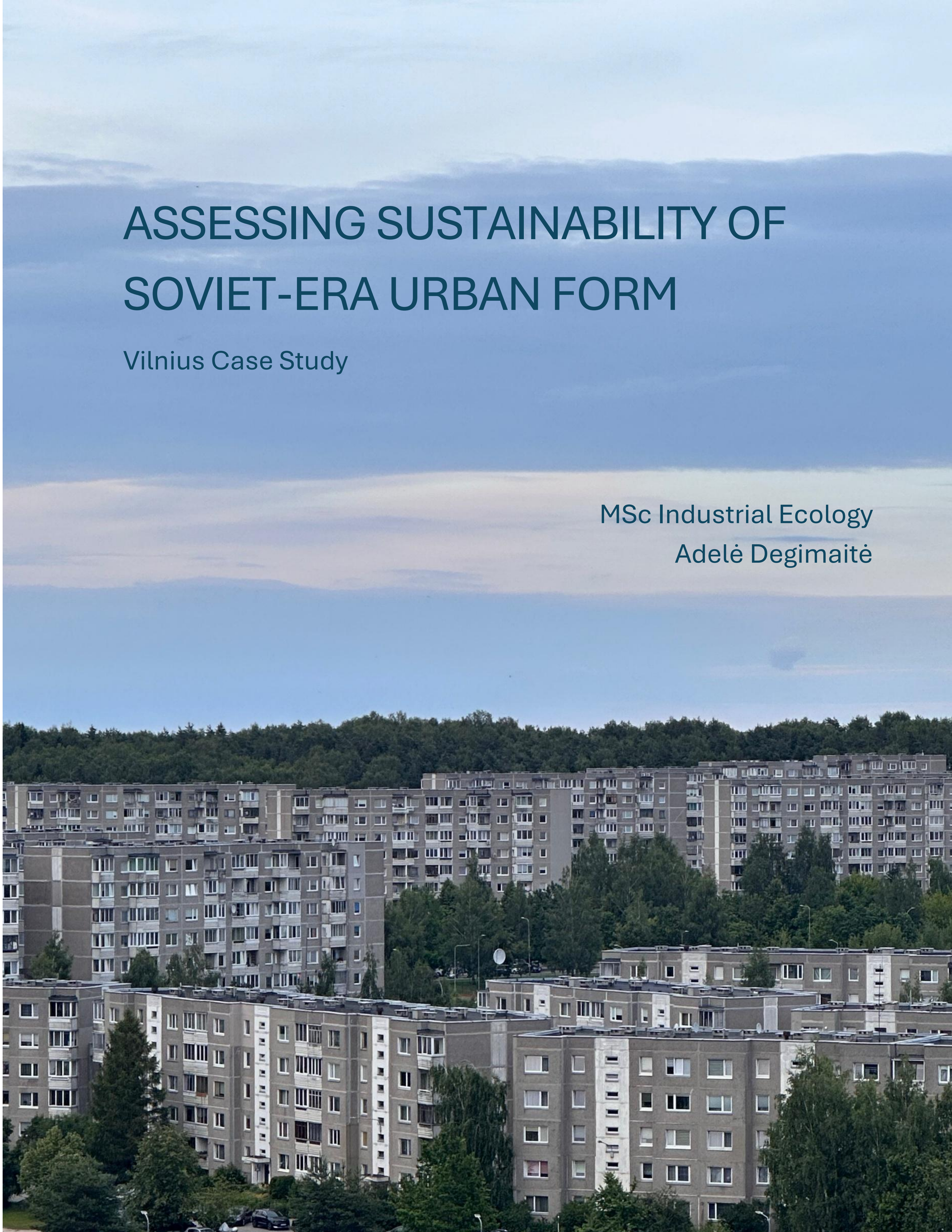
ASSESSING SUSTAINABILITY OF SOVIET-ERA URBAN FORM

Vilnius Case Study

MSc Industrial Ecology
Adelė Degimaitė



Assessing Sustainability of Soviet-Era Urban Form

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by

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To obtain the degree of Master of Science in

Industrial Ecology

at Leiden University and Delft University of Technology

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Preface & Acknowledgements

This thesis was written as part of my graduation project, marking the conclusion of my two-year study of the Master's programme Industrial Ecology at Leiden and Delft Universities. This degree has laid the foundation of my sustainability education, and, while at times challenging, has been an extremely rewarding experience. During this period, I deepened my understanding of sustainability in ways I could not have imagined.

This thesis emerges from the convergence of two research paths that are often pursued in isolation: the analysis of material stocks in the built environment and the evaluation of ecosystem services provided by urban green infrastructure. My interest in bridging these perspectives was shaped by a recognition that cities are, at once, both physical reservoirs of materials and living systems that regulate climate, biodiversity, and human well-being. This work is rooted in the belief that sustainable urban futures require us to think across disciplinary, temporal, and spatial boundaries.

This research would not have been possible without the guidance, encouragement, and generosity of many individuals. First and foremost, I would like to express my sincere gratitude to my supervisors, Dr. Tomer Fishman and Dr. Roy Remme, whose expertise, patience, and constructive feedback consistently pushed me to think more critically and articulate more clearly. Your ability to challenge while supporting has been invaluable.

I also extend my heartfelt thanks to Dr. Janneke van Oorschot for assistance with initial idea development, Dr. Rūta Ubarevičienė for contextual discussions, Dr. Balázs Szabó for providing valuable data, and Ignas Valentinavičius for assisting with data collection and for spirited discussion.

Finally, I wish to thank my family, especially my husband Augustas, for their unwavering belief in my ability to complete this work, and for reminding me to step away from the screen every now and then. Your support, in ways both large and small, has made all the difference.

Adelė Degimaitė

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In loving memory of my late grandparents, Marytė and Petras

Summary

This study investigates the intersection of two critical yet often separately studied domains of urban sustainability: the material stock embedded in the built environment and the ecosystem services provided by urban green infrastructure. Focusing on Soviet-era mass housing districts in Vilnius, Lithuania, the research combines material stock accounting and urban cooling modelling to inform future planning in post-socialist urban contexts. The study was guided by the overarching research question: How do the spatial configuration, material stocks, and green infrastructure performance vary across Vilnius's Soviet-era neighborhoods, and what implications does this have for sustainable urban planning? Further specified into five sub-questions:

1. What types of residential buildings are found among Vilnius's Soviet-era mass housing stock? What are the material intensities of structural building materials per each type?
2. What is the total quantity of structural material stock embedded in Soviet-era residential buildings in Vilnius?
3. How is this material stock spatially distributed: what materials are present, where, and in what quantities?
4. How effective is green urban infrastructure in Soviet-era neighborhoods in providing urban cooling and heatwave mitigation?
5. What insights emerge from the combined analysis of material stock and green infrastructure performance? How can they support more informed policymaking regarding end-of-life planning or retrofitting of Soviet-era districts?

Using established building typologies and material intensity coefficients, the study estimates structural material stocks (concrete, steel, brick, mortar, and plasterboard) in residential apartment buildings from 1948–1994 and maps their spatial distribution. Urban cooling effects were modeled with the InVEST® urban cooling tool (Natural Capital Project, 2025), producing neighborhood-level temperature anomalies and Heat Mitigation Index values. The combined analysis reveals spatial patterns and trade-offs between material density and ecological performance.

Findings show approximately 16 million tons of structural materials, mostly concrete, unevenly distributed, with western districts like Fabijoniškės, Pašilaičiai, and Šeškinė holding the largest stocks. Brick-heavy neighborhoods cluster in the southeast. Green infrastructure performance varies widely: areas adjacent to forests or with integrated greenery, such as Antakalnis and Lazdynai, achieve cooling effects exceeding 1.8°C, while

dense, vegetation-poor districts experience heat anomalies close to 2.0°C. Importantly, many high material stock neighborhoods coincide with poor ecological performance, creating urban heat risk hotspots. For decision-makers, this highlights key strategic opportunities:

- Prioritize combined material recovery and green retrofitting in aging, heat-vulnerable districts such as Tuskulėnai, Naujamiestis, and parts of Šnipiškės to reduce climate risks while advancing circularity.
- Preserve and enhance ecological functions in well-performing neighborhoods like Lazdynai, Antakalnis, and Baltupiai through careful renovation and protection of mature greenery.
- Target greening efforts in densely populated, low-canopy areas such as Fabijoniškės, Pašilaičiai, Justiniškės, and Šeškinė to reduce heat exposure for vulnerable residents.
- Adopt neighborhood-scale diagnostics integrating building materials and cooling metrics to tailor interventions effectively and identify priority zones, for example recognizing high per-capita material stocks in Salotė or early reinforced concrete clusters in Lazdynai.

These integrated insights provide a spatially nuanced basis for sustainable transformation of Vilnius's Soviet-era housing, balancing material circularity with climate adaptation to guide resilient urban futures.

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Nomenclature

Abbreviation	Definition
MICs	Material Intensity Coefficients
RA	Recycled Aggregate
ES	Ecosystem Services
LU	Land use
UHI	Urban Heat Island
GUI	Green Urban Infrastructure
CC	Cooling Capacity
HM	Heat Mitigation
HMI	Heat Mitigation Index
RC	Reinforced Concrete

1. Introduction

1.1 Problem background

Sustainable urban planning refers to the practice of designing and managing cities in ways that reduce environmental impact, support long-term resource efficiency, and enhance urban livability, both now and for future generations. It demands an integrated approach that considers not only the ecological functioning of urban systems, but also the material flows and built forms that shape how cities evolve and endure. Today, this challenge is especially pronounced in older urban areas shaped by the development logics of the 20th century. Many neighborhoods were constructed under ideological and planning frameworks that differ fundamentally from contemporary priorities centered on climate resilience, circularity, and ecosystem health. In post-Soviet contexts, these divergences are particularly stark, as inherited urban forms are now subject to both physical deterioration and changing climate exposure, yet remain underrepresented in international scholarship. As cities face the dual pressures of environmental degradation and climate change, rethinking how these inherited urban forms can be transformed has become a central task for sustainable urban planning.

The building and construction sector plays a central role in this transition. Globally, it's one of the most resource- and emissions-intensive sectors, responsible for around half of all materials extracted each year (Gallego-Schmid et al., 2020). Within Europe, the sector contributes approximately 50% of fossil fuel use, generates over 35% of total waste, and accounts for 5–12% of greenhouse gas emissions, depending on the country (Severin & Michaliková, 2024; European Commission, 2025). Despite its impact, the sector remains largely locked into a linear model, with little attention given to circular material use or the full life cycle of buildings (Benachio et al., 2020). This is especially critical for post-socialist cities, where vast stocks of prefabricated and masonry housing remain largely excluded from systematic material stock accounting, leaving local authorities without spatially resolved data to guide end-of-life planning, demolition, renovation, or reuse.

Much of the environmental cost is tied up in the existing building stock, which contains vast amounts of embedded material. About 90% of materials stored within human-made systems - anthropogenic stocks – are found in buildings and infrastructure (Schiller et al., 2019). Yet, the scale, composition, and potential of this stock remain poorly understood. As cities grow and change, there is a need for better accounting of this embedded stock and explore how it can be reused, recycled, or otherwise integrated into more sustainable planning. Developing such accounts is a prerequisite for evidence-based municipal decision-making, particularly where demolition without recovery risks landfill pressure, embodied carbon loss, and missed opportunities for circular economy integration.

At the same time, urban environments are facing increasing pressure from climate change. Rising temperatures, especially when combined with the thermal mass of dense urban fabrics, intensify the urban heat island (UHI) effect (IPCC, 2023). In such environments, green urban infrastructure (GUI) offers one of the most effective strategies for local climate regulation, as it reduces surface and air temperatures through processes of evapotranspiration and shading (Marando et al., 2022). It can be defined as “a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services” (van Oorschot et al., 2024). However, the actual performance of GUI in mitigating heat stress varies widely depending on spatial configuration, vegetation type, and land cover dynamics. Many cities still lack fine-grain neighborhood-scale assessments of how well existing GUI performs and where it can be most strategically improved.

Together, these two domains – material circularity and urban climate adaptation – represent core pillars of sustainable urban planning. Yet they are often addressed in isolation. Integrating them can offer new spatial insights, clarify trade-offs, and support more context-sensitive urban transformation. This integration also answers a wider research gap: as Hussein et al. (2023) note, Eastern European countries remain on the margins of green infrastructure literature, despite possessing substantial empirical knowledge on urban greening. Bridging material stock analysis and ecosystem service modelling in this underrepresented context advances both academic understanding and policy capacity.

To explore this integration, this thesis uses a case study approach. Case studies allow for grounded, spatially explicit analysis that can capture the complex interactions between built form and ecological function which are often lost in broader-scale assessments. Vilnius, Lithuania, presents a compelling case: like many post-socialist cities, it is shaped by a legacy of Soviet-era mass housing, now facing the dual challenge of aging material stock and increasing exposure to summer heat. This makes Vilnius an instructive context for testing how green infrastructure and material stocks interact spatially, and how these legacy systems might be aligned with emerging sustainability goals. By quantifying and mapping both the material and ecological dimensions of this legacy, the study produces spatial diagnostics directly relevant to municipal planners seeking to align climate resilience with circular economy goals.

1.2 Case study description

Vilnius, the capital and largest city of Lithuania, has a population of 604,806 residents and an area of 401 km^2, with a relatively low population density of 1,508 inhabitants per km^2 (Statistikos departamentas, 2025). It is located in the eastern part of Lithuania, about 30 km from the border with Belarus (Figure 1.1). Vilnius is among Europe's greenest capitals, with green spaces accounting for approximately 61% of the municipal area and forest cover approaching 35% – see Figure 1.2 Vilnius orthophoto (Bernat, 2020; Statistikos departamentas, 2025). Tree canopy alone covers 47% of the city, an unusually high figure for a national capital (HUGSI, 2023).

Figure 1.1 Location of Vilnius in Lithuania (Google Maps, 2025)

Figure 1.2 Vilnius orthophoto (Vilniaus erdvinių duomenų portalas, 2025)

Vilnius's built environment has evolved over centuries, but the most extensive transformation occurred during the Soviet era (1948–1990) (Burneika et al., 2010). Figure 1.3 shows the neighborhoods of Vilnius according to the Vilnius Municipality Master Plan categorization, with Soviet-era neighborhoods highlighted in red (Vilniaus miesto savivaldybės teritorijos bendrasis planas, 2018). A full list of neighborhoods can be found in Appendix A, and Table 1.1 provides key statistics on Soviet-era neighborhoods.

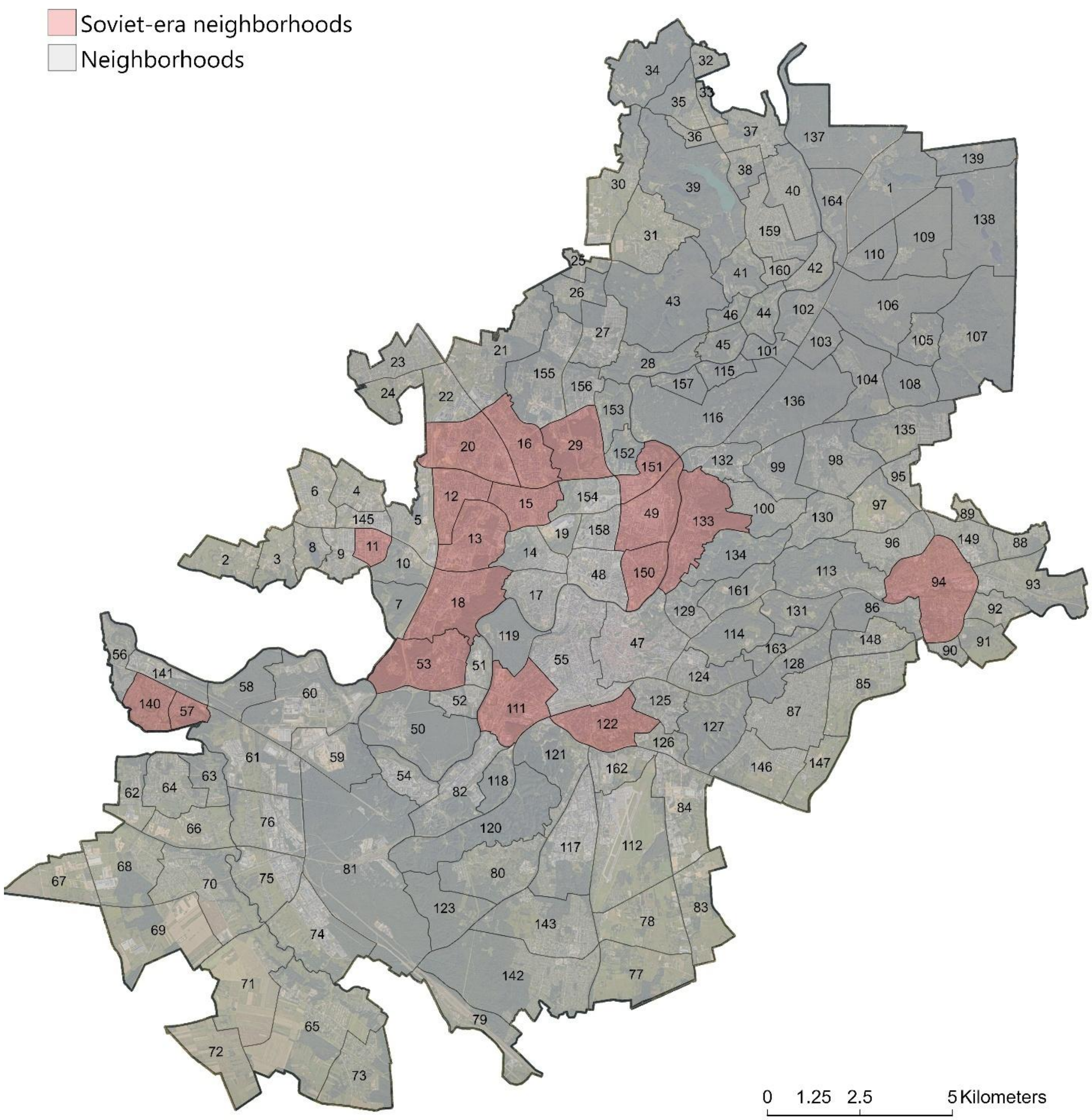

Figure 1.3 Vilnius neighborhoods according to Master Plan categorization (Vaivada et al., 2020)

Table 0.1 Key statistics on Soviet-era neighborhoods

Neighborhood ID	Name	Area (ha)	Total population	Median year of construction of Soviet-era residential buildings	% of all buildings that are Soviet-era residential buildings	% of population living in Soviet-era housing

11	**Salotė**	80.13	12909	1993	40.26	59.52
12	**Justiniškės**	186.74	25716	1985	68.01	92.90
13	**Viršuliškės**	270.65	15817	1977	41.32	88.06
15	**Šeškinė**	173.70	25573	1981	60.00	96.27
16	**Fabijoniškės**	242.83	29965	1989	39.53	89.80
18	**Karoliniškės**	368.79	24726	1974	56.53	93.37
20	**Pašilaičiai**	325.34	27736	1987	34.33	65.27
29	**Baltupiai**	260.09	9647	1982	17.55	68.20
49	**Šiaurės Miestelis**	260.09	18472	1966	21.82	63.99
53	**Lazdynai**	333.64	21979	1970	43.10	94.80
57	**Afindevičiai**	76.02	2941	1989	18.95	77.69
94	**Naujoji Vilnia**	442.18	16870	1979	10.58	69.39
111	**Vilkpėdė**	313.07	14320	1964	23.29	89.25
122	**Naujininkai**	259.27	18304	1972	17.68	76.05
133	**Antakalnis**	363.07	17792	1966	18.52	76.08
140	**Salos**	153.69	6244	1974	6.45	73.62
150	**Tuskulėnai**	163.95	17636	1969	33.79	79.39
151	**Žirmūnai**	137.35	6693	1968	29.14	93.47

Industrialization and rural-urban migration drove population growth during this period, multiplying the city's housing stock nearly fivefold with the construction of large-scale housing estates (Janušauskaitė, 2019). Today, these Soviet-era buildings constitute around 60% of Vilnius's total housing stock (Balázs & Burneika, 2020) and continue to shape both its urban morphology and social structure. The Soviet housing model followed a centralized, hierarchical planning paradigm characterized by bifurcated housing provision (state vs. municipal), prefabricated construction, modernist layouts, and monumental road infrastructure (Bernhardt, 2005; Glendinning, 2019).

Yet in the Baltic context, distinct regional adaptations emerged. Unlike most Soviet cities, Vilnius continued brick construction throughout the Soviet period (not limited to 1960s khrushchyovkas). Lithuanian architects incorporated Western influences - most notably in Lazdynai, a district lauded for integrating natural terrain and landscape into its urban layout (Drėmaitė, 2017; Glendinning, 2019). This contrasted sharply with later districts such as Justiniškės, where standardized high-rises were arranged in more monotonous, spatially extensive configurations with minimal pedestrian-scale public space (Hess & Tammaru, 2019). Across the city, many estates lacked sufficient amenities and human-scale infrastructure, especially in later development phases.

After Lithuania regained independence in the early 1990s, the housing sector was rapidly privatized, primarily through flat-level ownership transfers. While this helped address fiscal constraints and marked a political break from Soviet-era centralization, it also fragmented ownership and weakened capacity for coordinated maintenance and renewal (Liepa-Zemeša & Hess, 2016; Treija & Bratuškins, 2019). According to Kracka and Zavackas (2013), most buildings are stuck in a pre-renovation phase (t1), with many deteriorating beyond acceptable limits (see Figure 1.4). Today, less than 10% of Soviet-era housing in Vilnius has been renovated (Vilniaus miesto savivaldybė, 2024), and the pace of renewal of 300–400 buildings annually nationwide is insufficient given the scale of the aging stock (ELTA, 2023). Renovation efforts are also socially uneven: central, wealthier districts are prioritized, while peripheral areas with lower-quality housing, such as 1960s-era *khrushchyovkas*, are often neglected (Balázs & Burneika, 2020).

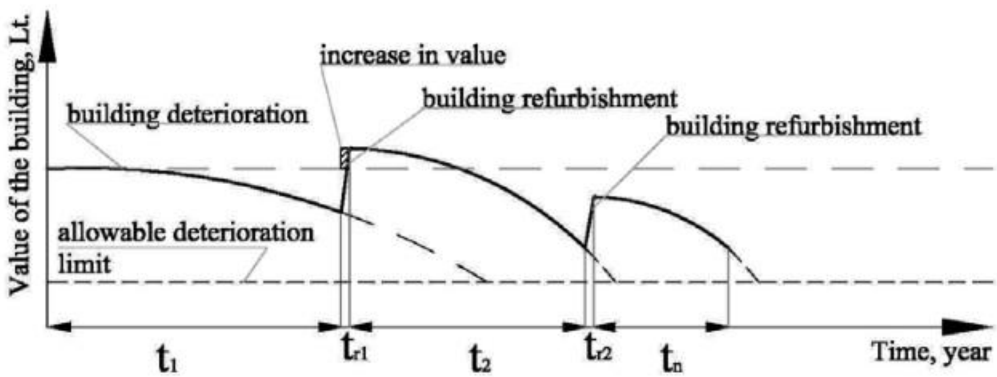

Figure 1.4 Building depreciation timeline; where t1 - building lifetime pre-renovation, tr1 - duration of the renovation process, t2 - building lifetime post-renovation (Kracka & Zavadskas, 2013)

Soviet-era housing makes up a significant portion of the city's anthropogenic material stock. Decisions on whether to demolish, renovate, or reuse these buildings carry substantial environmental implications: demolition without recovery contributes to landfill pressure and embodied carbon loss; poorly executed retrofitting risks locking in inefficient performance; while circular strategies such as selective reuse can reduce extraction, emissions, and construction waste. Yet, embedded materials and the potential for circular reuse remain overlooked in Lithuanian urban planning. As Kliučinskaitė (2025) notes, regulatory frameworks at the national level are fragmented and do not systematically incentivize building lifespan extension or material recovery. They do not encourage reuse, creating favorable conditions for demolition. As such, comprehensive stock accounting is essential to inform long-term planning and support a shift toward circular urban metabolism.

The ecological dimension of these districts also warrants attention. In some areas, original landscapes were levelled to make way for construction, but in others - particularly

Lazdynai - elements of the natural terrain and vegetation were retained, reflecting a socialist ideal of integrating nature into everyday life (Drėmaitė, 2017; Hess & Tammaru, 2019). Today, this inherited green infrastructure is highly variable among the Soviet-era neighborhoods in terms of its spatial quality and functionality. Its effectiveness in delivering ecosystem services - especially microclimate regulation - remains largely unassessed, even as urban temperatures rise and heatwaves become more frequent (Ramanauskas et al., 2024).

Since the 1990s, deregulated market-led development has fostered both sprawl and densification, often at odds with ecological resilience (Ubarevičienė, 2018). Today, the city faces complex trade-offs: many Soviet-era buildings are deteriorating, yet large-scale demolition is politically and economically infeasible given the sheer number of residents involved. Inaction risks deepening socio-spatial inequality, while fragmented renovation efforts fall short of systemic transformation. In this context, Vilnius offers a representative case for post-socialist cities navigating the material and ecological legacies of mass housing. It exemplifies two pressing urban sustainability challenges: how to manage and repurpose aging material stock, and how to enhance the climate-regulating role of inherited green infrastructure. Understanding where and how material and ecological assets are distributed - and how they can be strategically leveraged - offers valuable insights not just for Vilnius, but for post-Soviet urban regions across the Baltics and Eastern Europe.

1.3 Research description

1.3.1 Aim and goal

This research aims to support long-term, evidence-based sustainable urban planning in Vilnius's Soviet-era residential neighborhoods by integrating material and ecological analysis. Specifically, it quantifies and maps the structural material stocks embedded in the built environment, and assesses the performance of GUI in delivering urban cooling services. By combining these two perspectives, the study offers spatial diagnostics that reveal where embedded materials may be recoverable, where ecological performance is most or least effective, and how these patterns intersect. This contributes to a more actionable understanding of the spatial structure and sustainability potential of Soviet-era urban fabric. The findings are intended not only to fill an academic gap in post-Soviet urban studies, but also to support municipal planners and policymakers in prioritizing retrofitting, demolition, or greening interventions in ways that optimize both resource recovery and heat-mitigation benefits.

1.3.2 Research questions

The research is guided by the following overarching question:
How do the spatial configuration, material stocks, and green infrastructure performance vary across Vilnius's Soviet-era neighborhoods, and what implications does this have for sustainable urban planning?

This is addressed through a set of more specific sub-questions:

1. What types of residential buildings are found among Vilnius's Soviet-era mass housing stock? What are the material intensities of structural building materials per each type?
2. What is the total quantity of structural material stock embedded in Soviet-era residential buildings in Vilnius?
3. How is this material stock spatially distributed: what materials are present, where, and in what quantities?
4. How effective is GUI in Soviet-era neighborhoods in providing urban cooling and heatwave mitigation?
5. What insights emerge from the combined analysis of material stock and green infrastructure performance? How can they support more informed policymaking regarding end-of-life planning or retrofitting of Soviet-era districts?

1.3.4 Scope

This study focuses on Soviet-era mass housing in Vilnius, Lithuania. For the material stock quantification, the scope is limited to multi-family residential buildings (three or more floors) constructed during the Soviet period within the administrative boundaries of Vilnius municipality. Single-family homes, non-residential buildings, and structures not part of standardized mass housing are excluded. Out of approximately 60,000 total buildings in the city, 3,246 Soviet-era residential buildings fall within the scope of this analysis. The temporal boundary for the Soviet period is specified in Section 3.1.1.

For the green infrastructure and urban cooling analysis, the scope centers on neighborhoods primarily planned and developed during the Soviet era. This spatial delineation does not perfectly overlap with building-level distributions due to two factors: (1) some Soviet-era buildings are located in historically older neighborhoods (e.g. Centras, Naujamiestis), which follow different planning logics; (2) in some cases, Soviet-era buildings constitute only a minor component of a district that has undergone substantial post-Soviet development (e.g. Jeruzalė, Santariškės, Miškiniai), and thus do not reflect Soviet-era spatial structure in full.

1.4 Research outline

The structure of the report will follow the outline below.

Chapter 2. Theoretical Framework will elaborate upon the state of the art of scientific literature concerning the core themes of this research: material stock quantification and ecosystem services, particularly centered on urban cooling as UHI mitigation.

Chapter 3. Methods will outline the detailed methodology used in obtaining the answers to the research questions.

Chapter 4. Results will provide the results: material stock quantification, spatial distribution, urban cooling model and combined results.

Chapter 5. Discussion will discuss and critically analyze the results considering the broader context described in Chapter 2, also elaborating on the limitations of the research.

Chapter 6. Conclusions will provide final conclusions, reflections, and recommendations.

2. Theoretical Framework

2.1 Material analysis

2.1.1 Material stock accounting

Material stock accounting provides the empirical basis for analyzing the accumulation and distribution of materials within the built environment. As urbanization accelerates, cities become repositories of large quantities of anthropogenic material stocks embedded in buildings and infrastructure. These in-use stocks deliver necessary services such as shelter and mobility, while also representing concentrated investments of energy, capital, and resources. The concept of in-use stock accounting emerged from the broader field of urban metabolism and industrial ecology, disciplines that aim to quantify the flows and stocks of materials to better comprehend the environmental, social, and economic implications of urban systems (Aldebei & Dombi, 2021). Material stock accounting functions as a descriptive tool, offering a static snapshot of material quantities embedded in urban structures; and as a predictive tool, informing future scenarios related to material availability for resource recovery.

2.1.2 Top-down vs bottom-up approach

Material stock assessments typically rely on either top-down or bottom-up methodologies. The top-down approach, commonly used at national or global scales, estimates material flows and stocks using aggregate economic data (such as construction sector outputs) combined with lifespan models. The underlying assumption is that material accumulation correlates with per capita wealth, allowing estimates to be scaled from national to regional levels (Aldebei & Dombi, 2021). An example of this in the post-Soviet context is the study by West et al. (2014), which traces socio-metabolic trajectories but does not include the Baltic countries. While the top-down method is effective for analyzing long-term trends, it typically produces highly aggregated results and lacks the spatial resolution necessary for urban-scale or neighborhood-level planning (Aldebei & Dombi, 2021).

By contrast, the bottom-up approach starts from the physical building stock and calculates material quantities by multiplying material intensity coefficients (MICs) with building parameters such as gross floor area or height. This allows for a higher level of spatial and typological detail, particularly useful for urban-scale studies and urban mining applications. Although it requires more detailed data inputs and often a narrower geographic scope, the bottom-up approach yields more accurate and spatially explicit results (Aldebei & Dombi, 2021). It has been successfully applied in cities across Sweden

(Gontia et al., 2018), Austria (Kleemann et al., 2019), the USA (Marcellus-Zamora et al., 2016), China (Guo et al., 2019), and Germany (Ortlepp et al., 2018), among others, but to date, no such studies have been conducted in the Baltic states.

2.1.3 Material intensities

MICs are fundamental to bottom-up assessments, converting physical dimensions of buildings such as floor area or volume into material mass (Aldebei & Dombi, 2021). They are typically expressed as kg/m^2 or kg/m^3. Their use depends upon categorization of buildings into archetypes defined by structure, function, and typology. Recent efforts have focused on developing standardized MIC databases to facilitate comparative analyses and improve methodological consistency across studies - exemplified by databases such as Heeren & Fishman (2019), Yang et al., (2015), Gontia et al., (2018), and Sprecher et al., (2021).

2.1.4 Urban mining

Urban mining conceptualizes cities as sources of secondary raw materials embedded in existing structures (Cossu & Williams, 2015). Unlike traditional mining which extracts finite resources from the earth, it recovers materials such as metals, concrete, and wood from buildings nearing end-of-life. It proceeds through analogous stages to geological mining: prospecting, exploration, and exploitation. The exploration stage often employs bottom-up material stock assessments to quantify recoverable materials and assess the feasibility of reuse or recycling (Aldebei & Dombi, 2021). Graedel (2011) identifies three guiding questions: how much material is there, when will it become available, and in what form does it exist? As cities reach material saturation, where the input of new materials declines while the output from aging stocks increases, the relevance of urban mining grows.

Nonetheless, its viability depends not only on technical and economic factors but also on sociopolitical conditions (Cossu & Williams, 2015). For example, building codes may limit the reuse of recovered materials due to safety or certification standards, while heritage preservation policies may restrict demolition, even where structural materials are abundant and recoverable. In some cases, public opposition to the demolition of familiar or historically charged buildings – such as Soviet-era housing – can shape the availability of recoverable stocks. Likewise, the absence of legal requirements for selective demolition or a lack of market incentives for material recovery can undermine implementation (Kliučinskaitė, 2025). These sociopolitical dimensions must be considered when evaluating the practical potential of urban mining strategies.

2.1.5. Structural building materials and reuse / recycle opportunities

Structural building materials constitute the bulk of urban material stock. Among these, concrete, bricks, steel, mortar/plaster, and gypsum-based components such as plasterboard are the most prevalent. Their reuse or recycling potential varies significantly.

Concrete is the most abundant material in structural building stock, particularly in Soviet-era construction. It is difficult to reuse directly due to contamination and its monolithic nature. However, it is commonly recycled: typically crushed into recycled aggregates (RA) for low-grade applications like road base or backfilling. While there is technical potential for using these aggregates in structural concrete, this remains limited in practice. Despite standards like EN 206 allowing up to 30% replacement of natural aggregates with RA, only 8.2% of aggregates in the EU were recycled in 2019, and actual adoption of recycled aggregate concrete remains limited (Cristóbal García et al., 2023). Advances in processing technologies may improve future outcomes (Gebremariam et al., 2020; Zhang et al., 2020).

Bricks offer greater reuse potential, particularly when recovered via selective demolition (Cristóbal García et al., 2023). While non-selective demolition involves crushing bricks and downcycling into RA, careful recovery improves the quality of recovered material, enabling production of more uniform aggregates or whole-brick reuse. Additionally, processed brick waste also shows promise for secondary applications. Fine brick particles can be used in mortars or as a clay substitute in new brick production. Projects such as REBRICK (2013) have demonstrated technical feasibility of producing market-ready bricks from reclaimed materials, although such practices remain niche.

Steel, due to its durability, magnetic properties, and market value, is among the most efficiently recycled construction materials. Whether demolition is conventional or selective, steel is almost always recovered and reprocessed into secondary material of sufficient quality for most construction applications. Beyond recycling, steel elements if removed intact can also be reused directly in new structures, offering significant carbon savings (Cristóbal García et al., 2023).

Mortar and plaster, usually composed of lime, cement, or gypsum, present limited reuse opportunities. These materials are generally not separable from surrounding substrates and degrade under mechanical stress. Thus, they are usually treated as inert waste, though research into reversible binders suggests emerging possibilities. Catalin et al (2023) explores the possibilities of plastering mortar recycling as substitutes for aggregates in plaster mortar recipes, concluding that there are real possibilities for implementation and an achievement of natural resource use reduction.

Gypsum-based products, including plasterboards, are increasingly recognized for their recycling potential, though implementation challenges remain. Studies show that recycled gypsum retains its physical properties for at least three recycling cycles, making it technically feasible for reintroduction into the production of new building components, including binder agents and gypsum-based panels (Erbs et al., 2018). Despite it, the rate of recycling remains low, and a big portion still ends up in landfills. Kitayama & Iuorio (2023) propose two primary strategies: (a) disassembling plasterboards from steel frames for use in new partitioning or ceiling systems, and (b) retaining boards attached to their steel frames to be reused as prefabricated panelized wall units. These approaches allow for extended use within existing construction methods and could reduce material waste significantly.

As Catalin et al. (2023) observes, numerous approaches to material reuse already exist, and innovation in waste-based building materials continues. In the context of Soviet-era housing, where construction typologies are highly standardized, these material categories offer a fairly predictable profile for recovery potential. Integrating building-level material assessments within broader circular economy frameworks can enhance the reuse and recycling of structural materials, reduce dependency on virgin resources, and thus lower the environmental burden associated with demolition and redevelopment. Quantifying the stock embedded in currently in-use buildings is the first step in this process, assisting in circular planning for the end-of-life phase of these buildings.

2.2 Green urban infrastructure and ecosystem services

2.2.1. Ecosystem services in urban contexts

Ecosystem services (ES) refer to the benefits humans obtain from ecosystems, typically classified into provisioning, regulating, supporting, and cultural categories (MA, 2005) (see Figure 2.1). In cities, these services are delivered through green urban infrastructure (GUI): networks of natural and semi-natural spaces like parks, forests, wetlands, or green roofs that provide ecological, social, and climatic functions (Demuzere et al., 2014). Among the numerous ES provided by GUI, urban cooling is increasingly important in mitigating microclimate stress during heatwaves, intensification of which occurring due to climate change. Demuzere et al. (2014) highlight the spatial sensitivity of cooling benefits, with effects ranging from block to neighborhood scales.

Figure 2.1 ES classification (MA, 2005)

Beyond climate moderation, GUI is also linked to public health outcomes. Access to green space is associated with improved mental and physical well-being, but benefits depend on vegetation quality, connectivity, and accessibility (Demuzere et al., 2014; Bernat, 2020). As cities densify and climate risks intensify, understanding the spatial distribution and effectiveness of GUI becomes necessary for supporting urban resilience, especially in underserved neighborhoods.

2.2.2. Ecosystem services in Lithuania and Vilnius

In Lithuania, urban areas exhibit the lowest ES potential among land use types (Depellegrin et al., 2016), though forests, especially within cities, are identified as ES hotspots, especially in regulating and cultural services (Depellegrin et al., 2016; Bernat, 2020; Dabašinskas & Sujetovienė, 2024). In Vilnius and Kaunas, urban forests aid air purification and promote well-being, with proximity influencing access (Bernat, 2020).

At the city scale, Vilnius presents a contradictory case. It is one of Europe's greenest capitals in terms of overall vegetation cover, yet spatial inequalities and fragmented infrastructure mean that ES are unevenly distributed and often inaccessible in central urban areas. Many dense districts do not meet the 300-meter green space accessibility benchmark (Annerstedt Van Den Bosch et al., 2016), prompting car-based travel that undermines environmental goals (Klimas & Lideika, 2018; Pinto et al., 2022). Studies mapping ES supply and demand across Vilnius identify a mismatch between the location of green infrastructure and areas of highest social demand, particularly in Soviet-era neighborhoods like Šeškinė, Justiniškės, Žirmūnai, and Viršuliškės, identifying them as ES "cold spots" due to fragmented green areas and extensive impervious surfaces (Misiūnė & Veteikis, 2020; Misiūnė et al., 2021, 2022; Kalinauskas et al., 2023; Dabašinskas & Sujetovienė, 2024).

Central districts also face ES deficits. Studies on flood regulation (Pereira et al., 2022) and GUI fragmentation (Misiūnė et al., 2022) reveal that core green assets are mostly peripheral, reducing service delivery where population density is highest. These mismatches reflect broader urban legacies shaped by Soviet planning, post-1990 transitions, and socio-economic disparities (Misiūnė et al., 2022). While compound ES indicators have been mapped, individual service assessments remain rare - particularly for cooling - highlighting a gap this study seeks to address.

2.2.3 Urban heat island effect in Vilnius

The urban heat island (UHI) effect refers to elevated temperatures in urban areas compared to rural surroundings, a cumulative effect of dense construction, heat-absorbing materials, limited vegetation, and anthropogenic heat (IPCC, 2023; Deilami et al., 2018). From a methodological perspective, UHI is typically categorized into three forms: boundary, canopy, and surface UHI, depending on the altitude of temperature measurement (Deilami et al., 2018). This study focuses on canopy UHI, defined as the temperature difference from ground to rooftop level, which is most relevant for microscale studies and can be derived from local weather station data.

UHI amplifies and prolongs heat waves, thus increasing health risks and energy demand, particularly in cities like Vilnius that lack widespread cooling infrastructure (Bukantis & Klimavičius, 2024; Ramanauskas et al., 2024). Vilnius is identified among the European cities most vulnerable to future UHI intensification, given forecasted decreases in wind speeds and increases in extreme heat duration (Lauwaet et al., 2024; Ramanauskas et al., 2024). Intensifying UHI has already been observed. Heatwaves are becoming more frequent and severe, with urban–suburban temperature differences ranging from 0.9°C (2012–2019) to 3.2°C (2022–2023) (Bukantis & Urbanavičiūtė, 2022; Bukantis & Klimavičius, 2024). Heat-related mortality is projected to increase sixfold by 2100 without adaptation measures (Martinez et al., 2018).

Key UHI drivers include impervious surfaces, low vegetation cover, and urban morphology (Deilami et al., 2018). Green infrastructure, especially tree canopy, is an effective countermeasure: 16% canopy coverage can lower temperatures by 1°C (Marando et al., 2022). Yet UHI impacts vary socially and spatially, with certain populations being disproportionately exposed to thermal stress due to a combination of social vulnerability and urban form (IPCC, 2023; Fernandez Milan & Creutzig, 2015). In Vilnius, Soviet-era mass housing districts represent areas of concern due to outdated construction, insufficient passive or active cooling measures, and socio-economic vulnerability. This intersection of extrinsic (urban structure, vegetation, building design) and intrinsic (health status, age, socio-economic conditions) risk factors makes them particularly susceptible to UHI-related hazards. Differentiating the UHI effect across districts of the Soviet period is essential for effective tailoring of mitigation strategies, such as targeted greening, optimized street orientation, and improved building materials and ventilation (Fernandez Milan & Creutzig, 2015). This spatial differentiation informs the modelling approach adopted in this research, which seeks to identify intra-urban variability in cooling service provision.

2.2.4 InVEST urban cooling model

To evaluate cooling services across Vilnius, this study uses the InVEST Urban Cooling Model, a GIS-based tool developed by the Natural Capital Project (2025). The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model integrates land use, vegetation, and climate data to estimate cooling capacity and heat mitigation, based on shading, evapotranspiration, and albedo. A more detailed model description can be found in section 3.2.1. A study by Zawadska et al. (2021) has validated the model's accuracy compared to land surface temperature imagery in depicting thermal response of land surface. Further research by Hamel et al. (2024) found that model simulations perform well compared to an alternative physics-based model. InVEST supports a shift from qualitative ES assessments to quantitative, spatially explicit insights, aiding planning decisions (Palaima & Mierauskas, 2013). Its adaptability makes it well suited for Vilnius, where diverse neighborhood typologies demand fine-grained, evidence-based interventions. In this study, it helps identify where GUI is effectively mitigating UHI, and where additional interventions are needed.

In this study, the InVEST Urban Cooling Model is applied to assess cooling service provision across Vilnius neighborhoods, with a focus on Soviet-era mass housing areas. The model helps visualize where ecosystem-based cooling is currently effective, and where it may need to be strengthened through potential interventions.

3. Methods

This study combines a bottom-up material stock assessment with urban cooling modelling to evaluate the structural material quantities in Soviet-era residential buildings and their relationship to urban heat mitigation potential. First, a spatially explicit dataset of Soviet-era buildings in Vilnius was developed and used to estimate material stocks based on established MICs. This material dataset was then compared to previous estimates to validate coverage. In parallel, an urban cooling model was run to evaluate neighborhood-scale differences in cooling capacity during heatwave conditions. This methodology produced results relevant for the examination of both the material legacy of Soviet-era housing and its spatial overlap with areas of differing climate adaptation potential.

3.1 Material stock calculation

3.1.1 Buildings dataset creation

The first step was to develop a dataset of Soviet-era buildings in Vilnius. For this, I collected data from two institutional sources: (1) State Enterprise (SE) Centre of Registers (VĮ Registrų centras, 2025); and (2) ID Vilnius, owned by Vilnius City Municipality (ID Vilnius, 2025). In addition, I obtained an administrative unit map from the Construction Sector Development Agency (SSVA, 2025). The goal was to create a spatially explicit dataset containing building polygons and key information on each building - location, area, and material data. To isolate Soviet-era mass housing, I set the following boundaries:

- 3 or more floors;
- object type: residential or mixed type, according to the SE Centre of Registers (VĮ Registrų centras, 2025) classification
- object purpose type: multi-apartment or various social groups, according to the SE Centre of Registers classification
- constructed between 1946 and 1994. While some Soviet-type buildings continued to be completed up to the end of the decade, 1994 was selected as the cutoff based on analysis of the full building dataset. Buildings up to this year predominantly followed Soviet construction typologies, whereas from 1995 onward, more modern architectural forms gained prominence, marking a clearer shift in development patterns.

Buildings that did not match these were excluded during data cleaning operations.

Figure 3.1 provides an overview of the data operations executed in order to arrive at the final dataset. Below, key processes are described in more detail.

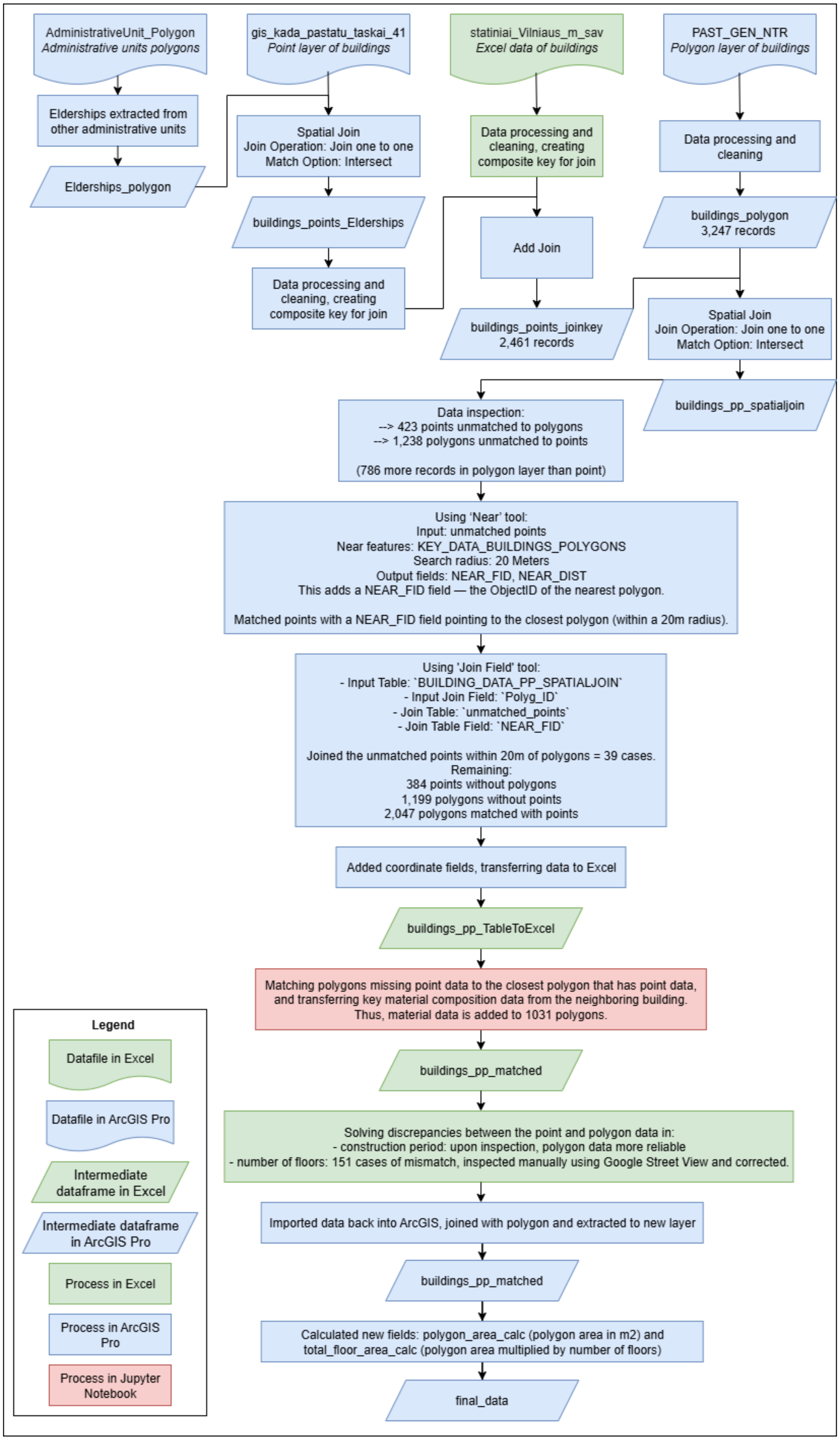

Figure 3.1 Buildings dataset creation flowchart

I obtained two datasets from the SE Centre of Registers: (1) GIS point layer of buildings, and (2) Excel file containing material data per building element, localized only to the eldership level. To spatially assign material data, I created a composite join key using shared variables (eldership, building category, object type, object purpose type, number of floors), enabling a join between the Excel and point datasets.

I then matched this joined dataset to a building polygon layer (ID Vilnius, 2025). Since the polygon layer (3,247 buildings) exceeded the point layer (2,461 buildings), many polygons lacked material data. To address this, I used a two-step matching process: (1) joining unmatched points within 20 meters of a polygon; (2) for the remaining unmatched polygons, assigning the material type of the nearest neighbor. The assumption here is that due to the homogenous nature of Soviet-era mass housing projects, buildings clustered together are likely to be of the same material type. Appendix B contains the Python script used for neighbor-matching. To validate, I randomly selected 30 matched buildings and reviewed them using Google Street View. Visual inspection confirmed that the assigned material types aligned with observable building features, supporting the reliability of the method. I excluded the buildings unmatched with a neighbor (168) from further analysis. The field join_status in the supplementary material buildings dataset tracks how each building received material data: 'matched_intersect' for overlap of point within polygon, 'matched_20m' for points within 20 meters of polygons, 'matched_neighbor' for neighboring building matches, and 'unmatched' for those missing materials data and thus excluded from calculations.

Next, I addressed the discrepancies between datasets. Construction year mismatches (mostly within five years) were resolved by retaining polygon data. This decision was informed by a spatial consistency check: for each mismatch, I compared the polygon construction year and the midpoint of the point-layer construction year interval to those of neighboring buildings within 50 meters. The option with smaller average deviation from nearby construction years was considered more plausible, which in the majority of cases was the polygon construction year. For the floor count mismatches (151 cases), I conducted a manual inspection using Google Street View and corrected accordingly. Finally, I calculated the building ground area from polygon geometry, and derived the total floor area by multiplying with floor count. Thus, I finalized the processed dataset in ArcGIS Pro.

3.1.2 Material stock calculations

To calculate material stock according to the bottom-up approach (elaborated in section 2.1), MICs were obtained from a database by Heeren & Fishman (2019). The selected MICs were based on the building typology of the IMPRO building project of the Institute for Prospective Technological Studies (Joint Research Centre) (2008), the typology specific to the Baltic countries. These sources were chosen as they were the only ones documenting building types in the Baltic countries from known material intensity and building typology literature. Table 3.1 provides an overview of the building typology from the IMPRO building project and its application to the Vilnius Soviet-era building dataset. Typology was applied after examining the material composition of the buildings in the dataset, based on several factors: (1) material of wall construction - brick or reinforced concrete (RC); (2) building construction period; (3) number of floors (for RC types). In addition, 16 buildings from the final dataset were classified in the original dataset (VĮ Registrų centras, 2025) as having a wooden overlay - the horizontal load-bearing partition structure of floors and ceilings. As this was not characteristic of Soviet-era mass housing, these buildings were excluded from further analysis. Figure 3.2 shows the process of applying the buildings typology to the final dataset.

Table 3.1 Building typology application (based on Institute for Prospective Technological Studies (Joint Research Centre), 2008)

Example image	Structural characteristics	Type name	Alias	Applied to dataset faction	Count
	Breeze concrete wall, reinforced concrete flooring, pitched roof	Z3_MF_002	RC_early	early soviet period (before and incl. 1960), reinforced concrete buildings	22
	Breeze and reinforced concrete wall, reinforced concrete flooring, flat roof	Z3_MF_005	RC_lowrise	reinforced concrete buildings constructed after 1960, with 6 or less floors	1058
	Concrete wall, reinforced concrete flooring, flat roof	Z3_MF_008	RC_highrise	reinforced concrete buildings constructed after 1960, with 7 or more floors	744
	Brick masonry, reinforced concrete flooring, pitched roof	Z3_MF_004	brick_early	brick buildings constructed before and incl. 1980	878
	Brick masonry, reinforced concrete flooring, pitched roof	Z3_MF_007_ex	brick_late	brick buildings constructed after 1980	360

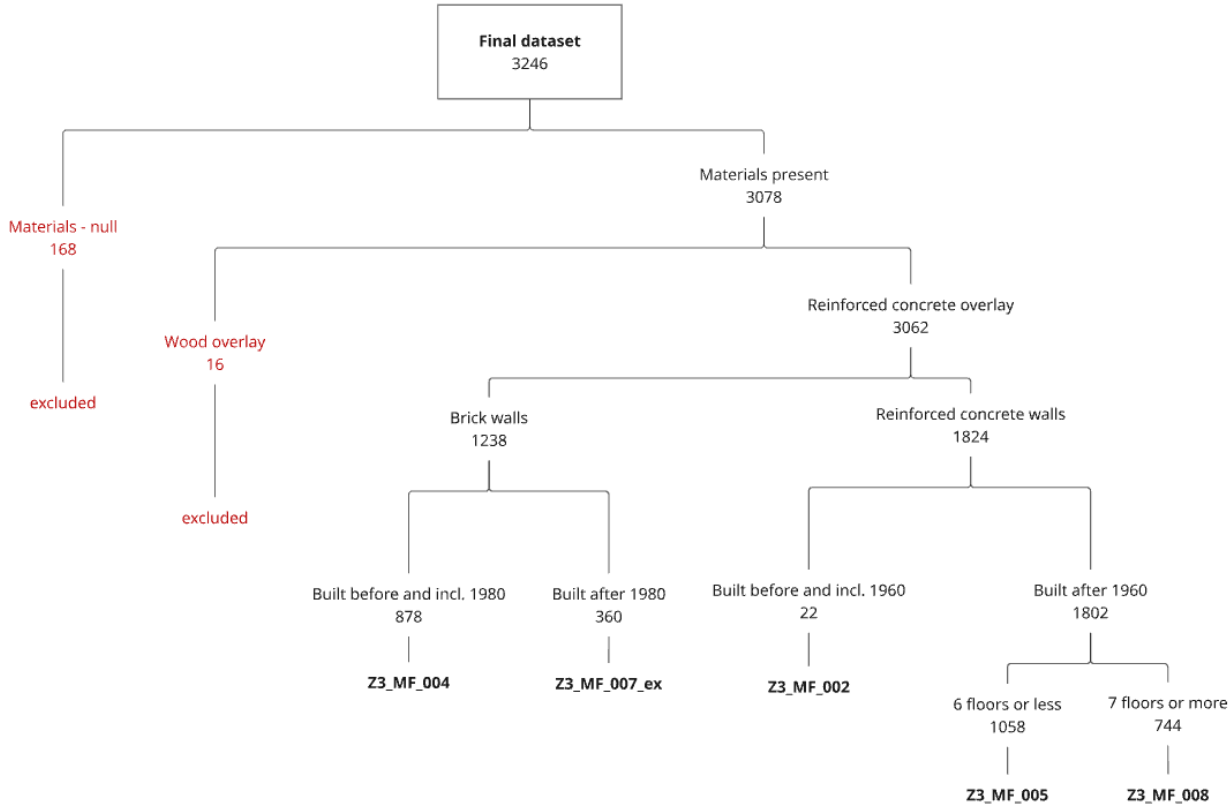

Figure 3.2 Decision tree of building categorization according to typology, with the numbers indicating the number of buildings within each subset

Each of the building types have different MICs for structural building materials. Appendix C shows the MI values per building type and construction material. Figure 3.3 shows the quantities of materials in kg/m2 of gross floor area per each type, and Figure 3.4 shows the respective contribution of each material to the total material intensity of each type.

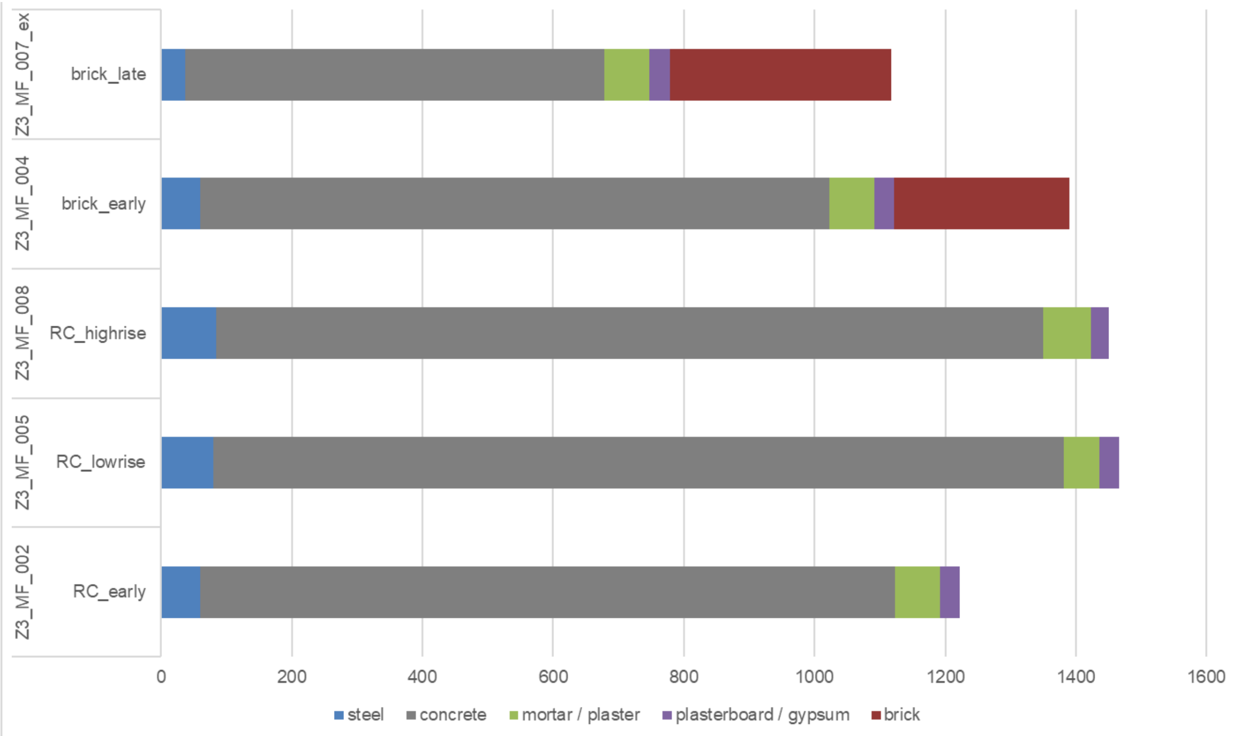

Figure 3.3 Total quantities of materials (kg/m2 of gross floor area) per type

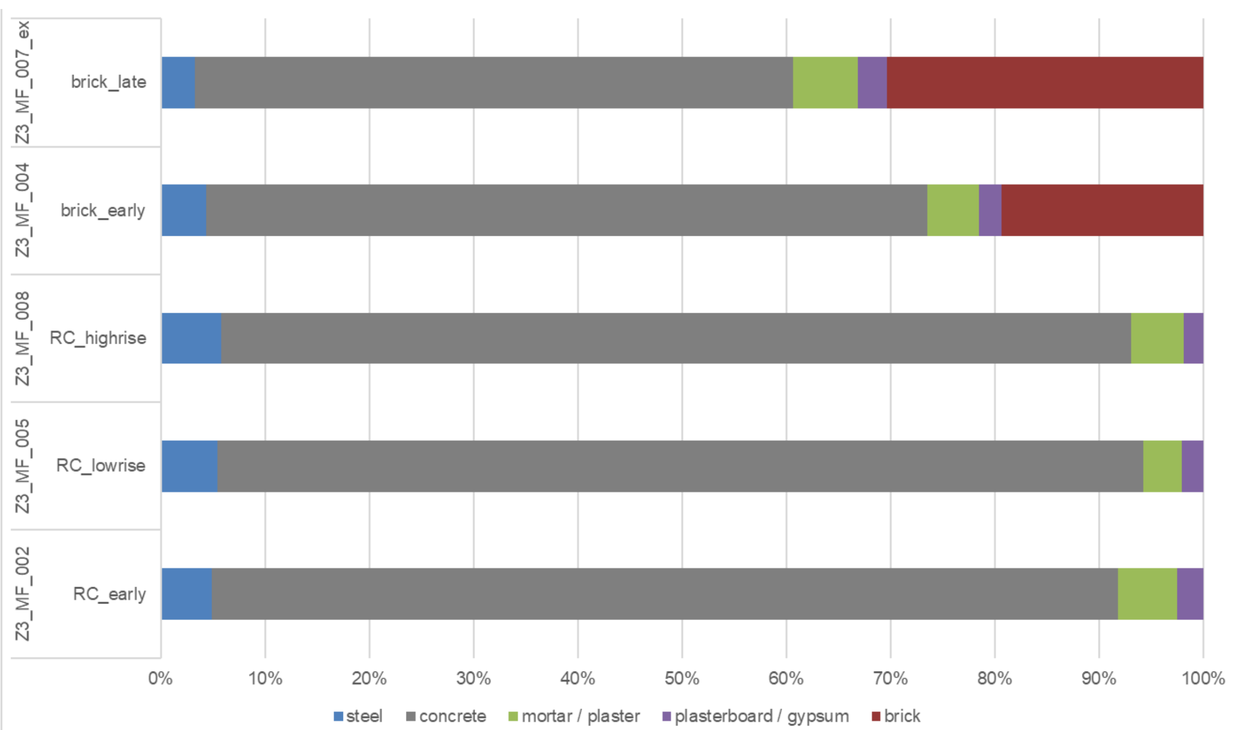

Figure 3.4 Relative contributions of materials to total material intensity per type

To calculate material stock, MICs (kg/m2) for each structural building material were multiplied per total floor area. Figure 3.5 provides an overview of the composition of the final Soviet-era buildings dataset including material stock calculations and indicates the source for each data point.

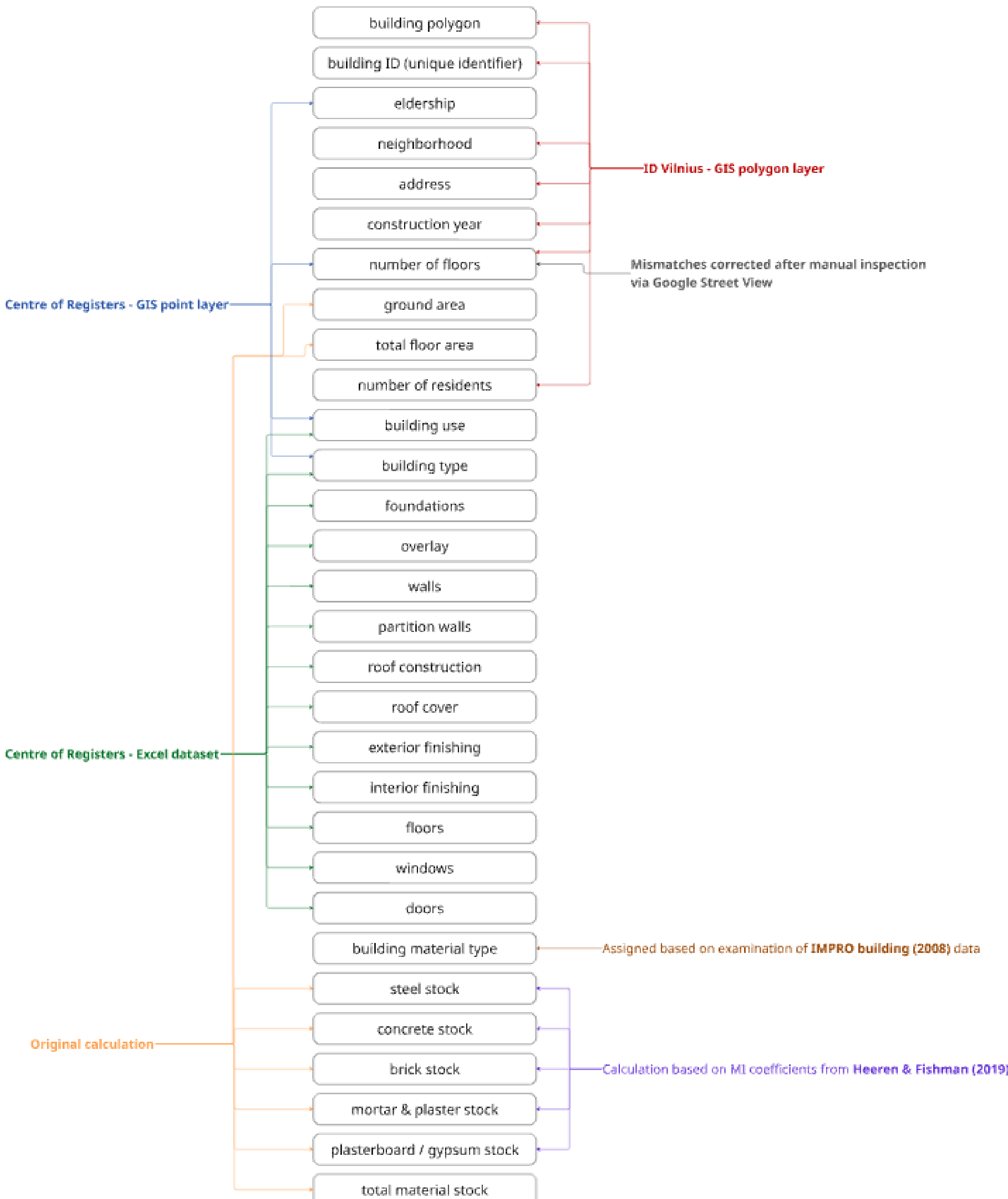

Figure 3.5 Buildings dataset composition & sources (incl. material stock calculations)

3.1.3 Dataset comparison to previous estimates

According to APVA (2025) 5183 multi-apartment buildings in Vilnius are in need of renovation - if we assume that this number reflects Soviet-era mass housing buildings, it can be used to estimate the percentage of calculated stock in my study. Here, the building dataset consists of 3246 buildings, thus 62%. From the sample, material stock was calculated for 3062 buildings, thus 59%. This provides an estimate of the coverage and potential margin of error: while the dataset might not include the full stock, it represents a significant share, supporting the reliability of city-scale material stock estimates derived from this sample.

Further, I conducted a cross-dataset comparison using the Soviet-era housing estate dataset from Balázs & Burneika (2020). Since their dataset is organized by elderships rather than neighborhoods, I compared the number of buildings across elderships, and applied my typology to their data using the same classification procedure (see Tables 3.2 and 3.3).

Table 3.2 Building count per eldership comparison with Balázs & Burneika (2020)

Eldership	Balázs & Burneika (2020) building count	Degimaitė (2025) building count	Difference
Antakalnis	187	289	102
Fabijoniškės	203	206	3
Grigiškės	60	55	-5
Justiniškės	283	287	4
Karoliniškės	72	241	169
Lazdynai	170	197	27
Naujamiestis	80	185	105
Naujininkai	172	185	13
Naujoji Vilnia	144	140	-4
Paneriai	5	27	22
Pašilaičiai	117	149	32
Pilaitė	92	63	-29
Rasos	40	48	8
Senamiestis	25	99	74
Šeškinė	213	213	0
Šnipiškės	62	83	21
Verkiai	166	180	14
Vilkpėdė	159	159	0
Viršuliškės	105	105	0
Žirmūnai	256	265	9

Žvėrynas	32	70	38
Total	2643	3246	603

Table 3.2 Building count per type comparison with Balázs & Burneika (2020)

Type	Alias	Balázs & Burneika (2020) building type count	Degimaitė (2025) building type count	Difference
Z3_MF_004	brick_early	552	878	326
Z3_MF_007_ex	brick_late	348	360	12
Z3_MF_002	RC_early	18	22	4
Z3_MF_005	RC_lowrise	1054	1058	4
Z3_MF_008	RC_highrise	671	744	73
Total		1743	1824	81

The dataset of Balázs & Burneika (2020) numbers 2643 housing estate buildings - 603 buildings less than my study. This is primarily due to: (1) their study defines housing estates as a group of 3 or more apartment buildings of the same type, while my study does not stipulate this condition and also includes stand-alone buildings; (2) differing data inputs - for instance, in the neighborhood of Karoliniškės, the most common type of building is a construction of a central part and four wings, of differing heights (5-9). In my dataset, these are counted as separate buildings with an exact number of floors, while in Balázs & Burneika (2020) they are counted as a single building of mixed height (5-9). (1) Explains the higher count of buildings of Z3_MF_004 type in such neighborhoods as Antakalnis and Naujamiestis, and (2) explains the higher count of buildings of Z3_MF_008 type in the neighborhood of Karoliniškės. On the other hand, the dataset of Balázs & Burneika (2020) had a temporal limit of up to the late 1990s - unspecified exact year, whereas for the present dataset, the limit was set to 1994. This is likely the reason for a smaller count of buildings in the neighborhoods of Pilaitė and Grigiškės in my study.

Unfortunately, the dataset of Balázs & Burneika (2020) could not be used for a direct comparison of material stock calculations because it lacks gross floor area data. However, the overall similarity in spatial distribution and typological representation supports the consistency of my classification and coverage across the city.

3.2 Urban cooling modelling

3.2.1 Model description

The urban cooling model first computes the cooling capacity (CC) index – a dimensionless value ranging from 0 to 1 that represents the potential of land cover to mitigate heat through shade, evapotranspiration, and surface reflectivity (albedo) (Natural Capital Project, 2025). Higher values indicate stronger cooling potential, typically associated with dense tree canopy or water bodies, while lower values reflect low vegetation or abundant impervious surfaces that contribute little to local temperature regulation. To account for the cooling effects of big green spaces (>2 ha), the model computes the urban heat mitigation index (HMI). HMI is equal to CC if the pixel is not affected by any big green spaces. Otherwise, it is set to a distance-weighted average of the CC values from the big green spaces and the select pixel. Same as CC, the HMI It is a unitless index measure ranging from 0 to 1, representing the relative capacity of the landscape to mitigate heat.

To measure heat reduction across the city, the model uses the magnitude of UHI at the city scale - for each specified area of interest, in this case neighborhood units, it calculates the average temperature and the corresponding temperature anomaly. In addition, with the work productivity valuation, the model calculates the impact of heat on light and heavy work productivity losses. For this, it converts air temperature into wet-bulb globe temperature using average relative humidity – where both air temperature and average relative humidity are provided by the user as data inputs. Light work corresponds to about 200 Watts metabolic rate, approximating office desk work, and heavy work corresponds to 400 W, approximating construction or agricultural work.

3.2.2 Data inputs

The goal for this model was to observe differences in urban cooling amongst neighborhoods during a heatwave, therefore the inputs were calibrated to reflect heatwave conditions. Table 3.4 summarizes the data inputs (including sources) for the urban cooling model. Appendix D contains the specific values for the biophysical table, and Appendix E contains the Python script used for calculation of the reference air temperature and average relative humidity.

Table 3.3 Data inputs and sources for the urban cooling model

Name parameter	Type, units	Input data	Source
Land Use / Land Cover	Raster	ESA WorldCover 2021 at 10m resolution Reprojected into linear units: WGS 1984 ➔ LKS 1994 Lithuania TM	European Space Agency https://esa-worldcover.org/en (Zanaga et al., 2022)
Reference Evapotranspira tion	Raster, units: mm	Global Aridity Index and Potential Evapotranspiration (ET0) Database: Version 3 Global ET0 monthly - July	Zomer & Trabucco (2019) https://doi.org/10.6084/m9.figshare.7504448.v6
Area Of Interest	Vector	Map of Vilnius neighborhoods according to the Master Plan	ID Vilnius server:

			https://gis.vplanas.lt/arcgis/rest/services/Interaktyvus_zemelapis2/Bendrasis_planas_2021_public/MapServer (Vilniaus erdvinių duomenų portalas, 2025)
Reference Air Temperature	number, units: °C	**28.19 °C** - calculated average daytime (09:00–21:00 local time) temperature during heatwaves (daily max temp > 30°C) for the period 2020-2024 for Vilnius meteorological station.	Meteo.lt API https://api.meteo.lt/ (Lietuvos hidrometeorologijos tarnyba prie Aplinkos ministerijos, 2025)
UHI Effect	number, units: °C	**3.2 °C -** based on most recent available research findings	Bukantis & Klimavičius (2024) https://doi.org/10.5194/ems2024-130
Air Blending Distance	number, units: m,	**550**	InVEST User Guidebook recommendation https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/urban_cooling_model.html#data-needs (Natural Capital Project, 2025)
Maximum Cooling Distance	number, units: m	**450**	InVEST User Guidebook recommendation https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/urban_cooling_model.html#data-needs (Natural Capital Project, 2025)
Cooling Capacity Calculation Method	choice of 2 options	Factors	InVEST User Guidebook recommendation for daytime temperature modelling https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/urban_cooling_model.html#data-needs (Natural Capital Project, 2025)
Average Relative Humidity	Percent	**50.62** - calculated average daytime (09:00–21:00 local time) relative humidity during heatwaves (daily max temp > 30°C) for the period 2020-2024 for Vilnius meteorological station.	Meteo.lt API https://api.meteo.lt/ (Lietuvos hidrometeorologijos tarnyba prie Aplinkos ministerijos, 2025)
		Biophysical table	
lucode	integer	Codes from ESA WorldCover LULC raster	European Space Agency https://esa-worldcover.org/en
kc	number, units: unitless,	Based on Bosch et al. (2020)	Bosch et al. (2020) https://doi.org/10.1101/2020.11.09.373779
green area	true/false	Assigned based on LU category type	

shade	ratio	Assigned based on visual examination of relevant areas	
albedo	ratio	Based on Stewart & Oke (2012)	Stewart & Oke (2012) supplementary material https://doi.org/10.1175/BAMS-D-11-00019.1

3.2.3 Sensitivity check

Crop coefficients are notoriously difficult to estimate for urban land uses (Hamel et al., 2024). For the present study, they were obtained from previous research of Bosch et al. (2020). To understand how vulnerable the model is to changes of evapotranspiration coefficient values for crops (Kc), a sensitivity check was conducted using alternative inputs for Kc based on differing sources (Hamel et al., 2024; Pohanková & Pechanec, 2024; Zawadzka et al., 2021; Zepp et al., 2023). Appendix F presents the differing inputs for Kc across sensitivity runs and main results. The analysis shows that the Kc values from Bosch et al. (2020) yield average HMI values across the five modeled options, representing a balanced choice that avoids overly pessimistic or optimistic outcomes. Overall, using different Kc inputs results in a city-level mean HMI range of 0.1 and a temperature anomaly range of 0.32°C. For Soviet-era neighborhoods specifically, the range of mean HMI is 0.05 and the range of temperature anomaly is 0.12°C - indicating the model's results are fairly stable, and the Soviet-era neighborhood analysis shows less sensitivity to Kc variations than the city-level analysis.

4. Results

4.1 Material stock of Soviet-era buildings

Table 4.1 summarizes the total stock in megatons (1 Mton = 1.000.000 tonnes), including stock per structural building material, of Soviet-era residential buildings in Vilnius. By mass, concrete makes up most of the stock (80.9%).

Table 4.1 Total material stock in Mton per structural building material

Material	***Mton***	***Percentage***
Concrete	12.96	80.9
Bricks	1.15	7.2
Steel	0.82	5.1
Mortar / plaster	0.75	4.7
Plasterboard & gypsum	0.34	2.1
Total	16.01	100.0

Appendix G shows the total stock per neighborhood for each structural building material. Measuring per neighborhood unit, the largest amounts of stock are concentrated in the neighborhoods of 16.Fabijoniškės (1.46 Mton), 15.Šeškinė (1.24 Mton), 12.Justiniškės (1.23 Mton), 18.Karoliniškės (1.17 Mton), 20.Pašilaičiai (1.08 Mton), and 53.Lazdynai (1.07 Mton), with other neighborhoods measuring at less than 1 Mton.

By building type (Figure 4.1), RC_highrise (Z3_MF_008) and RC_lowrise (Z3_MF_005) dominate total stock, followed by brick_early (Z3_MF_004). When concrete is excluded, RC_highrise remains dominant for mortar/plaster and plasterboard & gypsum, but brick_early (Z3_MF_004) surpasses RC_lowrise (Z3_MF_005) in mortar/plaster quantity despite its lower total stock.

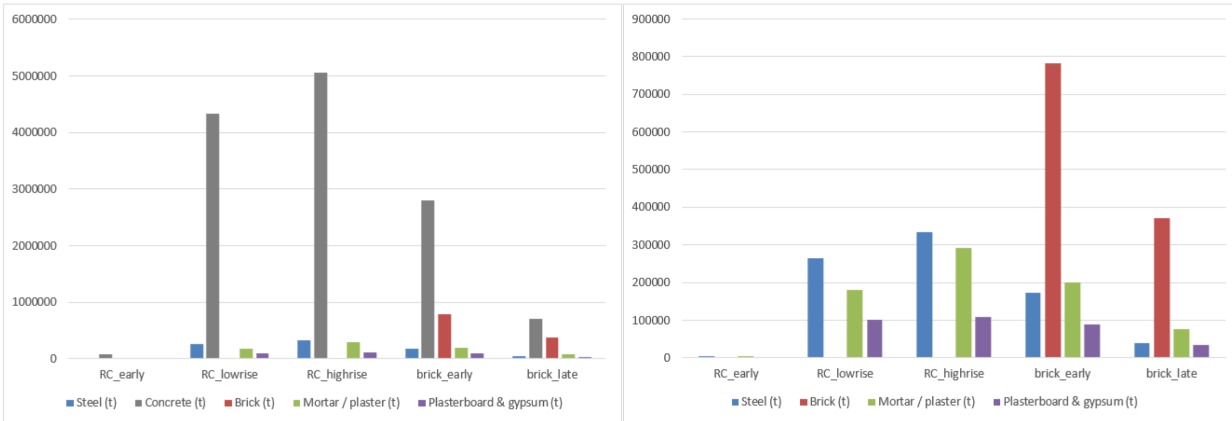

Figure 4.1 Material stock concrete distribution and quantity per building type (left side: including concrete; right side: excluding concrete)

Examining material stock distribution by building construction periods indicates (future) availability for material reuse. Over 70% of all stock is embedded in buildings constructed between 1971–1994 (Figure 4.2). Figure 4.3 shows the material stock composition per construction period - notable here is the decreasing share of brick stock, from 16.4% in the earliest period, to 5.4% in the latest.

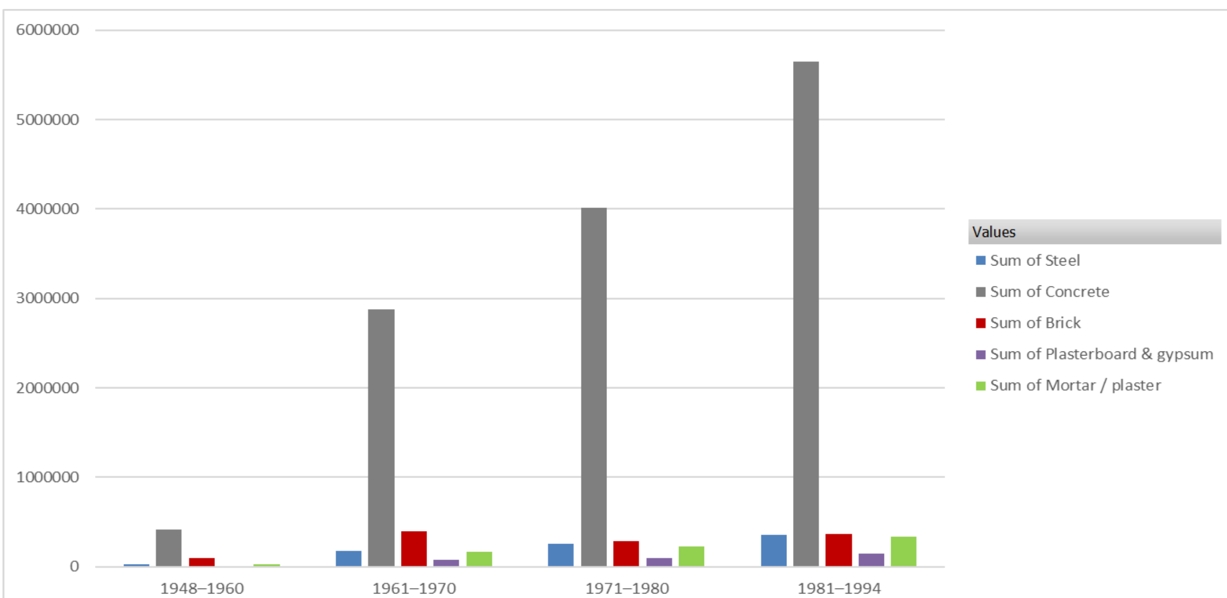

Figure 4.2 Absolute material stock quantity and distribution per construction period

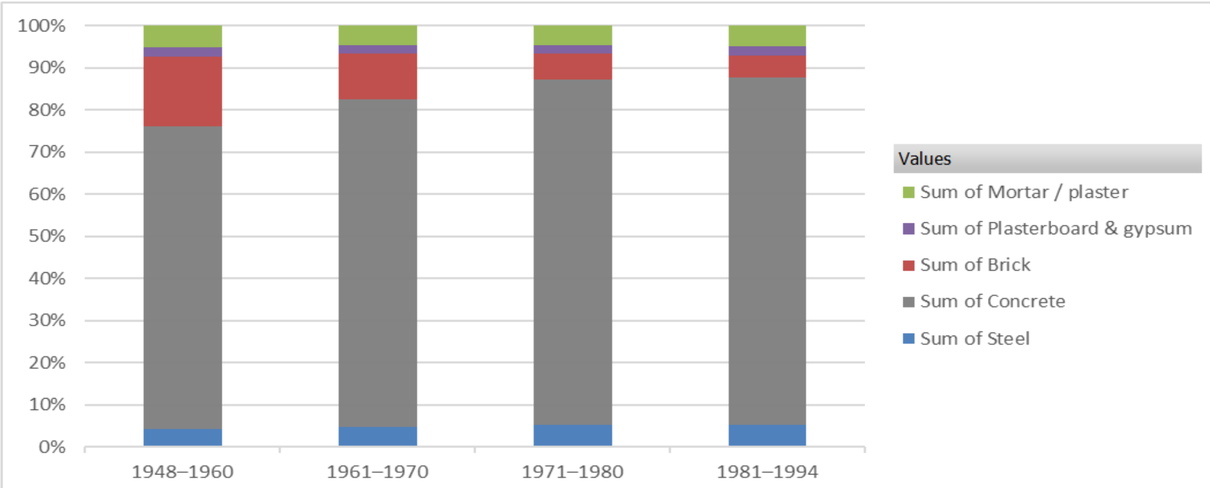

Figure 4.3 Relative contributions of materials to material stock per construction period

Focusing on Soviet-era neighborhoods in particular, Figure 4.4 depicts the material stock quantities and composition among them. In addition, Table 4.2 shows material stock per capita within Soviet-era neighborhoods (accounting only for Soviet-era buildings within those neighborhoods and their residents), ranked from highest to lowest.

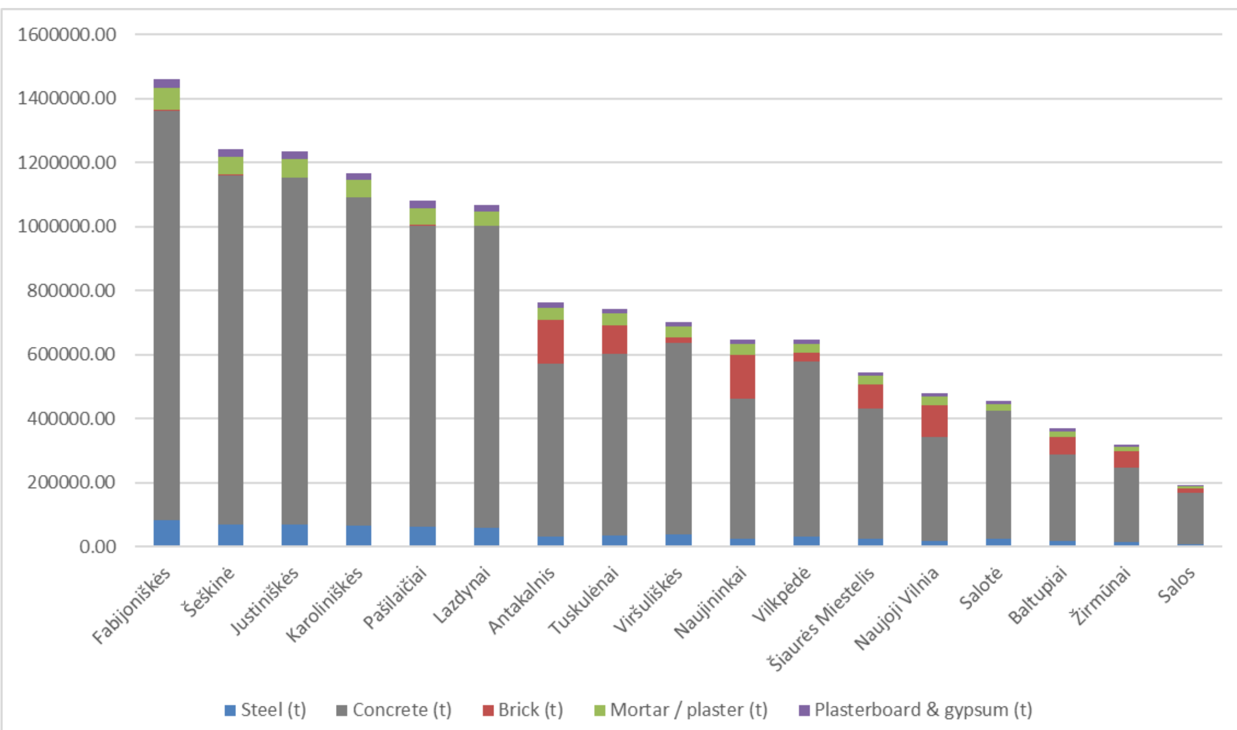

Figure 4.4 Material stock quantities and composition in Soviet-era neighborhoods

Table 4.2 Material stock per capita in Soviet-era neighborhoods

District ID	Name	Number of residents in Soviet-era housing	Stock per capita (t/person)
20	Pašilaičiai	18104	59.655
11	Salotė	7683	59.209
133	Antakalnis	13536	56.424
29	Baltupiai	6579	56.215
16	Fabijoniškės	26910	54.299
150	Tuskulėnai	14002	53.139
12	Justiniškės	23891	51.657
53	Lazdynai	20835	51.246
151	Žirmūnai	6256	51.187
111	Vilkpėdė	12780	50.743
18	Karoliniškės	23086	50.621
15	Šeškinė	24619	50.498
13	Viršuliškės	13928	50.487
122	Naujininkai	13920	46.616
49	Šiaurės Miestelis	11821	46.107
57	Afindevičiai	2285	44.226
140	Salos	4597	42.226
94	Naujoji Vilnia	11706	41.061

4.2 Spatial distribution of material stock in Soviet-era buildings

Figure 4.5 maps building types across Vilnius. There is a clear pattern of RC-dominant neighborhoods across the northwest side of the city, with brick types – most commonly, of the early period – dominating eastern and southern districts.

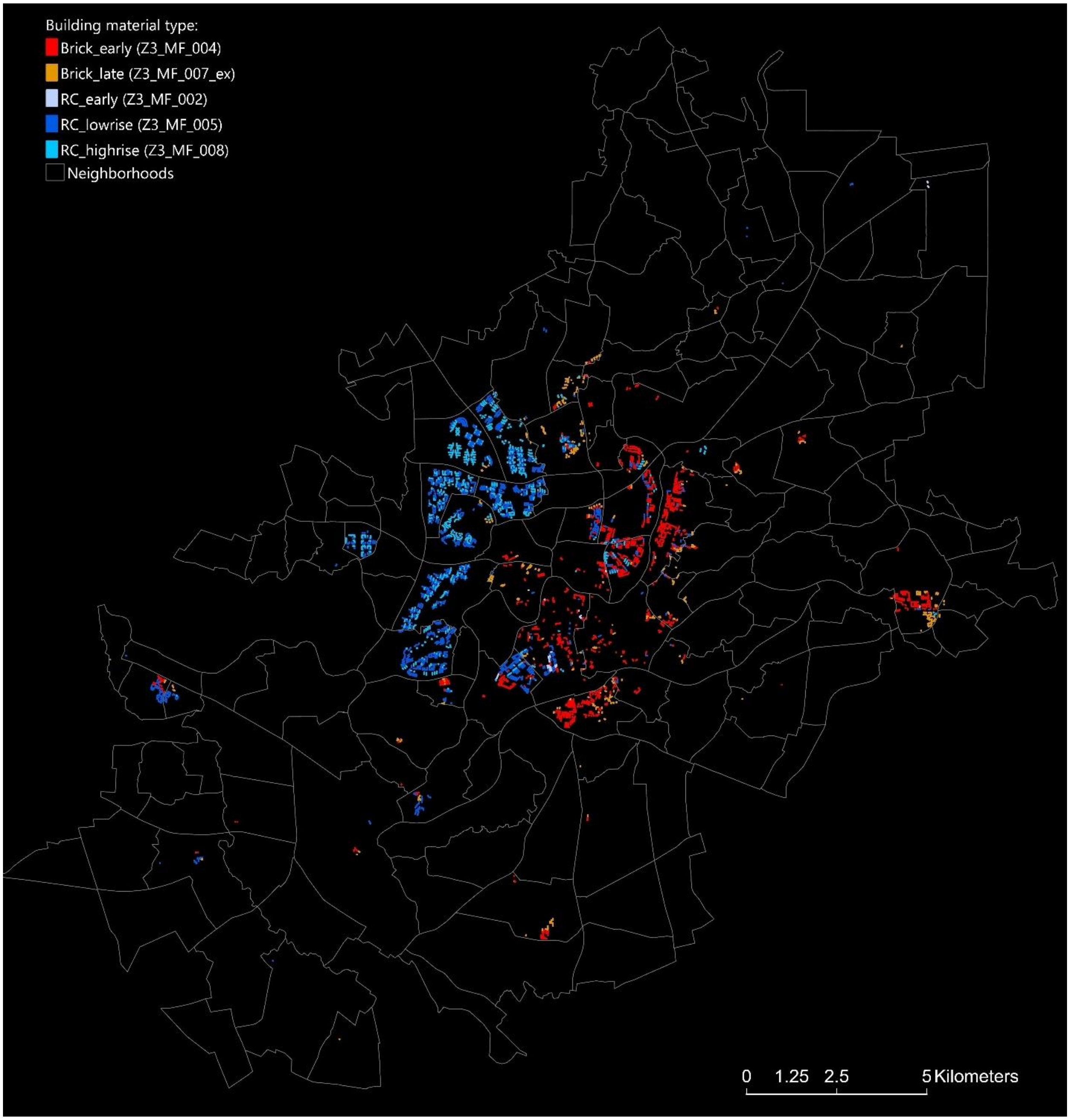

Figure 4.5 Soviet-era building types across Vilnius

In addition, Figure 4.6 shows building distribution by period of construction. Focusing on the earlier construction cohort of buildings (1948-1970) due to their rapidly approaching end-of-life and, thus, relevance for urban mining potential, Table 4.3 shows building count, proportion, and amount of stock (in Kilotons, 1 Kton – 1,000 tonnes) within the neighborhoods with the largest concentrations of this stock cohort, ranked by neighborhood ID. Summing up across both cohorts, results show that the largest amount of rapidly aging stock are concentrated within the neighborhoods of 55.Naujamiestis (765 Kton), 150.Tuskulėnai (625 Kton), 47.Senamiestis (551 Kton), 48.Centras (530 Kton), and 133.Antakalnis (454 Kton).

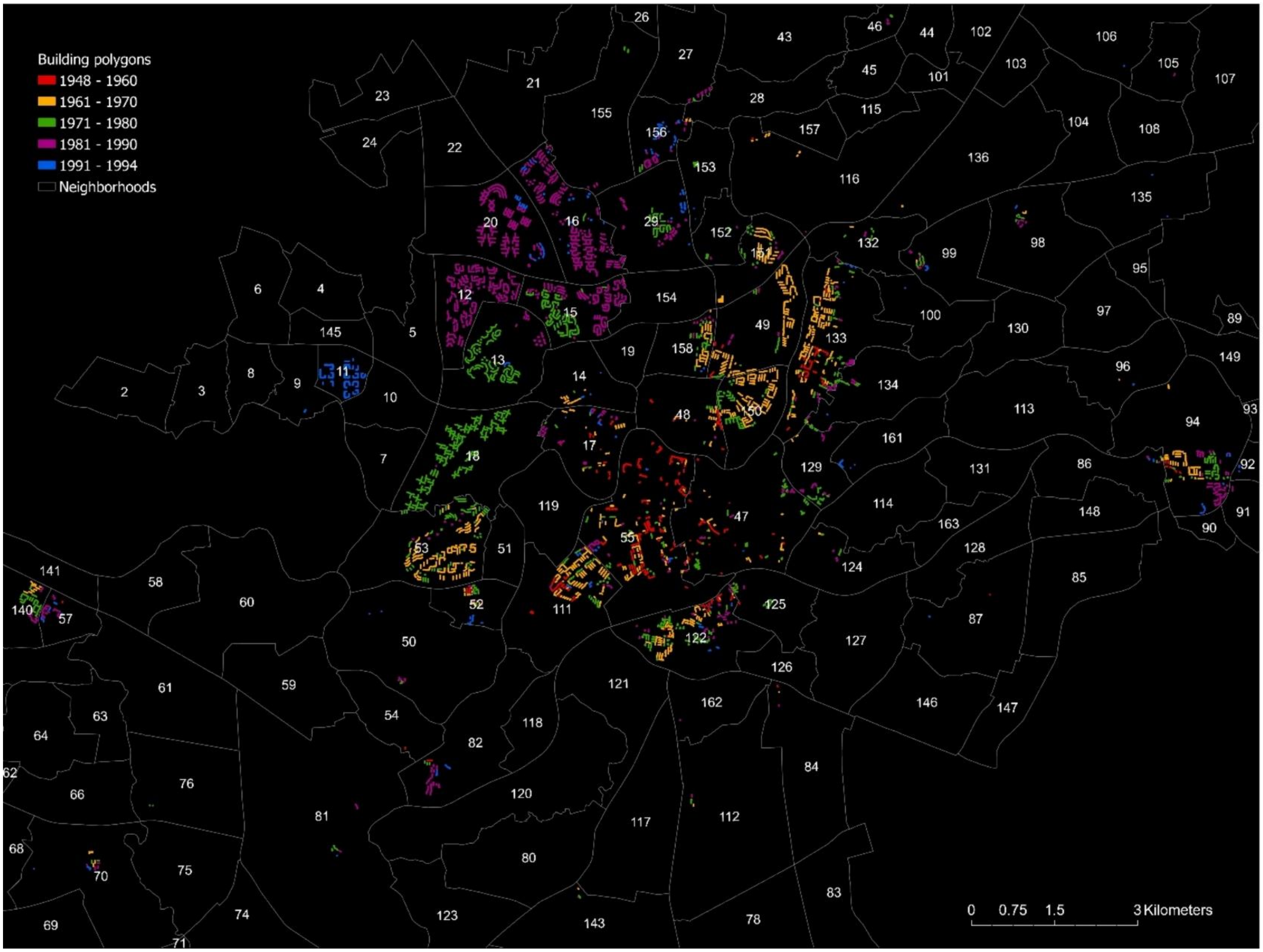

Figure 4.6 Soviet-era buildings in Vilnius city core and surrounding neighborhoods by period of construction

Table 4.3 Material stock distribution amongst the earlier construction cohorts

		1948-1960			1961-1970		
ID	Neighborhood	Building count	% within age cohort	Total stock (Kton)	Building count	% within age cohort	Total stock (Kton)
47	Senamiestis	23	13.22%	44	16	2.36%	45
48	Centras	10	5.75%	35	13	1.92%	51
49	Šiaurės Miestelis	0	0	0	70	10.32%	454
53	Lazdynai	0	0	0	91	13.42%	625
55	Naujamiestis	63	36.21%	305	53	7.82%	247
111	Vilkpėdė	16	9.20%	48	64	9.44%	386
122	Naujininkai	15	8.62%	32	52	7.67%	240
133	Antakalnis	26	14.94%	75	98	14.45%	455
150	Tuskulėnai	0	0	0	76	11.21%	469
Others		21	12.06%	41	145	21.39%	724

To visualize the spatial distribution of total material stock, kernel density mapping was utilized (Figure 4.7). The hotspots in the northern districts emerge as areas with the highest total stock concentration, especially the southern part of the neighborhood Fabijoniškės. Hotspot mapping of individual materials follows this pattern very closely thus are not included. Brick is the exception, having a different spatial distribution of hotspots (Figure 4.8), observed in the southeast part of Naujoji Vilnia and the western part of Naujininkai.

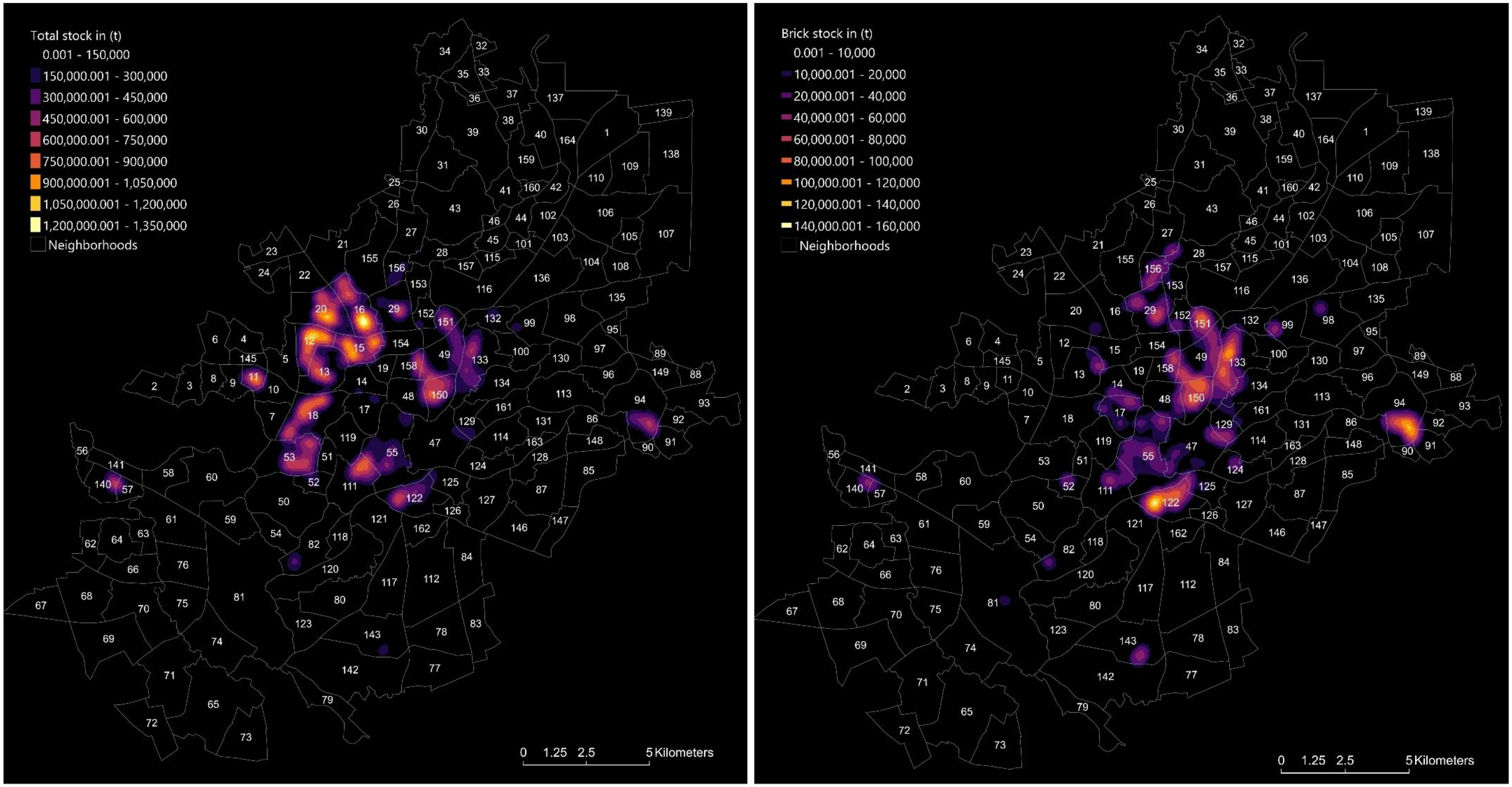

Figure 4.7 Kernel density maps of (left side) total material stock; and (right side) brick stock in Soviet-era buildings across Vilnius

4.3 Urban cooling model results

The HMI values across the city range from 0.16 to 0.71. The lowest capacity is observed in the central district (48.Centras), with a mean of 0.26. Among Soviet-era neighborhoods, mean HMI ranges from 0.28 (11.Salotė) to 0.60 (53.Lazdynai). Based on the HMI, I produced an estimated air temperature map for the modelled heatwave conditions (Figure 4.8) by adjusting the reference air temperature with the UHI effect moderated by local HM capacity. This illustrates how spatial differences in HM capacity translate into variations in actual temperatures during extreme heat events.

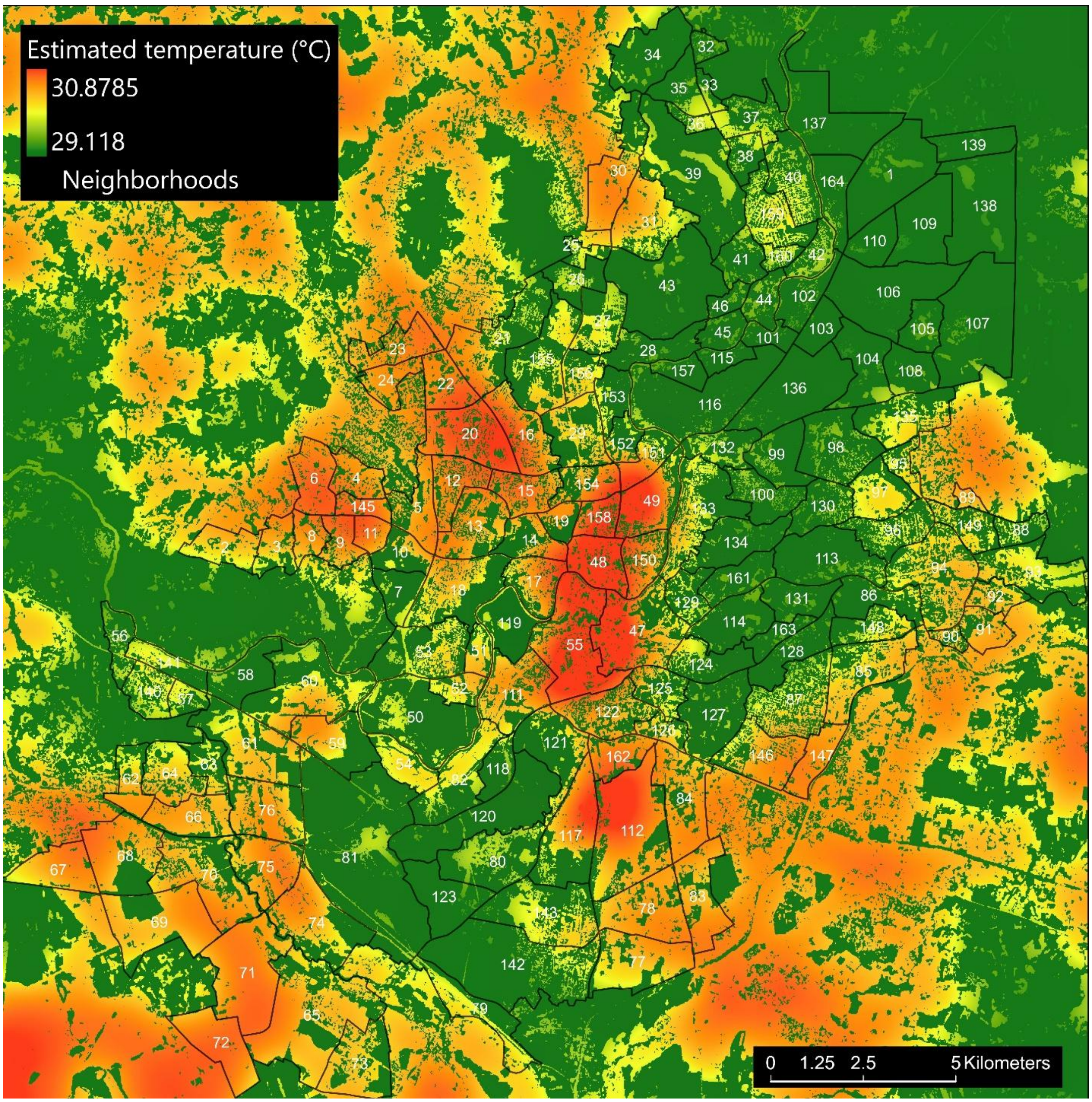

Figure 4.8 Map of estimated air temperature during heatwave conditions in Vilnius

Table 4.4 summarizes results of Soviet-era neighborhoods: mean and std. deviation of HMI values, average temperature anomaly (i.e. how much UHI burden remains), percentage of tree cover from LU categorization, with the entries ranked from highest mean HMI to lowest. In addition, neighborhood-level cooling effect was quantified by multiplying the mean HMI with the model input maximum UHI effect (3.2°C) - providing a measure in °C how much of the potential urban heat anomaly was mitigated by GUI within each neighborhood.

Table 4.4 Summary of urban cooling model results for Soviet-era neighborhoods

ID	Name	Mean HMI value	HMI std. deviation	Avg. temperature anomaly (°C)	Proportion of tree cover of total neighborhood area (%)	Neighborhood-level cooling effect (°C)
53	Lazdynai	0.602	0.134	1.295	63%	1.928
133	Antakalnis	0.582	0.149	1.341	59%	1.862
57	Afindevičiai	0.582	0.115	1.225	50%	1.862
140	Salos	0.572	0.119	1.227	47%	1.832
29	Baltupiai	0.569	0.164	1.520	58%	1.821
18	Karoliniškės	0.547	0.171	1.449	53%	1.751
94	Naujoji Vilnia	0.523	0.165	1.482	46%	1.673
122	Naujininkai	0.483	0.206	1.770	46%	1.547
13	Viršuliškės	0.457	0.203	1.744	40%	1.464
111	Vilkpėdė	0.438	0.189	1.649	32%	1.400
151	Žirmūnai	0.435	0.209	1.596	34%	1.392
150	Tuskulėnai	0.404	0.216	1.867	34%	1.294
12	Justiniškės	0.386	0.207	1.917	29%	1.235
15	Šeškinė	0.379	0.201	1.871	27%	1.214
49	Šiaurės Miestelis	0.366	0.222	1.844	29%	1.172
16	Fabijoniškės	0.365	0.193	1.841	24%	1.169
20	Pašilaičiai	0.307	0.197	2.040	20%	0.983
11	Salotė	0.272	0.092	1.860	4%	0.870

Amongst Soviet-era neighborhoods, 11.Salotė is found to be the most deficient in GUI: with 4% tree cover, it is the only of Soviet-era neighborhoods for which PCT90 (value below which 90% of HMI values fall) is notably low - 0.32 opposed to a consistent average of 0.7 for all other Soviet-era neighborhoods, showing that it lacks any GUI capable of delivering cooling services. Despite this, it displays a moderate cooling effect of 0.87°C, which suggests that proximity to nearby forest is the main contributor to its urban cooling service delivery. Implications of the results for other neighborhoods are further elaborated in section 5. Discussion.

Furthermore, there was a very strong positive correlation between the proportion of tree cover and the mean HMI across neighborhoods, $r(17) = .97$, $p < .001$. Figure 4.9 shows the scatterplot with a linear trendline, which explains 93.4% of the variance ($R^2 = 0.9337$). This indicates that tree cover within a neighborhood is a strong and consistent predictor of heat mitigation service delivery. In Vilnius, most neighborhoods benefit from a baseline cooling effect due to proximity to large forested areas (e.g., 11.Salotė), while additional variation in performance can be explained by internal green infrastructure.

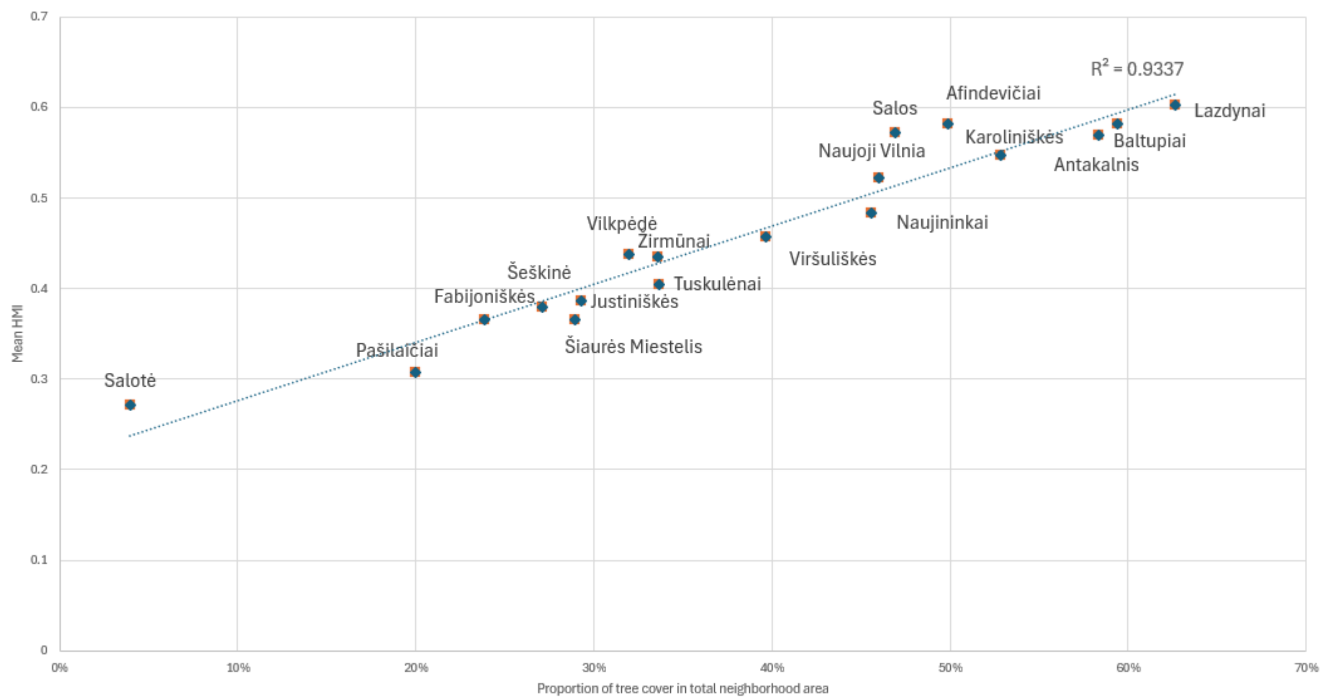

Figure 4.9 Scatterplot of mean HMI and proportion of tree cover in Soviet-era neighborhoods

The bottom-runner-up 20.Pašilaičiai is another noteworthy case: it has 16% more forest cover than 11.Salotė but performs almost the same in terms of urban cooling (0.307 mean HMI vs. 11.Salotė's 0.272). This result reflects a trade-off: while 20.Pašilaičiai benefits from internal GUI, it lacks proximity to large surrounding forested areas. The existing tree cover alone does not appear substantial enough to compensate for this, resulting in only marginally better cooling service delivery.

In addition, as outlined in section 3.2.1, the model estimates work productivity losses under heatwave conditions. This is relevant for identifying where insufficient green infrastructure may lead to reduced human comfort and performance – one aspect of ecological underperformance with planning implications. For light work, productivity losses were 0% in every neighborhood. However, significant work productivity losses can be observed for heavy work in several neighborhoods (Figure 4.10), most notably in the central districts (48.Centras, 55.Naujamiestis, 158.Šnipiškės), some peripheral-urban (22.Pavilionys) and suburban (72.Guobos, 6.Plytinė, 71.Daniliškės) neighborhoods, and amongst Soviet-era neighborhoods 20.Pašilaičiai stands out with the biggest productivity losses (avg. 49%).

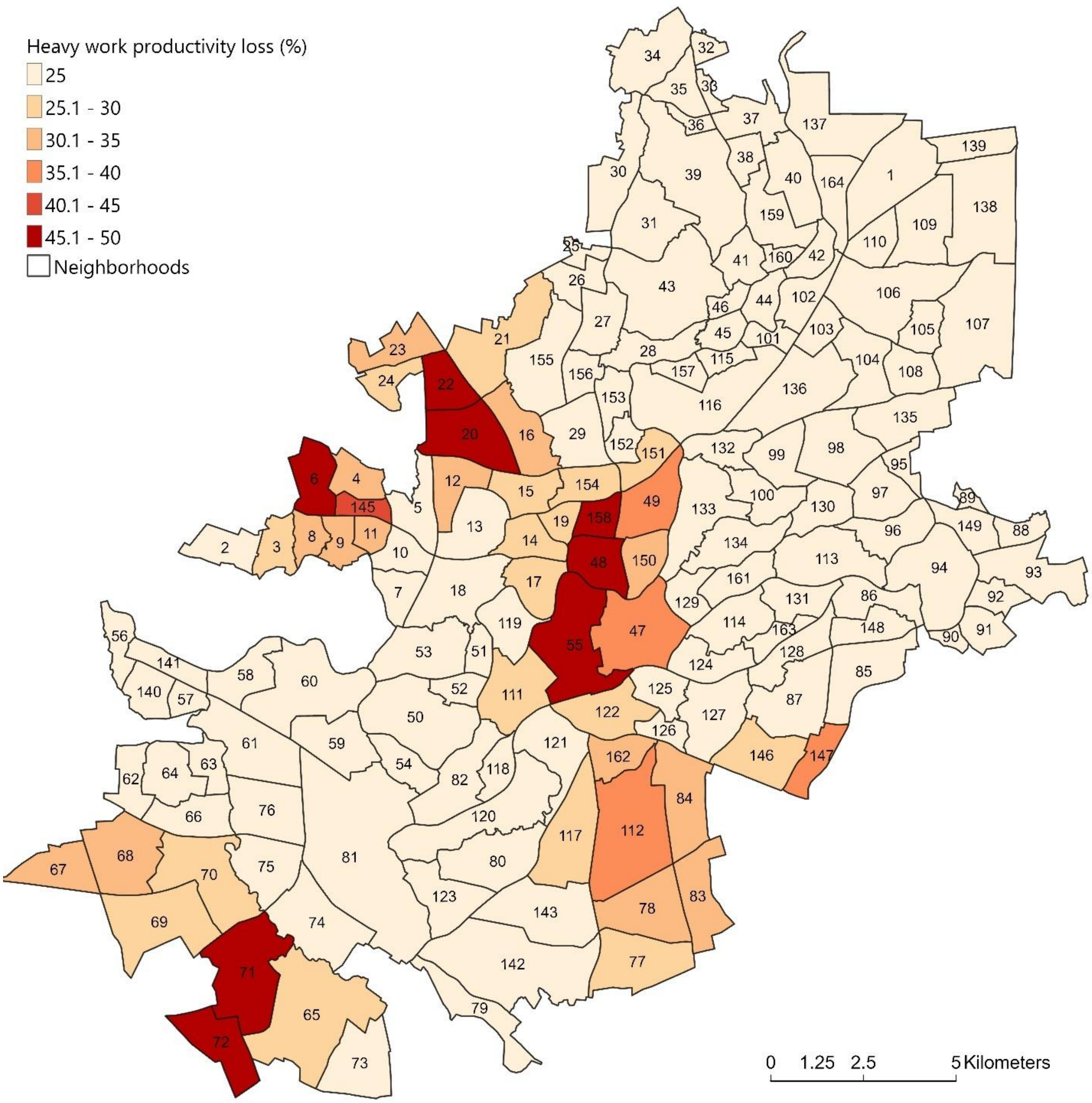

Figure 4.10 Heavy work productivity losses across neighborhoods in Vilnius

4.4 Combined results

A moderate positive correlation is observed between total material stock and average temperature anomaly across neighborhoods (Pearson's r = 0.47, $R^2 = 0.22$, $p = 0.0504$) (Figure 4.11). This indicates that neighborhoods with higher volumes of Soviet-era built mass tend to experience slightly greater heat intensities. Approximately 22% of the variation in local temperature anomalies can be statistically explained by differences in material stock. P value hovers just above the threshold for statistical significance, pointing to a potentially meaningful association, though not conclusively so. While this suggests a tangible relationship between urban form and thermal performance, the majority of variability remains influenced by other ecological or spatial factors, such as landscape context and the presence of material stock outside the scope of my sample.

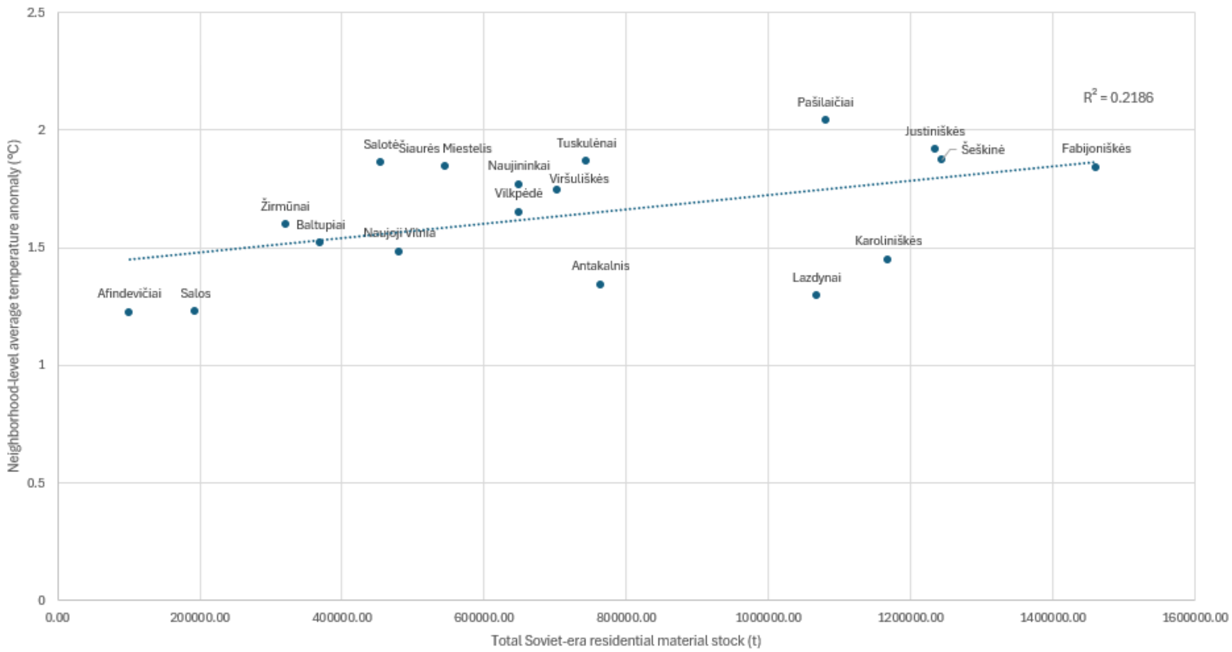

Figure 4.11 Scatterplot of neighborhood-level average temperature anomaly (°C) and total Soviet-era residential material stock (t)

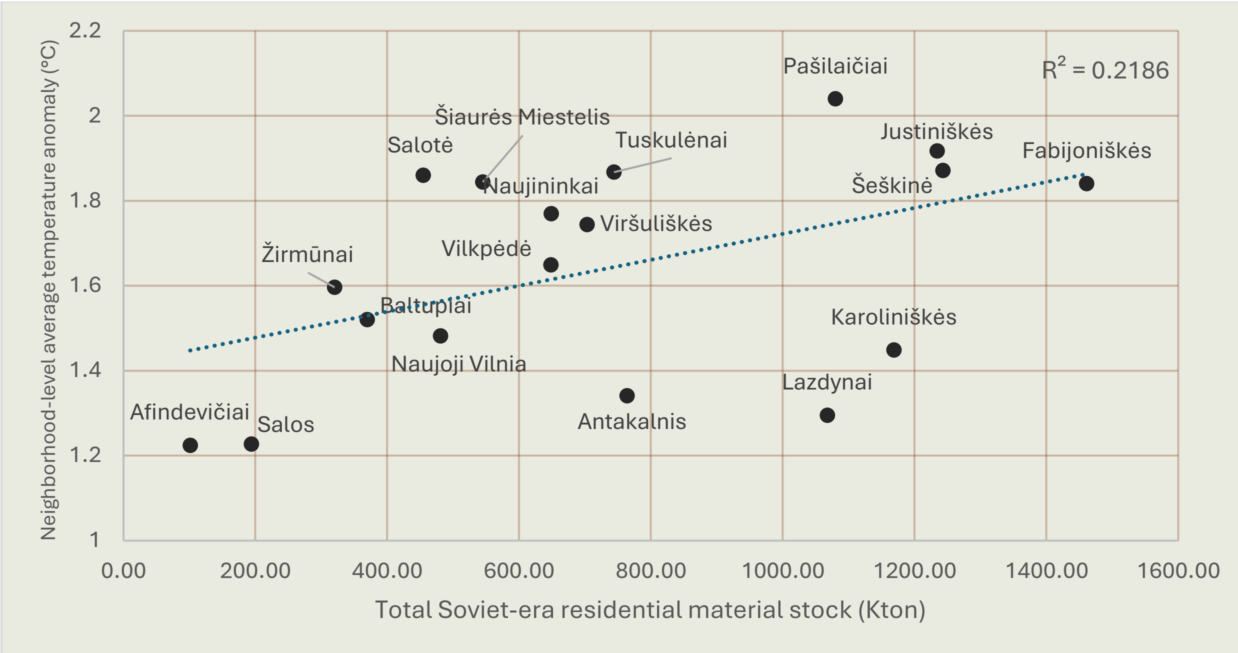

Figure 4.12 shows a box plot of neighborhood-level cooling effect distribution (°C) by the dominant type of Soviet-era residential building type within the neighborhood. Results indicate that brick-dominant neighborhoods perform better in terms of cooling than mixed or RC-dominant neighborhoods, with a symmetrical distribution among scores. The scores for both the mixed and RC-dominant neighborhoods are negatively skewed. The RC-dominant neighborhoods on average perform the worst; however, for this cohort the variance is big, as it contains both the best- and worst-performing neighborhoods.

- Brick-dominant neighborhoods provide better cooling than mixed or RC-dominant areas.
- RC-dominant neighborhoods perform worst on average, but show high variability

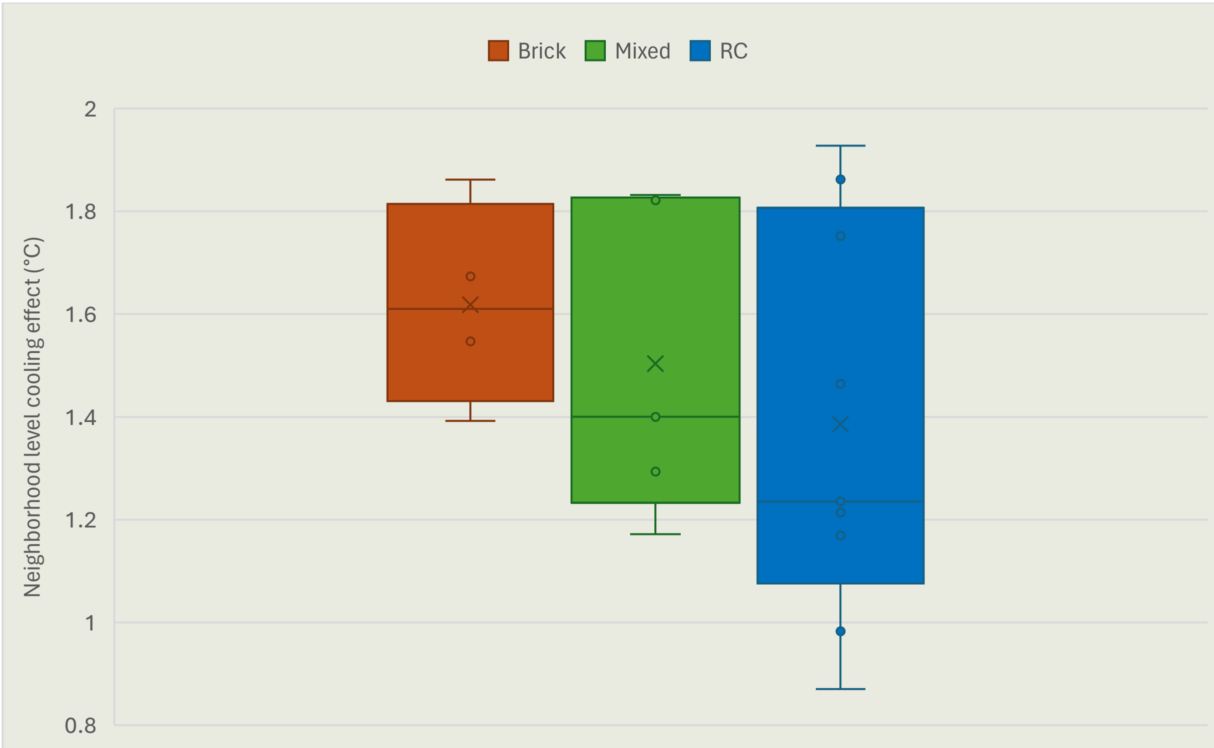

Figure 4.12 Box plot of neighborhood level cooling effect (°C) distribution within neighborhoods of different dominant building typology

A further analysis combining material stock per capita with cooling effect (°C) across Soviet-era neighborhoods (Figure 4.13), provides a resident-focused perspective, highlighting areas where individuals are surrounded by greater quantities of built mass and, simultaneously, where local green infrastructure delivers more or less thermal relief. Neighborhoods in the top left quadrant (Naujoji Vilnia, Salos, Afindevičiai and Naujininkai) combine a strong cooling effect and low stock per capita - being materially efficient and ecologically strong, they are low-priority zones from both a climate adaptation and urban mining perspective.

Neighborhoods in the top right quadrant combine high stock per capita and strong cooling effects. Three clusters are observed: 1) Lazdynai and Karoliniškės with a very strong cooling effect and an average stock per capita; 2) Baltupiai and Antakalnis, with very strong cooling effects and high stock per capita; and 3) Viršuliškės, Žirmūnai, Vilkpėdė, Tuskulėnai, that score slightly above average on both metrics. The former two present a case of strong existing GUI performance, where maintenance of existing GUI is more important than expansion. Cluster 2 of Antakalnis and Baltupiai, due to the high material footprint, could be part of the priority zones for urban mining considerations, especially Antakalnis due to the rapidly aging stock (median year of construction being 1966).

Lower-left quadrant contains only one neighborhood - Šiaurės Miestelis, marked by poor urban cooling performance and relatively low per capita stock. Urban greening initiatives are needed here to improve ecological resilience. While individual material burden is not high, due to the early median construction year (same as Antakalnis, 1966), it necessitates attention for sustainable renovation measures. Neighborhood in the lower-right quadrant emerge as priority zones for targeted interventions, as residents in these areas live in material-intensive environments with limited capacity for heat mitigation. GUI expansions and improvements are required here. Further, these neighborhoods are dominated by RC-types of fairly recent construction (median between 1981 and 1993), implying that they are high-priority zones for future urban mining considerations due to their substantial material footprint and the eventual large-scale release of recoverable structural materials at end-of-life.

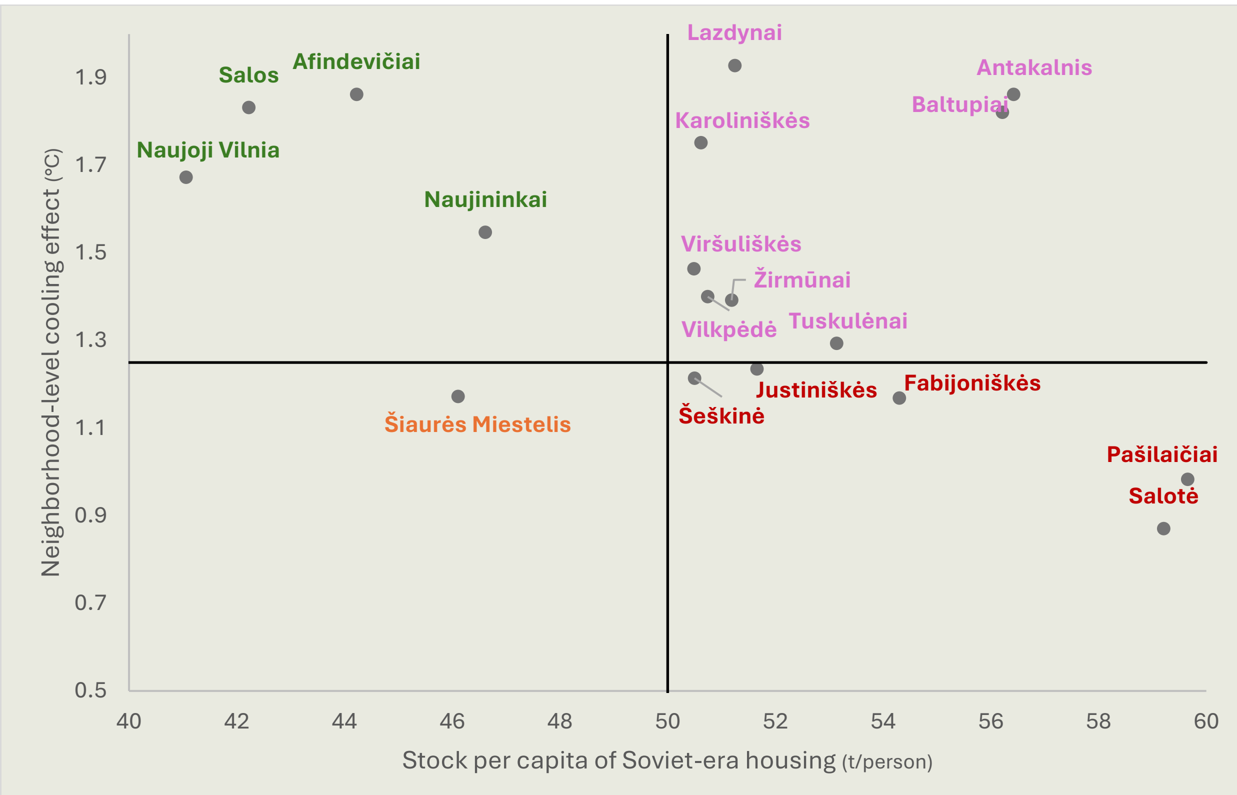

Figure 4.13 Quadrant map of neighborhood level cooling effect (°C) and stock per capita of Soviet-era housing (t/person)

5. Discussion

5.1 Neighborhood clusters

The combined analysis of building typology, material stock and urban cooling performance reveals distinct spatial patterns that correspond to characteristic Soviet-era neighborhood types in Vilnius. While the quadrant chart in section 4.4 isolates these along two axes (material stock per capita vs. cooling performance), the clusters also differ in age profile, structural composition, and socio-environmental vulnerability.

5.1.1 Large stock / poor cooling – heat-stressed, materially-dense peripheries

Fabijoniškės, Šeškinė, Justiniškės, Pašilaičiai and Salotė share a common late-Soviet morphology: dense RC construction from the 1981–1994 period, with minimal internal tree cover (4-29%) and large, contiguous impervious surfaces (58-80%). This combination yields some of the largest material stocks in the city (~5.5 Mton total), while their low HMI (0.27-0.39) and high modeled temperature anomalies (1.84-2.04 °C) signal acute cooling deficits. The productivity loss model confirms the human impact: Pašilaičiai shows an average heavy-work output reduction of ~49%, among the highest in the sample, while the others range from ~30-35%. Urban cooling findings are in line with previous research, identifying some of these neighborhoods as ecosystem service cold spots (Misiūnė & Veteikis, 2020; Misiūnė et al., 2021, 2022; Kalinauskas et al., 2023; Dabašinskas & Sujetovienė, 2024).

Fabijoniškės, while benefitting from the presence of adjacent large parks along its eastern edge, has sparse internal tree cover (24%). This is particularly concerning given its demographic weight: with nearly 30,000 residents, it is the most populous Soviet-era neighborhood in Vilnius. Approximately 90% of its population lives in Soviet-era apartment blocks, which are typically thermally inefficient and ill-equipped to cope with heat stress. Thus, the lack of effective internal GUI significantly amplifies residents' exposure to thermal discomfort during heatwaves. Pašilaičiai, the second-most populous among the Soviet-era neighborhoods with 27,736 inhabitants, combines extensive built-up areas (60%) with minimal GUI (20% of tree cover & 16% grassland) and no surrounding forest, leaving a large population exposed to elevated urban heat. Meanwhile, Salotė is notable as it was constructed in the 1990s and early 2000s – technically beyond the Soviet period – representing a continuation of outdated planning principles in the absence of a strong post-Soviet urban development vision. The result is a neighborhood that is heavily built-up (80%) and poorly integrated with surrounding ecological assets.

These areas offer the most potential for large-scale future material recovery (given the sheer mass of embedded RC and other structural building materials) but also face urgent climate-adaptation needs. Their younger building stock implies later availability for demolition, yet interim retrofits and major green-infrastructure upgrades could mitigate thermal exposure until recovery or deep retrofitting becomes viable.

5.1.2 Strong cooling / small stock – green-buffered low-density districts

Neighborhoods such as Afindevičiai, Salos, Naujoji Vilnia, and Naujininkai have modest total material stocks (~1.4 Mton total) and strong neighborhood-level cooling performance (1.55-1.86 °C) due to adjacency to extensive forests and high internal tree cover (46-50%). Their ecological setting provides natural thermal regulation and high HMI scores (0.48-0.58), resulting in low heavy work productivity losses (~25%) during heatwave conditions. However, buildings here are generally of poorer quality, these neighborhoods have the lowest social status in the city, and they are among the least attractive segments of the housing market (Burneika et al., 2019) - factors that contrast sharply with their ecological strengths. Building periods here are more varied, with Naujininkai, Salos and Naujoji Vilnia constructed around 1972-1979 and Afindevičiai during a later period (median construction year 1989). Typologies are mixed: Naujininkai and Naujoji Vilnia are brick-dominant, Salos combines low-rise RC with early-period brick, and Afindevičiai is dominated by low-rise RC. These neighborhoods have almost no high-rise RC buildings. From a resource perspective, these areas remain less strategic for near-term urban mining due to their modest material stocks. However, their lower building quality, low market attractiveness, and disadvantaged social profile may make them more vulnerable to redevelopment pressures. This heightens the importance of protecting their extensive green buffers during potential redevelopments, which are critical ecological assets.

5.1.3 Large stock / strong cooling – integrated-green mass housing

Lazdynai, Antakalnis, and Baltupiai combine substantial material mass (~2.2 Mton total) with strong cooling performance, exemplifying how dense Soviet-era housing can coexist with effective urban microclimate regulation. Antakalnis and Baltupiai are notable for their high material stock per capita (~56 t/person). Lazdynai also contains a significant portion (13.22%) of the oldest building stock in the city (dating from 1948 to 1960), with this historical construction increasing its importance in regard to material recovery and reuse considerations.

Lazdynai stands out as the clear leader in urban cooling among Soviet-era neighborhoods. Historically celebrated as a model of Soviet urban planning, Lazdynai was purposefully designed to integrate the natural landscape: approximately 63% of its area is covered by tree canopy with minimal built-up surface, benefiting from extensive internal greenery and its location almost entirely encircled by large forested areas. Consequently, Lazdynai achieves the highest HMI (0.6) of any Soviet-era neighborhood studied. Beyond the Soviet-era districts, only neighborhoods within major forested areas or low-density suburban zones with single-family homes and minimal impermeable surfaces outperform Lazdynai in cooling capacity. Examples include Saulėtekis, Gojus, Lazdynėliai, and Markučiai - modern urbanizations that combine proximity to forested land with strong integration of greenery within the urban fabric, achieving cooling benefits greater than 2°C.

Antakalnis similarly balances a substantial Soviet-era reinforced concrete housing stock (~0.76 Mton) with widespread internal tree cover (59%), reinforced by an extensive forested park along its eastern edge, contributing to a strong cooling performance (1.86°C). Baltupiai presents a somewhat different case; despite minimal cooling effects from surrounding forest, it attains a notable cooling effect (1.82°C) through two large internal parks embedded within its residential fabric. Together, these three neighborhoods demonstrate that a heavy material presence can coexist with effective cooling when mature vegetation is preserved and integrated into the urban plan. The material recovery potential in these areas must therefore be carefully weighed against the risk of degrading ecological functions, favoring adaptive reuse and renovation strategies over demolition.

5.1.4 Mixed-performance central and transitional districts

Centras, Naujamiestis, Šnipiškės, Šiaurės Miestelis and Žirmūnai form complex central and near-central mosaics where high building density and intensive land uses elevate local heat burdens, while riverfront corridors and historic green spaces provide partial thermal relief. Of these, only Šiaurės Miestelis and Žirmūnai are Soviet-period neighborhoods and were within the main scope of this study; the others fall outside the core Soviet-era analysis. However, Naujamiestis, despite not being classified as a Soviet-period district, contains the single largest share (36.21%) of oldest-construction-period Soviet-era residential buildings, marking this area as highly relevant for urban mining considerations. Building stocks in these districts are diverse, ranging from early-period brick to mid-century reinforced concrete and later infill, resulting in varied MI profiles and staggered end-of-life timelines. Cooling performance shows a distinct spatial split: river-adjacent residential sectors in Žirmūnai and Šiaurės Miestelis perform relatively well, while inland commercial and industrial zones in both neighborhoods act as UHI hotspots. This spatial juxtaposition creates complex microclimatic conditions that the InVEST model only partially captures. Further study using more advanced temperature modeling, particularly models sensitive to daytime vs nighttime conditions and material-specific heat retention could help clarify the extent to which the current GUI distribution is sufficient to serve residential cooling needs. In line with earlier research identifying them as cold spots for ecosystem service delivery (Misiūnė et al., 2022), the central neighborhoods of Naujamiestis, Centras, and Šnipiškės emerge with weak urban cooling capacity (0.82-1°C). Given their functional importance, heterogeneity, and mixed heritage value, these areas call for targeted, fine-grained interventions - such as green roofs, depaving, and selective tree planting - rather than wholesale demolition or uniform material recovery approaches.

5.2 General material discussion

The majority of structural material stock in Vilnius's Soviet-era residential buildings is concentrated in neighborhoods built from the late 1970s through to 1990s (~73%), which are not expected to reach end-of-life for several more decades. As such, the bulk of this material stock will only become available for urban mining further into the future. Given the scale of this stock within Vilnius's residential fabric, its eventual obsolescence carries significant environmental and policy implications. Proactive end-of-life planning is needed to avoid missed opportunities for circular reuse and to prevent future strain on waste and infrastructure systems.

In contrast, early period buildings (1948-1970) are approaching, or have already surpassed their lifespan. These structures are associated with lower construction quality and have seen minimal renovation investment (as discussed in section 2.3), making them more vulnerable to structural degradation and more likely candidates for demolition or deep retrofit in the near term. This cohort represents approximately 27% of the total Soviet-era residential stock, and is dominated by two types: 68% are early period brick buildings (Z3_MF_004), and 35% are low-rise RC buildings (Z3_MF_005). This cohort is especially important short-term, given the mass of embedded materials and their approaching availability as these buildings near the end of their lifespan.

This study's neighborhood-level approach offers greater spatial precision compared to prior eldership-scale analyses (Dabašinskas & Sujetovienė, 2024; Das et al., 2024; Laurinavičius & Burneika, 2021; Misiūnė et al., 2021), but it also introduces certain trade-offs. For instance, the eldership of Žirmūnai emerges as a material stock hotspot when assessed at the eldership level but appears with diluted visibility when divided into neighborhoods. Neighborhood- and eldership-level results can be compared in Appendix G, highlighting the implications of spatial unit selection for material stock assessments.

In this study, material stock is conceptualized as a future urban mine. While this potential exists citywide, the economic and demographic conditions that influence its feasibility vary. Vilnius has experienced steady population growth over the past decades (Ubarevičienė, 2018), placing pressure on the housing supply and thus incentivizing the extension of service life for aging Soviet-era buildings. Conversely, in other Lithuanian regions facing continued depopulation (Ubarevičienė & Burneika, 2020), the incentive to preserve underused buildings is weaker. In such areas, material recovery through demolition and circular reuse is more feasible. The material stock quantification methodology applied here can therefore serve as a transferable framework for evaluating urban mining potential in other municipalities across Lithuania.

5.3 General urban cooling discussion

The cooling analysis confirms a clear, city-wide pattern: proximity to large forested tracts provides a baseline cooling advantage, but the internal distribution and quality of GUI largely determine neighborhood-level performance. This is supported quantitatively by the very strong positive relationship between tree cover and mean HMI (linear $R^2 = 0.9337$, $p < .001$) This affirms previous research that positions forests as ecosystem service hotspots in Lithuania (Depellegrin et al., 2016; Bernat, 2020; Dabašinskas & Sujetovienė, 2024) but also emphasizes the importance of internal GUI as a key determinant of local cooling delivery. Conversely, poorly performing neighborhoods tend to lack both nearby forest cover and sufficient internal greenery. Finally, several mixed or underperforming cases highlight the importance of nuanced spatial configuration, where even modest but well-placed green spaces can significantly influence outcomes. This points toward the potential for retrofit strategies focused on tree planting, greening commercial zones, and integrating small-scale cooling interventions to bolster overall neighborhood ES delivery.

5.4 Limitations

5.4.1 Material analysis

This study estimates the structural material stock embedded in 3,062 Soviet-era residential buildings, which accounts for approximately 5.24% of the total building stock in Vilnius (58,391 buildings in total). While the analysis focuses on a well-defined and impactful subset - standardized, multi-family residential buildings constructed during the Soviet period - it represents only a small fraction of the city's overall built environment. The total material recovery potential for Vilnius is therefore almost certainly underestimated.

It is important to note that the utilized MIC values represent the state of building construction without renovations. Data of building material intensity changes due to renovations was not available, thus, for the present study, renovation activities are not taken into account. As of the date of this study, 330 multi-apartment buildings in Vilnius have been renovated, thus it can be assumed that for around 10.1% of the buildings in the sample, stock estimations may not be accurate due to renovation activities.

A key limitation lies in the lack of available material intensity (MI) datasets for cross-validation. In the absence of alternative region-specific MI coefficients, the stock estimates presented here rely on literature-derived values. This makes it difficult to perform a formal sensitivity analysis to test how variations in MI inputs might influence the overall stock estimations. In addition, it discounts a certain amount of variance within the building sample: for instance, for reinforced concrete building types, buildings are grouped under the same type regardless of the specific type of wall construction - whether they are monolithic, blocks, slabs or sandwich panels. The lack of certainty regarding the representativeness of utilized MIC values may influence not only embodied material quantities but also the feasibility and yields of demolition-based recovery. Measuring specific local material intensities and developing a more detailed typology remains an important task for future research.

The study also excludes non-residential buildings, which represent a significant portion of the total built environment and are often more likely to be targeted for demolition or redevelopment. These buildings present a largely untapped opportunity for circular material use. However, their inclusion was beyond the scope of this study due to the difficulty in assigning representative MI coefficients to such highly variable and non-standardized structures. Future studies should prioritize this building class to gain a more comprehensive understanding of urban mining potential.

Furthermore, basements and underground structures were not included in the stock calculations, as no reliable data was available regarding their dimensions. Since the dataset accounted only for floors above ground, the total stock values reported here are likely slight underestimations. As an illustration, Table 5.1 presents a summary of total material stock changes if a uniform 1-extra-floor per building was applied as a basement estimation - this results in a change of +16.4% to total stock.

Table 5.1 Total material stock with and without basement stock estimation

	Current stock calculation (Mton)	**With basement estimation (+1 floor per building) (Mton)**	**% stock increase**
Steel	0.82	0.95	16.03%
Concrete	12.96	15.06	16.21%
Brick	1.15	1.37	18.84%
Mortar & plaster	0.75	0.87	16.03%
Plasterboard & gypsum	0.34	0.39	16.66%
Total	16.01	18.64	16.39%

Finally, it is worth noting that this analysis is static and descriptive, capturing the current state of material stock without modeling its dynamic evolution under different demolition, renovation, or densification scenarios. Integrating the temporal dimension and demolition forecasting would add valuable foresight to circular economy strategies in urban planning.

These constraints do not undermine the value of the spatial and typological patterns identified in the selected Soviet-era housing stock. The results can be considered robust in indicating which neighborhoods hold the greatest relative quantities of material, both in total and per capita, and in clarifying the structural types that dominate these patterns. However, the absolute material quantities should be regarded as indicative rather than definitive. Extrapolation to the city scale or the derivation of precise recovery targets would require additional calibration and a broader inclusion of building types and substructures.

5.4.2 Urban cooling

Several limitations of this modelling should be acknowledged. First, the model does not account for wind dynamics, which have been shown to significantly influence heatwave conditions in Vilnius by affecting heat dispersion and microclimatic regulation (Bukantis & Urbanavičiūtė, 2022). Incorporating wind speed and direction could enhance the spatial accuracy of cooling service assessments.

Second, the land use classifications used in the model are relatively coarse and do not distinguish between finer variations in vegetation types. Important ecological differences, such as those between broadleaf, coniferous, and mixed forests are not captured, despite their differing evapotranspiration rates and shading capacities, which likely affect local cooling performance.

Third, this study models daytime heatwave conditions only. The vertical dimension of built infrastructure captured by building intensity is not accounted for here, though it can play a big role in nighttime temperature regulation. Buildings store heat during the day and release it at night, a process particularly relevant during heatwaves. The InVEST model does allow for the inclusion of building intensity data, and future studies should integrate this feature to assess cooling performance during nighttime conditions. This is especially important in light of increasing tropical nights in Vilnius (nights with temperatures above 20 °C), which have major implications for public health and thermal comfort.

In light of these limitations, the modeled Heat Mitigation Index values are best understood as first-order indicators of relative daytime cooling potential. The finding that neighborhoods with extensive canopy cover and proximity to large green areas achieve higher cooling performance is likely to remain valid even with refined modelling. However, the HMI values should not be interpreted as a comprehensive measure of thermal exposure or heat risk. Without integrating nighttime conditions, wind dynamics, and more detailed vegetation classifications, these results are not suitable for direct prediction of health outcomes or for setting precise adaptation targets.

6. Conclusion

6.1 Answers to the research questions

1. What types of residential buildings are found among Vilnius's Soviet-era mass housing stock? What are the material intensities of structural building materials per each type?

Based on typology established by the IMPRO building project (Institute for Prospective Technological Studies (Joint Research Centre), 2008), Soviet-era residential buildings in Vilnius can be categorized into several types, based on the dominant material of the wall construction, their construction period, and number of floors. The types are: (1) Z3_MF_002 - buildings of breeze concrete walls built in the early Soviet period, before and incl. 1960; (2) Z3_MF_005 - buildings of breeze and reinforced concrete walls, constructed after 1960, with 6 or less floors (5 being the standard); (3) Z3_MF_008 - buildings of reinforced concrete walls, constructed after 1960, with 7 or more floors; (4) Z3_MF_004 - brick masonry buildings constructed before and incl. 1980; and (5) Z3_MF_007_ex - brick masonry buildings constructed after 1980. The material intensities per type are summarized in Appendix C.

2. What is the total quantity of structural material stock embedded in Soviet-era residential buildings in Vilnius?

The total quantity of structural building materials in Soviet-era mass housing is 16.01 Mton, composed of 12.96 Mton of concrete, 1.15 Mton of bricks, 0.82 Mton of steel, 0.75 Mton of mortar / plaster, and 0.34 Mton of plasterboard & gypsum.

3. How is this material stock spatially distributed: what materials are present, where, and in what quantities?

Materials are dispersed mostly throughout the Soviet-era neighborhoods, with some buildings also within the central districts (Centras, Naujamiestis, Žvėrynas) - although these do not represent large quantities.

Particularly high concentrations of materials - hotspots - are identified in Fabijoniškės, Šeškinė, Pašilaičiai and Justiniškės. Brick concentrations follow a different spatial pattern than total material stock, with hotspots in Naujininkai and Naujoji Vilnia.

4.How effective is GUI in Soviet-era neighborhoods in providing urban cooling and heatwave mitigation?

For Soviet-era neighborhoods, HMI ranges from 0.28 to 0.6, translated to actual cooling effect this ranges from 0.87 to 1.92 °C. Some neighborhoods benefit mostly from proximity to large forest areas, while others have integrated greenery throughout the neighborhood and derive cooling benefits from this. Neighborhoods with the strongest cooling effects are Lazdynai, Antakalnis, Afindevičiai, Salos and Baltupiai - these neighborhoods experience cooling of 1.8°C and above. Neighborhoods with the weakest urban cooling service delivery are Salotė, Pašilaičiai, Fabijoniškės, Šiaurės Miestelis, Šeškinė and Justiniškės - these neighborhoods have less than 30% tree cover and a temperature anomaly of 1.8-2.0°C, necessitating interventions to improve existing green areas for increased urban cooling delivery.

5. What insights emerge from the combined analysis of material stock and green infrastructure performance? How can they support more informed policymaking regarding end-of-life planning or retrofitting of Soviet-era districts?

The combined analysis reveals trade-offs between built mass and green infrastructure, highlighting how these elements interact to shape urban thermal conditions. Soviet-era districts with the highest material stock, such as Fabijoniškės, Šeškinė, and Pašilaičiai underperform in urban cooling due to high built density and limited vegetation. In contrast, greener and less materially intensive neighborhoods like Afindevičiai, Salos, and Antakalnis deliver significantly better cooling outcomes. These findings can directly inform policy decisions around end-of-life planning and retrofitting. Neighborhoods with aging building stock from 1948–1970 and poor cooling performance present strategic opportunities for targeted material recovery combined with greening interventions. At the same time, areas like Lazdynai and Antakalnis, which combine older buildings with effective ecological performance, require a more cautious approach, potentially favoring renovation and preservation over demolition, to avoid undermining existing cooling capacities. Thus, policy makers and urban planners can utilize neighborhood-level insights for a mindful future development of these districts based on the specific challenges faced by each.

6.2 Reflections and Recommendations

This study set out to better understand the environmental implications and spatial dynamics of Vilnius's Soviet-era residential fabric by integrating material stock quantification with urban cooling analysis. While section 6.1 has addressed the empirical outcomes in direct response to the research questions, this section reflects on their broader significance, the methodological choices underpinning the analysis, and the potential implications for future research and policy.

6.2.1 Contribution to academic knowledge

This research makes several contributions to the field of Industrial Ecology (IE), particularly in the domains of urban material stock analysis and ecosystem service assessment. First, it addresses a significant empirical gap in the growing body of work on urban material stock accounting. While many recent studies have quantified the built environment of cities in Western Europe (Gontia et al., 2018), North America (Marcellus-Zamora et al., 2016), or East Asia (Guo et al., 2019), post-Soviet countries remain underrepresented. With the focus on Vilnius, this study is the first comprehensive material stock quantification of Soviet-era housing in a post-Soviet Baltic city, contributing novel data and spatial insights on a typology of mass housing that has so far received limited attention in IE literature. Second, the integration of material stock analysis with ecosystem service modelling – specifically the assessment of urban cooling using the InVEST urban cooling model – offers a multidisciplinary approach that aligns with current efforts in IE to understand urban systems as coupled socio-ecological-material metabolisms (Baccini & Brunner, 2012). The integration of these two approaches allows for the identification of spatial correlations and trade-offs between material intensity and green infrastructure function. Finally, the study contributes to addressing regional blind spots in peer-reviewed environmental research. As Hussein et al. (2023) note, Eastern European countries remain on the margins of green infrastructure literature, despite having substantial empirical knowledge on topics like allotment gardens and urban greening. By applying ecosystem service models in this underrepresented context, this study helps bring Eastern European urban experiences into broader scholarly conversations on climate adaptation and urban sustainability.

6.2.2 Contribution to sustainable urbanism goals of Vilnius

As the city faces the dual challenge of aging Soviet-era housing and rising urban temperatures, there is an urgent need for spatially resolved data to guide long-term planning. This study offers a baseline for understanding the location, quantity, and composition of material stocks embedded in the residential built environment. Such information is needed for end-of-life planning, including decisions about demolition, renovation, and circular material reuse - areas that are currently underdeveloped in local policy frameworks (Kliučinskaitė, 2025). In parallel, the assessment of green infrastructure effectiveness in mitigating urban heat offers valuable input for climate adaptation strategies. Heatwaves are becoming more frequent and intense in Vilnius (Ramanauskas et al., 2024), and it is important to identify which neighborhoods are most vulnerable. By identifying spatial patterns in cooling provision, this research supports evidence-based decisions on where to enhance, preserve, or reconfigure urban green space, particularly in the context of proposed densification or redevelopment initiatives in Soviet-era districts.

Together, these findings can inform more integrated, sustainable urban strategies that align with both climate resilience and circular economy goals, offering a roadmap for how Vilnius can manage its Soviet-era legacy in light of 21st century challenges.

6.2.3 Methodological reflections

The study's neighborhood-scale approach marks a methodological difference from previous assessments conducted at broader administrative levels, such as elderships. This finer granularity reveals local disparities in both material concentration and green infrastructure performance that would otherwise remain obscured. It enables more targeted spatial diagnostics and can serve as a replicable model for similar analyses in other Lithuanian and Baltic cities. However, as discussed, this approach also introduces certain trade-offs like masking cumulative effects observable at higher scales. Such is the case of Žirmūnai, which loses visibility as a material hotspot when divided into three subunits. This suggests that future studies may benefit from multi-scalar frameworks that allow toggling between different levels of case granularity.

In terms of urban cooling assessment, the use of the InVEST model provided a valuable baseline for similar specific ES assessment in Lithuania which supplements the existing research base of examining ES as compound indicator. Although, its limitations point to directions for further refinement. Integrating remote sensing with on-the-ground thermal measurements, or coupling cooling analysis with vulnerability indices, could significantly enhance the precision and policy relevance of future research.

6.2.4 Recommendations for practice and future research

The combined material and urban cooling analysis of this study points to specific intervention pathways for Vilnius's Soviet-era housing districts related to improving their environmental performance and circular potential:

1. Align material recovery with ecological retrofitting.
In neighborhoods where the earliest reinforced concrete and brick stock (1948–1970) is approaching obsolescence and urban cooling performance is weak - such as Tuskulėnai, Naujamiestis, and parts of Šnipiškės - material recovery should be paired with significant ecological upgrading. The results indicate that these districts combine aging, material-heavy stock with low canopy cover and fragmented green space, making them vulnerable to intensifying urban heat island (UHI) effects. Here, demolition or deep energy retrofits should proceed together with green infrastructure measures, such as park creation, shade tree planting, and permeable surface conversion, to ensure that circular economy goals do

not exacerbate climate risk.

2. Preserve ecological function in well-performing districts.
Neighborhoods like Lazdynai, Antakalnis and Baltupiai demonstrate that large Soviet-era housing stocks can coexist with strong cooling performance when mature vegetation and surrounding forest edges are maintained. Given their high HMI values and relatively high material stock per capita (particularly in Antakalnis and Baltupiai), the policy priority should be to prolong the lifespan of existing buildings through careful renovation and selective infill, while safeguarding internal greenery. Wholesale redevelopment or aggressive densification in these districts would risk undermining ecological functions that have already been proven to buffer extreme heat.

3. Focus greening efforts where population exposure is greatest.
Densely populated districts with weak internal green infrastructure, particularly Fabijoniškės, Pašilaičiai, Justiniškės and Šeškinė should be prioritized for greening initiatives to reduce human exposure to heat stress. Targeted interventions might include street tree corridors along main pedestrian routes, green roofs and walls on large-panel buildings, depaving and shading of surface parking, and better connectivity between isolated green patches. Linking these measures with Vilnius's existing rich natural framework would enhance both immediate thermal relief and long-term ecological resilience.

4. Institutionalize neighborhood-scale diagnostics in municipal planning.
The study's neighborhood-level approach revealed patterns - such as the high per-capita stock in Salotė and the concentration of early RC buildings in Lazdynai - that would be invisible in aggregated city-wide metrics. Municipal planning should therefore adopt neighborhood-scale diagnostics that integrate building age and typology, estimated material stock, tree canopy cover, and modeled cooling performance into spatial planning workflows. This would enable early identification of areas with high demolition risk, material recovery potential, or heat exposure, and support the tailoring of interventions to local conditions.

5. Strengthen interdisciplinary urban sustainability research.
By combining material flow analysis with urban cooling modeling, this study demonstrated that environmental performance and circularity potential can be assessed in an integrated way. Future research should refine such interdisciplinary models to include dynamic time horizons for material release, ecological performance under both daytime and nighttime heat events, and socio-economic factors such as demographic change and housing

demand. This would enhance the capacity of urban planning to manage the built environment as both a material reservoir and a climate-regulating system.

6. Develop a Baltic-specific building typology and material intensity database.
The accuracy of material stock estimates remains constrained by reliance on generalized EU-wide MI values. Developing a harmonized Baltic typology and empirically measured MI dataset would allow for finer differentiation between construction methods (e.g., monolithic vs. sandwich-panel RC walls) and better capture local material compositions. This is particularly relevant for Vilnius, where significant intra-type variation exists within the Soviet-era housing stock, influencing both the feasibility of selective demolition and the economics of material recovery.

7. Treat cooling performance as a primary planning metric, not just a co-benefit.
The results confirm that neighborhoods with strong cooling capacity - whether from contiguous forest edges, as in Antakalnis, or well-distributed internal parks, as in Baltupiai - experience significant modeled temperature reductions during heatwaves. Cooling performance should therefore be explicitly integrated into zoning, building permitting, and renovation incentive schemes, rather than treated as a secondary benefit of greenery. With climate projections indicating more frequent tropical nights in Vilnius, HMI values and modeled thermal impacts can serve as measurable targets for adaptation planning.

8. Plan for material stock as a long-term urban resource.
Most structural material in Vilnius's Soviet-era housing will remain in place for decades, with large-scale release unlikely before the late 21st century. Nevertheless, the scale of this latent resource warrants long-term planning. Measures such as creating material passports for large buildings, establishing selective demolition protocols, and mapping potential future recovery clusters would ensure that when end-of-life does occur, materials are retained in the economy rather than lost to landfill.

9. Tailor strategies to demographic and market contexts.
Vilnius, unlike many other Lithuanian municipalities, is experiencing steady population growth. In this context, preserving structurally sound Soviet-era stock and focusing on ecological retrofitting may be preferable to demolition, even where buildings are materially rich. Conversely, in shrinking municipalities, strategic deconstruction could unlock material recovery without compromising housing needs. National policy frameworks should therefore allow municipalities to calibrate circular economy and adaptation strategies to their demographic realities.

In summary, the legacy of Soviet-era mass housing is neither uniformly problematic nor easily resolved. By applying a spatially integrated, cross-disciplinary lens, this research contributes to a more differentiated and constructive understanding of how to adapt and transform these districts for a sustainable urban future.

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Appendix A. Vilnius neighborhoods list

Table A.1 Vilnius neighborhoods list

ID	Name
1	Antaviliai
2	Platiniškės
3	Kriaučiūnai
4	Zujūnai
5	Buivydiškės
6	Plytinė
7	Gudeliai
8	Padekaniškės
9	Varnė
10	Pilaitė
11	Salotė
12	Justiniškės
13	Viršuliškės
14	Saltoniškės
15	Šeškinė
16	Fabijoniškės
17	Žvėrynas
18	Karoliniškės
19	Šeškinės Kalnas
20	Pašilaičiai
21	Bajorai
22	Pavilionys
23	Tarandė
24	Gineitiškės
25	Vanaginė
26	Skersinė
27	Santariškės
28	Verkiai
29	Baltupiai
30	Didieji Gulbinai
31	Mažieji Gulbinai
32	Bireliai
33	Ustronė
34	Šilinė
35	Sakališkės
36	Pagubė
37	Naujaneriai
38	Krakiškės
39	Žalieji Ežerai
40	Kryžiokai
41	Verkių Riešė
42	Ožkiniai
43	Ežerėliai
44	Staviškės
45	Šiaurinės Turniškės
46	Krempliai
47	Senamiestis
48	Centras
49	Šiaurės Miestelis
50	Lazdynėliai
51	Šaltūnai
52	Miškiniai
53	Lazdynai
54	Jankiškės

ID	Name
55	Naujamiestis
56	Kauno Vokė
57	Afindevičiai
58	Neravai
59	Gariūnai
60	Jočionys
61	Kadriškės
62	Mačiuliškės
63	Kulokiškės
64	Bališkės
65	Vaidotai
66	Gureliai
67	Račkūnai
68	Vaidegiai
69	Dobrovolė
70	Trakų Vokė
71	Daniliškės
72	Guobos
73	Pagiriai
74	Degeniai
75	Kazbėjai
76	Liudvinavas
77	Daškūnai
78	Popinė
79	Vaidotų Terminalas
80	Užusienis
81	Aukštieji Paneriai
82	Žemieji Paneriai
83	Ąžuolijai
84	Kuprijoniškės
85	Pietinės Rokantiškės
86	Žaliakalnis
87	Aukštasis Pavilnys
88	Ivaniškės
89	Egliškės
90	Grigaičiai
91	Karklėnai
92	Žvirbliai
93	Verbos
94	Naujoji Vilnia
95	Galgiai
96	Mažieji Pupojai
97	Didieji Pupojai
98	Dvarčionys
99	Pylimėliai
100	Mileišiškės
101	Gelvadiškės
102	Smėlynė
103	Gvazdikai
104	Baniškės
105	Vismaliukai
106	Žemoji Veržuva
107	Aukštoji Veržuva
108	Šilai

ID	Name
109	Aukštieji Karačiūnai
110	Žemieji Karačiūnai
111	Vilkpėdė
112	Oro uostas
113	Kučkuriškės
114	Belmontas
115	Turniškės
116	Valakupiai
117	Kirtimai
118	Riovonys
119	Vingio Parkas
120	Panerių Kalvos
121	Burbiškės
122	Naujininkai
123	Raisteliai
124	Markučiai
125	Rasos
126	Liepkalnis
127	Ribiškės
128	Žemasis Pavilnys
129	Gojus
130	Šiaurinės Rokantiškės
131	Pučkoriai
132	Saulėtekis
133	Antakalnis
134	Sapieginė
135	Kairėnai
136	Aukštagiris
137	Vyriai
138	Tapeliai
139	Meiriškės
140	Salos
141	Grigiškės
142	Kelmija
143	Salininkai
145	Smalinė
146	Kalnėnai
147	Nemėžis
148	Strielčiukai
149	Sodeliai
150	Tuskulėnai
151	Žirmūnai
152	Trinapolis
153	Kalvarijos
154	Ozas
155	Visoriai
156	Jeruzalė
157	Rukeliškės
158	Šnipiškės
159	Balsiai
160	Babiniai
161	Lyglaukiai
162	Vikingai
163	Tuputiškės
164	Liepynė

Appendix B. Python script for building matching

Python script for matching polygons to neighboring ones to obtain missing materials data

```
import pandas as pd import numpy as np from sklearn.neighbors import NearestNeighbors

df = pd.read_excel('Buildings_PP_TableToExcel.xlsx')

# Defining the material fields

material_fields = [ 'pamatai_12', 'sienos_12', 'stogo_konstrukcija_12', 'stogo_danga_12',
'perdanga_12', 'isores_apdaila_12', 'vidaus_apdaila_12', 'pertvaros_12', 'grindys_12',
'langai_12', 'durys_12' ]

# Finding rows where any material field is missing

missing_material = df[df[material_fields].isnull().any(axis=1)]

# Finding rows where all material fields are present

valid_material = df[df[material_fields].notnull().all(axis=1)]

# Setting up Nearest Neighbors to find the closest buildings by X, Y coordinates

neighbors = NearestNeighbors(n_neighbors=5,
algorithm='ball_tree').fit(valid_material[['X_Coord', 'Y_Coord']])

# Finding the nearest neighbors for each building with missing material data

distances, indices = neighbors.kneighbors(missing_material[['X_Coord', 'Y_Coord']])

# Function to select the best match based on floor count or construction year

def find_best_match(missing_row, candidates): for idx in candidates: candidate =
valid_material.iloc[idx] if (candidate['Polyg_MAX_AUKSTIS_12'] ==
missing_row['Polyg_MAX_AUKSTIS_12']) or

(candidate['Polyg_STATMETAI_12'] == missing_row['Polyg_STATMETAI_12']): return
candidate return None

# Loop over each material field and fill missing data

for material_field in material_fields: filled_materials = []

# Fix to ensure we are not out of bounds
for i in range(len(missing_material)):
   missing_row = missing_material.iloc[i]
```

```
    candidates = indices[i]  # get neighbors for current row
    match = find_best_match(missing_row, candidates)
    if match is not None:
        filled_materials.append(match[material_field])
    else:
        filled_materials.append(None)

# Updating the missing material field with the filled values
missing_material[material_field] = filled_materials


# Updating the main DataFrame with the filled material data

df.update(missing_material)

df.to_excel('Buildings_PP_filled_with_materials.xlsx', index=False)
```

Appendix C. MI values

Table C.1 Absolute MI (kg/m2) values per building type and construction material

Type	Alias	Steel MI	Concrete MI	Mortar / plaster MI	Plasterboard & gypsum MI	Brick MI
Z3_MF_002	RC_early	59.7975	1063.17125	69.24479	30.625	
Z3_MF_005	RC_lowrise	79.26938	1302.293125	53.90625	30.625	
Z3_MF_008	RC_highrise	83.82179	1265.463929	73.32589	27.25	
Z3_MF_004	brick_early	59.7975	962.39	69.24479	30.625	268.75
Z3_MF_007_ex	brick_late	36.76625	641.67125	69.24479	30.625	339.84375

Appendix D. Biophysical table

Table D.1 Biophysical table for urban cooling model data inputs & descriptions

LU code	Land use	Description	KC *Evapotranspiration coefficient values for crops.* Values based on Bosch et al. (2020)	Green area *Boolean 0/1*	Shade *The proportion of area in this LULC class that is covered by tree canopy at least 2 meters high.*	Albedo *The proportion of solar radiation that is directly reflected by this LULC class.*
10	Tree cover	This class includes any geographic area dominated by trees with a cover of 10% or more. Other land cover classes (shrubs and/or herbs in the understorey, built-up, permanent water bodies, ...) can be present below the canopy, even with a density higher than trees.	1	1	0.8 to balance out: scattered tree cover in between buildings can be sparse, but concentrated plots are 100%.	0.15 Based on Stewart & Oke (2012) supplementary material: 0,10-.0.20 range for dense trees
20	Shrubland	This class includes any geographic area dominated by natural shrubs having a cover of 10% or more. Shrubs are defined as woody perennial plants with persistent and woody stems and without any defined main stem being less than 5 m tall. Trees can be present in scattered form if their cover is less than 10%. Herbaceous plants can also be present at any density.	0.8	1	0	0.22 Based on Stewart & Oke (2012) supplementary material: 0.15-0.30 range for bush, scrub
30	Grassland	This class includes any geographic area dominated by natural herbaceous plants (Plants without persistent stem or shoots above ground and lacking definite firm structure): (grasslands, prairies, steppes, savannahs, pastures) with a	0.75	1	0	0.2 Based on Stewart & Oke (2012) supplementary material: 0.15-0.25 range for low plants

		cover of 10% or more, irrespective of different human and/or animal activities, such as: grazing, selective fire management etc. Woody plants (trees and/or shrubs) can be present assuming their cover is less than 10%. It may also contain uncultivated cropland areas (without harvest/ bare soil period) in the reference year.				
40	Cropland	Land covered with annual cropland that is sowed/planted and harvestable at least once within the 12 months after the sowing/planting date. The annual cropland produces an herbaceous cover and is sometimes combined with some tree or woody vegetation.	0.73	1	0	0.2 Based on Stewart & Oke (2012) supplementary material: 0.15-0.25 range for low plants
50	Built-up	Land covered by buildings, roads and other man-made structures such as railroads. Buildings include both residential and industrial building. Urban green (parks, sport facilities) is not included in this class.	0.75	0	0	0.19 Based on Stewart & Oke (2012) supplementary material: 0.12-0.25 range for open mid rise/open high rise
60	Bare / sparse vegetation	Lands with exposed soil, sand, or rocks and never has more than 10 % vegetated cover during any time of the year	0.68	0	0	0.22 Based on Stewart & Oke (2012) supplementary material: 0.15-0.30 range for bare rock / paved
80	Permanent water bodies	This class includes any geographic area covered for most of the year (more than 9 months) by water bodies: lakes, reservoirs, and rivers.	0.75	1	0	0.06 Based on Stewart & Oke (2012) supplementary material: 0.02-0.10 range for water
90	Herbaceous wetland	Land dominated by natural herbaceous vegetation (cover of 10% or more) that is permanently or	0.73	1	0	0.22

		regularly flooded by fresh, brackish or salt water. It excludes unvegetated sediment (see 60), swamp forests (classified as tree cover) and mangroves see 95)				Based on Stewart & Oke (2012) supplementary material: 0.15-0.30 range for bush, scrub

Appendix E. Python script for urban cooling model inputs calculation

Python script used for calculation of the reference air temperature and the average relative humidity

import requests from datetime import datetime, timedelta import pandas as pd

Configuration

station_code = "vilniaus-ams" years = [2020, 2021, 2022, 2023, 2024] summer_months = [6, 7, 8] heatwave_threshold = 30 # °C local_offset_hours = 3 # Lithuania summer time (UTC+3)

Functions

def get_observations(date_str): url = f"https://api.meteo.lt/v1/stations/{station_code}/observations/{date_str}" try: response = requests.get(url) response.raise_for_status() return response.json().get("observations", []) except requests.RequestException: print(f" Failed to fetch data for {date_str}") return []

def is_heatwave_day(observations): temps = [obs["airTemperature"] for obs in observations if obs["airTemperature"] is not None] return max(temps) > heatwave_threshold if temps else False

def extract_daytime_data(observations): daytime_temps = [] daytime_rh = [] for obs in observations: time_utc = datetime.fromisoformat(obs["observationTimeUtc"].replace("Z", "+00:00")) local_hour = (time_utc.hour + local_offset_hours) % 24 if 9 <= local_hour <= 21: # Local 09:00–21:00 if obs.get("airTemperature") is not None: daytime_temps.append(obs["airTemperature"]) if obs.get("relativeHumidity") is not None: daytime_rh.append(obs["relativeHumidity"]) return daytime_temps, daytime_rh

Main script

results = []

for year in years: for month in summer_months: for day in range(1, 32): # Loop over all possible days try: date = datetime(year, month, day) date_str = date.strftime("%Y-%m-%d") observations = get_observations(date_str)

```
    if not observations:
        continue
```

```
            if is_heatwave_day(observations):
                temps, rhs = extract_daytime_data(observations)
                if temps and rhs:
                    results.append({
                        "date": date_str,
                        "avg_daytime_temp": sum(temps) / len(temps),
                        "avg_daytime_rh": sum(rhs) / len(rhs)
                    })
                    print(f" Heatwave day: {date_str} — Avg Temp: {sum(temps)/len(temps):.2f}°C,
Avg RH: {sum(rhs)/len(rhs):.2f}%")
        except ValueError:
            continue  # Skip invalid dates
```

Results summary

df = pd.DataFrame(results) if not df.empty: overall_temp = df["avg_daytime_temp"].mean() overall_rh = df["avg_daytime_rh"].mean() print(f"\n Summary:") print(f"Total heatwave days: {len(df)}") print(f"Average daytime temperature on heatwave days: {overall_temp:.2f}°C") print(f"Average daytime relative humidity on heatwave days: {overall_rh:.2f}%") else: print("No heatwave days found in the specified period.")

Appendix F. Kc sensitivity analysis

Table F.1 Kc sensitivity analysis – differing Kc inputs per run

LU code	**Land use**	**Run_1** Kc based on **Bosch** et al. (2020)	**Run_2** Kc based on **Zawadska** et al.(2021)	**Run_3** Kc based on **Hamel** et al. (2024)	**Run_4** Kc based on **Pohanková & Pechanec** (2024)	**Run_5** Kc based on **Zepp** et al., (2023)
10	Tree cover	1	0.98 (average of broadleaf and coniferous for unspecified tree cover)	0.83	0.682	1.3
20	Shrubland	0.8	0.95	0.83	0.719	1
30	Grassland	0.75	0.95	0.83	0.619	1
40	Cropland	0.73	0.95	0.2	0.477	1.3
50	Built-up	0.75	0.001	0.35	0.56	0
60	Bare / sparse vegetation	0.68	0.001	0.83	0.001 (borrowed from Zawadska et al., (2021) due to lack of matching LU category)	0
80	Permanent water bodies	0.75	0.6525	0.83	0.6525 (borrowed from Zawadska et al., (2021) due to lack of matching LU category)	0.9
90	Herbaceous wetland	0.73	0.95	0.83	0.95 (borrowed from Zawadska et al., (2021) due to lack of matching LU category)	1

Table F.2 Kc sensitivity analysis – differing key outputs per run

ID	Neighborhood name	Mean HMI					Mean temperature anomaly				
		Run_1	**Run_2**	**Run_3**	**Run_4**	**Run_5**	**Run_1**	**Run_2**	**Run_3**	**Run_4**	**Run_5**
53	Lazdynai	0.601411793	0.599285485	0.574131544	0.548652999	0.652050881	1.299473299	1.305442627	1.385123407	1.466508147	1.138340298
57	Afindevičiai	0.583340672	0.583242217	0.558218973	0.532737654	0.633296522	1.226581521	1.229383726	1.313318873	1.396997852	1.059866612
29	Baltupiai	0.57004802	0.568068685	0.543779774	0.519449044	0.61865272	1.519499942	1.525145252	1.597349872	1.669245912	1.376424197
133	Antakalnis	0.581537659	0.578589639	0.555064817	0.530893616	0.629728872	1.343219795	1.355779162	1.431052489	1.505957469	1.193268315
140	Salos	0.572762407	0.572485051	0.548138267	0.523366582	0.621475918	1.229528424	1.233739688	1.316145826	1.398716239	1.064844807
18	Karoliniškės	0.547148881	0.545911733	0.522408546	0.498643209	0.594242455	1.450534571	1.454108409	1.529366811	1.605868919	1.299361911
94	Naujoji Vilnia	0.521851014	0.522860905	0.499038537	0.476047674	0.567830809	1.485740497	1.478575639	1.561644081	1.63775803	1.329840712
122	Naujininkai	0.482204737	0.481752201	0.460457648	0.439399051	0.524105312	1.77154205	1.77909648	1.84460511	1.904440967	1.653408203
13	Viršuliškės	0.45784724	0.458560188	0.437522018	0.416746665	0.498980963	1.742034218	1.738934295	1.806390856	1.873274781	1.609763883
111	Vilkpėdė	0.437056446	0.436208158	0.417849572	0.398124601	0.475192763	1.650428695	1.659175985	1.723896373	1.790319306	1.521865964
151	Žirmūnai	0.434063682	0.430283777	0.412410881	0.394719442	0.468575708	1.600306631	1.618474894	1.683927553	1.745068598	1.478283025
12	Justiniškės	0.386551176	0.389919868	0.370155229	0.35101996	0.424368677	1.91586766	1.905626876	1.97058636	2.03331659	1.791021666

150	Tuskulėnai	0.405752805	0.404333936	0.3877201	0.369744916	0.440733743	1.863947416	1.879997383	1.934448463	1.990001843	1.761401625
15	Šeškinė	0.379701596	0.380957291	0.362913308	0.345319234	0.414844307	1.868301989	1.866462906	1.928230757	1.98885008	1.747927811
16	Fabijoniškės	0.366675192	0.367826432	0.350602748	0.333589167	0.400214109	1.837797008	1.834749543	1.898659233	1.960427213	1.71405068
20	Pašilaičiai	0.309621445	0.31465008	0.296562488	0.280649672	0.342930582	2.036149793	2.02289056	2.08611602	2.143666834	1.918030494
11	Salotė	0.27295045	0.279662053	0.263053	0.246907394	0.304870636	1.861110255	1.845804195	1.915806614	1.983655239	1.726118901
49	Šiaurės Miestelis	0.367037267	0.352682207	0.338712914	0.330593277	0.383920885	1.843447772	1.869426702	1.923952803	1.970772139	1.751338808

Appendix G. Material stock breakdown

Table G.1 Total material stock (in t) per neighborhood for each structural building material, ranked from largest total stock to smallest

ID	Neighborhood	Steel	Concrete	Brick	Mortar / plaster	Plasterboard & gypsum	Total
16	Fabijoniškės	82544.01	1278224.72	3847.69	68083.98	28475.07	1461175.48
15	Šeškinė	69280.48	1090687.89	3875.68	54627.50	24748.67	1243220.22
12	Justiniškės	69455.12	1085001.31	0.00	55430.17	24255.12	1234141.72
18	Karoliniškės	65753.55	1027463.74	0.00	52434.06	22975.65	1168627.00
20	Pašilaičiai	61228.55	941085.94	4953.98	51842.60	20887.92	1079998.99
53	Lazdynai	59219.41	942272.74	0.00	44750.34	21470.30	1067712.79
133	Antakalnis	33150.07	537689.48	138192.73	37672.35	17044.62	763749.25
55	Naujamiestis	35120.05	572425.61	91021.04	36083.00	16579.84	751229.55
150	Tuskulėnai	35924.31	567481.59	88740.33	36274.94	15634.71	744055.88
13	Viršuliškės	38350.71	599430.64	18013.55	33195.19	14186.64	703176.73
122	Naujininkai	26754.91	435651.09	137910.82	33680.15	14895.77	648892.75
111	Vilkpėdė	33613.75	544862.15	29168.55	27229.15	13625.58	648499.19
49	Šiaurės Miestelis	25424.01	407854.25	74006.26	26006.41	11745.05	545035.99
94	Naujoji Vilnia	19805.45	323654.65	100511.37	25458.21	11226.87	480656.55
11	Salotė	25738.21	399366.97	0.00	20936.60	8863.86	454905.64
29	Baltupiai	16836.07	271721.57	53141.45	19632.19	8505.65	369836.94
151	Žirmūnai	14418.50	231466.33	51351.21	15951.19	7039.79	320227.02
158	Šnipiškės	15093.80	246531.14	30285.18	13996.22	6862.64	312768.97
47	Senamiestis	9886.69	160757.65	44368.99	11652.17	5241.02	231906.51
140	Salos	9735.30	159342.60	12843.76	8032.62	4160.20	194114.48
156	Jeruzalė	6829.31	112942.99	36362.32	9670.32	4200.94	170005.88
17	Žvėrynas	6096.53	102037.87	37586.63	8756.75	3919.93	158397.71
82	Žemieji Paneriai	6485.27	106988.46	6532.33	5224.63	2790.45	128021.14
48	Centras	5174.07	83394.90	20752.47	5939.80	2612.86	117874.10

129	Gojus	4407.97	72425.99	21114.76	5446.45	2467.46	105862.63
57	Afindevičiai	5166.78	85046.88	4497.63	4148.11	2198.05	101057.44
52	Miškiniai	4279.61	69279.70	10738.13	4196.63	1969.11	90463.18
143	Salininkai	3072.52	51121.70	19653.70	4450.70	1968.42	80267.05
132	Saulėtekis	4014.24	60769.82	750.68	3558.89	1336.25	70429.87
125	Rasos	2804.17	45756.71	12020.60	3260.26	1483.78	65325.51
99	Pylimėliai	2262.53	37296.71	13255.70	3091.53	1367.30	57273.77
152	Trinapolis	2079.04	33460.34	9343.89	2407.50	1064.77	48355.54
27	Santariškės	1668.96	28572.21	13484.15	2846.56	1258.95	47830.83
124	Markučiai	1907.41	31683.99	9724.90	2469.23	1126.73	46912.26
14	Saltoniškės	1594.54	25892.84	7970.53	1969.29	870.96	38298.15
134	Sapieginė	1401.00	23205.54	5993.41	1671.84	778.72	33050.51
98	Dvarčionys	1203.91	20040.58	7734.22	1749.01	773.54	31501.26
155	Visoriai	1285.90	20846.95	1209.00	1092.19	536.23	24970.27
70	Trakų Vokė	1161.51	19154.34	1517.22	975.05	511.53	23319.65
81	Aukštieji Paneriai	941.40	15447.45	3926.26	1092.95	503.64	21911.71
153	Kalvarijos	705.81	11393.01	3289.85	835.30	369.43	16593.40
116	Valakupiai	695.82	11198.65	3127.25	805.75	356.36	16183.84
161	Lyglaukiai	398.44	6953.92	3682.96	750.42	331.89	12117.63
112	Oro Uostas	464.72	7646.42	2672.81	627.37	277.47	11688.79
50	Lazdynėliai	339.62	5737.95	2477.56	538.56	238.19	9331.88
46	Krempliai	287.44	4853.43	2086.65	454.25	200.90	7882.67
86	Žaliakalnis	315.61	5153.35	1676.51	404.89	179.07	7729.43
91	Karklėnai	211.50	3691.30	1955.00	398.34	176.17	6432.32
1	Antaviliai	288.20	4734.70	0.00	195.98	111.34	5330.22
138	Tapeliai	253.95	4515.15	0.00	294.07	130.06	5193.24
92	Žvirbliai	164.72	2874.77	1522.54	310.23	137.20	5009.46
9	Varnė	231.39	3801.37	0.00	157.35	89.39	4279.50
28	Verkiai	139.42	2243.79	626.58	161.44	71.40	3242.64

141	Grigiškės	155.04	2547.10	0.00	105.43	59.90	2867.47
105	Vismaliukai	90.52	1579.78	836.69	170.48	75.40	2752.87
159	Balsiai	122.28	2008.92	0.00	83.16	47.24	2261.59
54	Jankiškės	81.71	1314.99	367.21	94.61	41.85	1900.36
87	Aukštasis Pavilnys	61.37	1036.16	445.17	96.93	42.87	1682.50
162	Vikingai	49.51	864.15	457.68	93.25	41.24	1505.84
65	Vaidotai	75.84	1245.87	0.00	51.57	29.30	1402.58
76	Liudvinavas	56.99	917.16	256.12	65.99	29.19	1325.44
73	Pagiriai	39.83	695.14	368.16	75.02	33.18	1211.33
100	Mileišiškės	27.12	473.24	250.64	51.07	22.59	824.65
42	Ožkiniai	30.91	507.81	0.00	21.02	11.94	571.68
56	Kauno Vokė	15.37	268.19	142.04	28.94	12.80	467.35
136	Aukštagiris	0.00	0.00	0.00	0.00	0.00	0.00
135	Kairėnai	0.00	0.00	0.00	0.00	0.00	0.00
84	Kuprijoniškės	0.00	0.00	0.00	0.00	0.00	0.00
96	Mažieji Pupojai	0.00	0.00	0.00	0.00	0.00	0.00
106	Žemoji Veržuva	0.00	0.00	0.00	0.00	0.00	0.00

Table G.2 Total material stock (in t) per eldership for each structural building material, ranked from largest total stock to smallest

Eldership	Steel	Concrete	Brick	Mortar / plaster	Plasterboard & gypsum	Total
Žirmūnai	75766.8189	1206802.177	214097.7983	78232.54231	34419.55668	1609318.893
Fabijoniškės	84056.815	1301762.007	5056.690228	69482.2095	29051.25544	1489408.978
Šeškinė	74258.20634	1171189.681	21889.22381	60836.06724	27391.69268	1355564.871
Justiniškės	69455.12493	1085001.307	0	55430.17186	24255.11607	1234141.72
Karoliniškės	66320.83653	1036783.599	0	52819.84046	23194.82262	1179119.099
Lazdynai	63271.3488	1007970.529	13215.69793	49099.74719	23458.43745	1157015.761
Pašilaičiai	61228.55413	941085.9414	4953.982106	51842.595	20887.91771	1079998.99
Antakalnis	44552.92699	720885.2226	175598.1987	50716.15682	22669.34672	1014421.852

Vilkpėdė	40180.73127	653165.5961	36068.1014	32548.39677	16457.86964	778420.6952
Naujamiestis	35120.05366	572425.6066	91021.04369	36083.00164	16579.84005	751229.5456
Naujininkai	30341.66635	495283.3717	160695.0008	38851.48529	17182.90587	742354.43
Verkiai	28472.32783	465013.7353	118334.8952	35805.70719	15691.27632	663317.9419
Viršuliškės	33372.97669	518928.851	0	26986.62458	11543.61976	590832.0721
Naujoji Vilnia	20558.65794	336410.2181	106110.589	26668.59996	11762.19211	501510.2571
Pilaitė	25969.59509	403168.3364	0	21093.94979	8953.256293	459185.1376
Šnipiškės	20267.86473	329926.0352	51037.65485	19936.01799	9475.498111	430643.0709
Grigiškės	15072.4904	247204.7712	17483.43203	12315.09859	6430.950316	298506.7425
Senamiestis	9886.690342	160757.6494	44368.98821	11652.16953	5241.015421	231906.5129
Rasos	8352.426918	137439.0254	41086.33522	10471.17995	4736.682001	202085.6495
Žvėrynas	7691.071668	127930.7061	45557.15514	10726.04034	4790.886287	196695.8595
Paneriai	2275.569707	37459.97123	6067.759679	2260.577152	1106.82489	49170.70266