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UNIVERSIDADE D
COIMBRA

João Pedro Medina Monteiro

FORM AND FUNCTION
BENCHMARKING REAL AND IDEAL CITIES
VOLUME 1

PhD Thesis in Doctoral Program in Spatial Planning, supervised by Professor João Manuel Coutinho Rodrigues, Professor Nuno Miguel Marques de Sousa, and Professor Eduardo Manuel Ferreira Almeida da Natividade de Jesus, submitted to the Department of Civil Engineering of the Faculty of Science and Technology of the University of Coimbra.

December 2023

Faculty of Sciences and Technology, University of Coimbra
Department of Civil Engineering

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Fundação
para a Ciência
e a Tecnologia

By far the greatest and most admirable form of wisdom is that needed to plan and beautiful cities and human communities.

Σωκράτης (Socrates) [1]

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To my grandparents that taught me how the world works and how I should behave in it. I am what I am today also because of you. Avó Alice, demorou, mas o teu neto é doutor!

Thank you for all your unconditional love.

Resumo

As cidades são sistemas complexos, com um crescimento exponencial de concentração de população, de criação de riqueza e de interações sociais e económicas. Contudo, também é nas cidades que um grande parte da energia global é consumida e da poluição é gerada. O desenvolvimento de uma cidade deve, assim, ter em consideração questões de sustentabilidade, resiliência e equidade, tendo como principal objetivo a qualidade de vida dos seus habitantes. Este desenvolvimento está diretamente relacionado com a sua forma, isto é, com as suas características físicas, a sua dimensão, a estrutura das redes de transporte, o uso do solo e configuração espacial, mas também com a sua função: a forma como a sociedade está estruturada e organizada, o que incluiu, as características sociais e económicas e todas as atividades que ocorrem no espaço da cidade. A forma e a função das cidades são, por isso, conceitos essenciais na definição da cidade, e deverão possibilitar uma tomada de decisão consciente sobre a evolução do espaço urbano.

A presente investigação tem como objetivo contribuir para o desenvolvimento de indicadores e metodologias de análise quantitativa do desempenho da forma e função das cidades, analisando e comparando cidades reais e modelos de cidades ideais que influenciaram o planeamento urbano no último século. De facto, são vários os modelos de cidade que têm vindo a ser utilizados e sujeitos a debate, em parte ou na íntegra por todo o mundo. Contudo, e tanto quanto é do conhecimento do autor, nunca foram desenvolvidas análises de desempenho quantitativas que possibilitem uma avaliação e comparação formal e objetiva entre cidades reais e as várias formas e funções preconizadas pelos diferentes modelos de cidades. Esta tese resume a investigação efetuada pelo candidato no sentido de colmatar essa lacuna da literatura.

Uma análise de desempenho de natureza quantitativa requer o desenvolvimento de indicadores adequados a serem usados na avaliação. Nesse sentido, foram concebidos seis indicadores baseados em características espaciais urbanas: acessibilidade, repartição modal dos transportes ativos, consumo de energia dos transportes, permeabilidade da rede, uso misto do solo e agradabilidade. Para cada um destes indicadores foi efetuada, de forma quantitativa, a análise do desempenho entre uma cidade real (Coimbra, Portugal) e seis reconfigurações espaciais desta, baseadas em cinco modelos de cidade ideal e uma estratégia particular de (re)planeamento urbano (o infill).

Por último, foi efetuada uma análise multicritério agregadora, com o objetivo de comparar o desempenho da cidade real e das suas seis reconfigurações, tendo por base os seis indicadores. Foi usado um Sistema de Informação Geográfica (SIG) para armazenar, gerir e representar espacialmente toda a informação, bem como para a implementação de capacidades analíticas adaptadas às necessidades da análise e representação dos resultados desta.

Os resultados, fornecendo respostas objetivas e quantificáveis, são esclarecedores sobre o desempenho de cada uma das formas urbanas testadas, apontando para uma maior eficiência dos modelos mais compactos. Pretende-se contribuir para o desenvolvimento de diretrizes, estratégias e políticas de planeamento urbano que possam ser aplicadas diretamente em áreas urbanas atuais no contexto de programas de expansão, ou de ações de regeneração urbana, e que conduzam ao desenvolvimento de cidades mais sustentáveis, resilientes e equitativas.

O trabalho apresentado está dividido em dois volumes: o volume I possui um total de dez capítulos, dos quais oito correspondem a artigos científicos já publicados (seis) ou submetidos (dois) a revistas internacionais ISI/WoS. O volume II contém todo o material suplementar relevante.

Palavras-chave: Desenho urbano, acessibilidade, análise comparada, SIG – Sistemas de Informação Geográfica

ODS: 10 – Reduzir as Desigualdades; 11 – Cidades e Comunidades Sustentáveis

Abstract

Cities are complex systems, places of increasing population concentration, wealth generation, and social and economic interactions. However, cities are also places where large amounts of energy are consumed and pollution is produced. The development and evolution of a city must consider issues of sustainability, resiliency, and equity, prioritizing the quality of life of its residents. This development is directly related to its form, i.e., its physical characteristics such as size, transportation network's structure, land use, spatial arrangement, and its function, related to society, including social and economic factors and all activities that take place in its space. The form and function of cities are essential concepts for defining a city and should enable a conscious decision-making process about the evolution of its urban space.

This research aims to contribute to the development of indicators and methodologies to quantitatively gauge the performance of the form and function of cities, analyzing and comparing real cities and concepts of ideal cities that have influenced urban planning in the last century. Different concepts of cities have been developed and put into practice, in part or in their entirety, in cities around the world. However, to the best of the author's knowledge, there are no quantitative analyses on the comparison of the various forms and functions presented by different concepts of cities and real cities. This thesis summarizes the research carried out by the candidate to fill that literature gap.

A quantitative benchmark requires developing indicators that can be used in this analysis. Six were developed, based on spatial characteristics, and selected for the purpose of this thesis: accessibility, active modal share, transport energy consumption, route directness, mixed land use, and pleasantness. For each indicator, a quantitative analysis of the performance of a real city (Coimbra, Portugal) was carried out and compared to spatial reconfigurations of Coimbra according to five ideal city concepts and an urban planning strategy (the infill).

Finally, a multicriteria analysis was conducted to compare the performance of the real city and the six city layouts based on the six developed indicators. A Geographic Information System (GIS) was used for storing, managing, and spatially represent information, as well as for the implemention of analytical capabilities tailored to the analysis' needs.

The results, providing objective and quantifiable answers, are enlightening about the performance attributable to each of the tested urban forms, and suggest that the more compact forms have an efficiency edge over the other layouts. The aim of the results is to contribute towards guidelines, urban planning strategies, and policies that can be directly applied in current urban areas. Results can be taken into consideration in the context of expansion programs, urban regeneration projects, and, in general, for the adaptation of urban planning policies and strategies to make cities more sustainable, resilient, and equitable.

The presented work is divided into two volumes: Volume I has a total of ten chapters, eight of which correspond to scientific papers already published or submitted to ISI/WoS international journals. Volume II contains all relevant supplementary material.

Keywords: Urban design, accessibility, comparative analysis, GIS – Geographic Information System

UN SDG: 10 - Reduced Inequalities; 11 - Sustainable Cities and Communities

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1. INTRODUCTION

"On a planet with vast amounts of space we choose cities."

Edward Glaeser [2]

1.1. Research framework

Cities have survived and triumphed over centuries. From wars, plagues, industrialization, overcrowding and financial crisis, adverse and prosperous eras scarred cities worldwide. Cities may have the ability to be at the same time, the best and the worst place to live in. Cities provide better housing standards, multiple job opportunities, more social interactions, better education and higher health standards [3]. They are universally seen as places where the path from poverty to prosperity is the shortest. But if over the past centuries cities have won, often citizens seem to lose [2].

Cities and human conglomerations have had many guises. Cities tend to improvise, adapt, and overcome adversities towards resiliency, reinventing and redesigning themselves. Small and narrow cobble stone streets filled with houses that were ideal to travel when walking or riding animals were the only transport modes. Hilly cities, on top of the hills protected with ramparts and castles from an era when wars were mostly fought within an arms-length. Big industrial buildings surrounded by long and wide roads, prepared for high traffic volumes of people and goods. The contrast between densely populated areas with residential skyscrapers housing hundreds of residents or sparsely populated outskirts with single-family houses with big lawns and big driveways. Cities have in fact improvised, adapted, and overcome adversities, however, not always in a planned way.

Over time, the role of city planners and designers has been to remain aware that cities must not only solve the problems of today, but also the problems of tomorrow, as Ebenezer Howard, Le Corbusier, Kevin Lynch and Jane Jacobs underline in their lives' works [4–7]. The concept of sustainability has become one of the main goals on an ever changing and evolving society, that has cities as their core and prime habitat.

Cities are growing [8], with currently 56% of world's population living in urban areas and an expected 70% by 2050 [8,9]. Cities contribute to local and global economies, generating over 80% of the world's wealth, while consuming 60-80% of all the energy produced on the planet and emitting 75% of carbon emissions [9,10].

Cities grow, but so do the challenges they face. As of 2023, in just a few years, the world has seen a global pandemic, a war in Europe and in the Middle East, and a continuous increase in pollution and greenhouse gas (GHG) emissions.

In an ever-changing world, this thesis analyzes the way cities are and how they could evolve in a quest for sustainability and livability, by developing and building a set of analytical tools that enable decision makers and stakeholders to objectively compare different urban development scenarios and find the best solutions.

"Some people say it will be very expensive. The vast majority of our recommendations are peanuts. What is really costly is the big infrastructures we've made for cars. That costs a lot of money. But even if there are costs, I would argue it is loss of money not to do something." - Jan Gehl

1.2. Research objetives

"Designing a dream city is easy; rebuilding a living one takes imagination."

Jane Jacobs [11]

From Ebenezer Howard, with the Garden City concept, and Le Corbusier, with *La Ville Radieuse,* to more recent concepts such as Transect Planning, Transit-Oriented Development (TOD) or the 15-Min City [4,5,12–14], over the last century different city concepts and theoretical proposals have been crafted with the goal of improving overall quality of life. These concepts differ in their genesis, as many of the first presented concepts focused on a specific urban design with clear measurements and land-use allocations, while later ones revolved more around principles and policy implementation. Classic city concepts, such as the Garden City, *Ville Radieuse*, or even the Linear City, have all been used as frameworks, or base ideas for more modern concepts.

Because there is neither quantitative nor empirical evidence on how those ideal concepts would perform, the modern concepts sip from what are essentially qualitative arguments, shedding doubt as how the latter concepts would themselves perform. Taking advantage of computing capabilities, it is now possible to benchmark and compare the different concepts with each other, with the aim of understanding the pros and cons of each concept and learn how they can be used to improve cities.

Three main objectives are defined for this thesis:

1. The first objective is the creation and development of quantitative indicators that separately, or via multicriteria analysis, can be applied to benchmark existing and conceptual cities. Six quantitative indicators – accessibility, active modal share, transport energy consumption, route directness, mix land use and perceived neighborhood pleasantness were developed.

These indicators do not take into consideration any subjective evaluation and are based purely on geometric and land use elements of the urban form. The indicators require solely data that should be readily available in municipal or national databases and their associated calculations require software and computer capabilities that municipal authorities should have on demand. For some indicators a deeper mathematical, urban and transport planning knowledge might be required for interpreting the results, as well as knowledge regarding local context, that should also exist in the municipal workforce.

Results are conveniently depicted in maps in order to convey the useful information to decision makers and all stakeholders, with possible integration on collaborative planning strategies, a growing tendency in spatial planning in recent years. Most importantly, all the geometric and land-use characteristics that are being considered and evaluated can be intervened and improved by municipal authorities, by enforcing new policies, new planning strategies or updating municipal master plans.

Thus, the methodology was developed towards the possibility of a dynamic environment, to test possible changes and their impact, and the potential of future interventions in the urban form.

2. The second objective is the practical application of the same indicators to benchmark real and ideal cities, analyzing and comparing different city concepts and planning practices.

This will be pursued by redrafting a real city (Coimbra, Portugal), according to different city concepts, based on their original drawings and guidelines, respecting as much as possible the real-world data, and to compare all the outputs with each other, based on the indicators developed for this purpose. The results of this thesis may lead to the emergence of more questions, such as: is it possible for one of the concepts to outperform other concepts in all criteria? If not, is it possible to reconcile the different advantages and best qualities of each concept?

3. The third, and last, main objective is the creation of a multicriteria comparative analysis – CSCI: Combined Spatial City Index – that aggregates in a single, quantitative number the compromise between the all global indicator scores for an urban layout.

This multicriteria methodology (MCM) is directed at policymakers, as it is capable of providing quantitative results that can be used to analyze and compare the different urban planning solutions. TOPSIS, a multicriteria ranking method whose output is a quantitative figure, was selected as the multicriteria method for implementing the CSCI.

The methodology developed contributes to the literature on city model benchmarking by providing a means to carry out comprehensive comparative analyses between real and ideal cities based on quantitative indicators, which depend solely on the urban spatial layout.

In general, the goal of this thesis is to provide additional knowledge and tools to quantitatively analyze, compare, and benchmark different cities concepts and layouts. Since all kinds of models can be compared, it will be possible to gauge whether it is still worth looking at ideal city concepts for ideas and inspiration or if they are just part of history. As far as the author is aware, other quantitative comparisons between different city concepts based on their urban form and resorting to objective indicators do not exist in the literature. This research fills that gap by proposing both a methodology and by carrying out an extensive benchmarking study on the best-known city concepts.

It has been an especially complex and demanding research, with multiple analyzes in areas of knowledge that are underdeveloped, making it clear that this was not an easy task, which furthermore does not end with the delivery of this thesis, as it opens new research avenues and yields questions to be answered. Regardless, the work carried out, the results obtained, and the recognition it already gathered from peers from the scientific community allow to conclude that the project was successful in developing an innovative process which contributes to answer old and new questions in the field of spatial planning and, more specifically, in the areas of urban design and sustainability.

1.3. Outline

This is thesis is divided into two volumes. Volume I, the main body of the thesis with ten chapters, is organized as a collection of scientific papers (chapters 2 to 9), allowing the reader to both read in succession or each one independently and is the main body of the thesis. Volume II is reserved for the supplementary materials. A small description of chapters contents is presented, as well as a graphical structure (see Figure 1.1).

Chapter 1 (this chapter) is the thesis introduction, where initial considerations are presented, along with motivation and research objectives, outline, and research dissemination.

Chapter 2 provides a comprehensive literature review on the challenges ahead on sustainable cities, based on their spatial and transport planning situation and its effect on energy consumption and efficiency. Energy concerns, that directly connect to GHG emissions and pollution, are a fundamental topic of research and practical application on cities towards their sustainable future.

Chapter 3 also provides a comprehensive literature review, in this case on planning cities for pandemics. During this research the world literally came to a halt due to a worldwide pandemic. The COVID-19 pandemic brought new challenges to the way cities are viewed and planned and this chapter provides a review of urban and transport planning lessons from the COVID-19 pandemic [15].

Chapter 4 presents the first quantitative indicator and city concept under analysis. It presents the first steps in the research and provides a methodological approach and an accessibility comparison between the real city of Coimbra, Portugal, and its redraft as the Garden City of Ebenezer Howard [16].

Chapter 5 deepened the research on quantitative citywide indicators. Following the work developed on chapter 4 with the introduction of the accessibility indicator, two new indicators are developed: active modal share and transport energy consumption indicators. The indicators are used to evaluate the potential of cycling in the city of Coimbra, Portugal [17].

Chapter 6, now with the previous three indicators at our disposal, analyzes and compares a real city with its infill redraft (designated as "Infill Coimbra"), a layout of the city achieved by filling in the available urban spaces with new residential buildings, facilities and jobs located on the outskirts of the city, in full compliance with the Municipal Master Plan. An analysis towards the attainability of the 15-Minute City concept in Coimbra and its infill redraft is also discussed [18].

Chapter 7 presents a new methodology aimed at quantifying the perceived pleasantness of urban neighborhoods. This new quantitative indicator measures the impact of geometric and land-use elements on the perceived pleasantness of urban layouts [19] and complements the previous, accessibility-oriented ones.

Chapter 8 continues the work developed on chapter 7 by applying the pleasantness indicator to two cities: Coimbra, Portugal and Belo-Horizonte, Brazil. This chapter provides a first quantitative answer to whether people live in more pleasantness neighborhoods by correlating the perceived pleasantness with socioeconomic variables [20].

Chapter 9 completes the three main objectives of the thesis: first, the previous four quantitative indicators, described in chapters 4 to 8, are complemented with two new indicators: route directness and mix land use. Then, all the indicators are considered simultaneously, as urban attributes, in a multicriteria analysis. The aim is to benchmark the form and function of seven city layouts, corresponding to (i) a real city (Coimbra, Portugal), (ii) its Infill version, and its five redrafts as ideal city concepts existing in the literature: (iii) Garden City, (iv) *Ville Radieuse*, (v) Compact City Theory, (vi) Transit-Oriented Development, (vii) Transect Planning.

Finally, Chapter 10 summarizes and presents the general conclusions, future work and new research avenues that emerged from the work presented in the thesis.

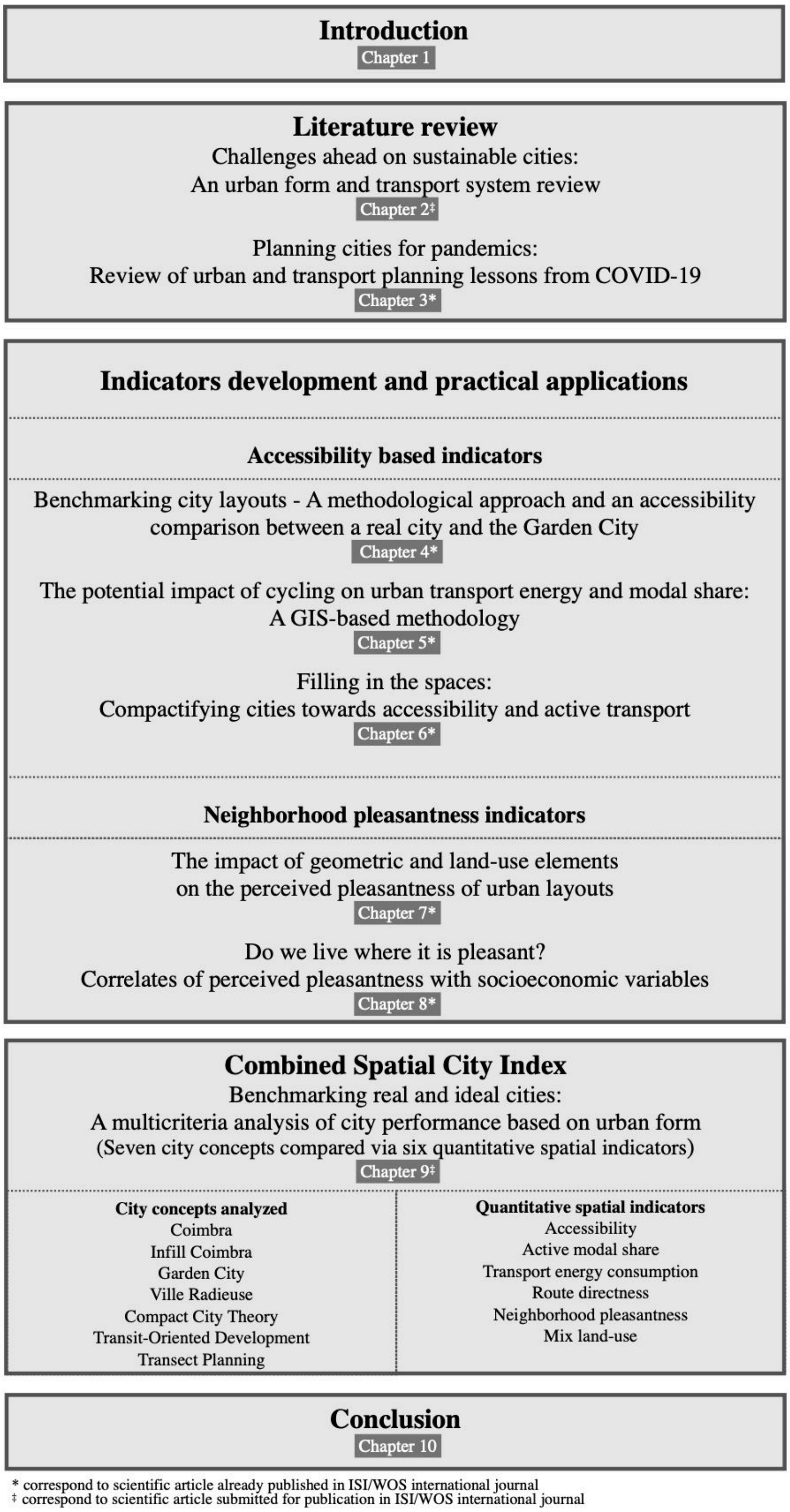

Figure 1.1. Thesis graphical structure.

Most chapters have already been submitted, gone through peer-review process, and are now published in different international scientific journals all part of the ISI/WoS ranks (see 1.4. Research dissemination for publication details). For this reason, there are some repetitions throughout the thesis that could not be avoided. Chapters have mostly not been altered in any aspect which may also lead to some notation differences between chapters.

Please note that maps are extremely important to convey the data used and results obtained in the several instances that form this thesis. Different journals, editors, and reviewers input result in heterogenous maps layouts. A map representing the same results might have different geographic and color scales, as each scale has been adapted to the context of each paper. As previously mentioned, there will be maps repetitions throughout the thesis that could not be avoided.

1.4. Research dissemination

The work comprising this thesis has been validated and disseminated according to the articles that are integral part of this thesis, as presented in Table 1.1.

Table 1.1. Chapters and articles correspondence.

Chapter	Article
2	Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. **Challenges ahead on sustainable cities: An urban form and transport system review**. Submitted for publication
3	Monteiro, J., Sousa, N., Pais, F., Coutinho-Rodrigues, J., Natividade- Jesus, E. (2023). **Planning cities for pandemics: A review of urban and transport planning lessons from COVID-19**, *Municipal Engineer – Proceedings of the Institution of Civil Engineers*, 0(0), https://doi.org/10.1680/jmuen.22.00030
4	Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. **Benchmarking City Layouts—A methodological approach and an accessibility comparison between a real city and the Garden City**. *Sustainability* **2022**, 14, 5029. https://doi.org/10.3390/su14095029 **Editor's Choice*

Chapter	Article
5	Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. **The potential impact of cycling on urban transport energy and modal share: A GIS-based methodology**. *ISPRS Int. J. Geo-Inf.* **2023**, 12, 48. https://doi.org/10.3390/ijgi12020048
6	Monteiro, J.; Para, M.; Sousa, N.; Natividade-Jesus, E.; Ostorero, C.; Coutinho-Rodrigues, J. **Filling in the spaces: Compactifying cities towards accessibility and active transport**. *ISPRS Int. J. Geo-Inf.* **2023**, 12, 120. https://doi.org/10.3390/ijgi12030120
7	Sousa, N.; Monteiro, J.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. **The impact of geometric and land use elements on the perceived pleasantness of urban layouts**. *Environment and Planning B: Urban Analytics and City Science* **2022**, 50, 3. https://doi.org/10.1177/23998083221129879
8	Monteiro J, Carrilho AC, Sousa N, Oliveira LKd, Natividade-Jesus E, Coutinho-Rodrigues J. (2023). **Do We Live Where It Is Pleasant? Correlates of Perceived Pleasantness with Socioeconomic Variables**, *Land*, 12(4):878. https://doi.org/10.3390/land12040878
9	Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. **Form and function: Benchmarking real and ideal cities - A multicriteria analysis of city performance based on urban form**. Submitted for publication

The research has also been discussed in conferences and lectures that have contributed for its dissemination among professionals, researchers, students, and the general public. In particularly, four students in the field of Civil Engineering from different institutions (Universidade de Coimbra, Politenico di Torino, Universidade Federal de Minas Gerais and Instituto Superior de Engenharia de Coimbra) profited from this research, as well as the data collected, having tested the methodologies in particular contexts and study cases.

Conferences:

- CEES-2023 – International Conference on Construction, Energy Environment & Sustainability, Funchal, 27-30 June, 2023.
- openDEC – Civil Engineering and Sustainable Cities, Instituto Superior de Engenharia de Coimbra, Portugal, 2022, 2021, 2020 editions.

Lectures:

- Title: **Form & Function: Benchmarking real and ideal Cities**; Graduate studies: Doctoral Program in Sustainable Energy Systems; Course: Energy and Transport, Institution: University of Coimbra, Portugal, 2020, 2021 and 2022;
- Title: **Benchmarking City Layouts—A methodological approach;** Graduate studies: Master's in Civil Engineering; Branch: Urban, Transport and Road Planning; Courses: Regional and Urban Planning, Public Facilities Planning; Institution: University of Coimbra, Portugal, 2021, 2022 and 2023;
- Title: **The potential impact of cycling on urban transport energy and modal share;** Graduate studies: Master's in Sustainable and Smart Cities; Course: Smart Systems for Cities; Sustainable and Intelligent Cities, Instituto Superior de Engenharia de Coimbra, Portugal, 2020, 2021, 2022 and 2023;
- Title: **The potential impact of cycling on urban transport energy and modal share;** Graduate studies: Master's in Civil Engineering; Course: Urban Regeneration and Sustainability Sustainable and Intelligent Cities; Instituto Superior de Engenharia de Coimbra, Portugal, 2020 and 2021.

Posters:

- Planeamento Territorial, Ambiental e Cidades Sustentáveis, Investigação na Universidade de Coimbra, Portugal, May, 2022

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2. Challenges ahead on sustainable cities: An urban form and transport system review

"The opportunities of the twenty-first century make those of us who care about cities feel like kids in a candy store: How will cities survive and lead the way in the transformation required to combat global warming? Resilient cities gives us a road map for this epic journey upon which we are embarking" – Greg Nickels [21].

This chapter reviews the critical issues surrounding the development of sustainable urban environments, focusing on the impact of urban form and transport systems on energy consumption and GHG emissions. Current research and practices are synthesized, highlighting the interdependence of urban form and transportation systems in achieving sustainability goals. Important dimensions and practices of city planning, and transport policies are explored, including urban form, urban sprawl, mixed land use, densification and infill, urban public spaces, and how all these dimensions directly influence transport dynamics, including modal choices and energy consumption. Innovative approaches in urban planning, such as transit-oriented development (TOD), and technological advancements, such as electric mobility, are also examined, and their potential roles in sustainable urban transport. Furthermore, the review emphasizes the additional challenges and the need for tailor-made policy interventions and collaborative governance, considering the varying contexts of cities in developing countries. The conclusion underscores the urgency of adopting holistic and adaptable strategies to foster sustainable urban environments, calling for concerted efforts from policymakers, urban planners, and communities. Finally, the authors summarize and analyse important directions for future research and practical applications towards developing cities that are not only environmentally sound but also socially equitable and economically viable.

2.1. Introduction

Urban population has been rising for past decades, with currently more than half (55%) of the world population living in cities, a number expected to increase to 68% by 2050 [22–24]. Cities are the main engines of global economic growth, and despite occupying just 3% of the earth's surface [24], they are responsible for more than 75% of a country's gross domestic product [25,26]. Cities consume large quantities of energy and require an interrupted supply, amounting to 78% of global primary energy, consequently totalling 70% of annual global carbon emissions [23–25,27]. Urban transport and buildings encompass most of this energy consumption and carbon emissions [23,28]. In fact, urban transport accounts for 4 billion tonnes of CO_2-eq/year, more than 40% of the transport sector's total emission, while buildings consume more than one-third of the final energy consumption globally and this value is even higher in developed countries (according to the U.S. Energy Information Administration (EIA) in 2023 residential and commercial buildings accounted for 40% of total energy in the United States [29]). It has become essential to optimise resource consumption on cities [30], as cities are often associated with energy inefficiency, misuse of land and non-renewable resources, and air, sound and water pollution [31]. There is a growing mismatch between energy supply and demand in developing countries, as supply remains stable while demands grows 7% annually due to increased population growth, rapid urbanisation, and expanding economies [25], leading to frequent blackouts [32–34]. The relationship between cities and climate is reciprocal [35], and it is of extreme importance to create, develop, and aim for a more sustainable built environment. Planning to improve city sustainability is crucial for city dwellers' quality of life and our planet's overall sustainability.

Energy consumption in urban areas is on the spotlight of local and worldwide research and decision-makers [36,37], and the choices made by municipal authorities and urban planners can significantly impact a city energy efficiency and emissions [38] and the thermal comfort of city dwellers [39].

There is an undeniable link between the urban built environment, transport systems, and human behaviour, a link that has been an important avenue of research in both spatial and transport planning fields [40]. This spotlight on the built environment puts it as an instrumental piece for paving the development of cities and is often at the centre of conflicting interests.

A simple form to define built environment, and the one used for the purpose of this review, is a multidimensional concept that *"comprises urban design, land use, and the transport system, and encompasses patterns of human activity within the physical environment"* [40]. Handy et al. [40] identify six dimensions of the urban built environment: density and intensity, mixed land use, street connectivity, street scale, aesthetic qualities and regional structure. A desirable and pleasant urban built environment has to be able to improve energy efficiency, environmental quality, accessibility, comfort, feel at ease sensation and overall quality of life of urban residents [19,40,41].

As form and function of the built environment impacts energy consumption, urban strategies are crucial to reach energy efficiency and climate targets [42–47]. City-level energy planning presents itself as a strenuous task, typically referred as "wicked problems", implying ill-defined, multi-faceted and dynamic problems that require carefully curated strategies and policies, facing many obstacles and additional challenges [48]. One of the biggest challenges is the consolidated urban built environment, i.e., existing urban areas, where changes, regeneration or renovation is demanding and also requires altering people's behaviour in order to reduce energy consumption [49].

City resiliency, i.e., its ability to withstand a wide array of shocks and stresses [50–52], is another central component of sustainable development and has been an active avenue of research in urban planning [50,53–59]. Technical and economically viable solutions are needed to reduce the cost of urban energy transition towards sustainable and resilient cities. Otherwise, the transition could be too expensive to undertake [42,58–61].

Given the number of publications on energy efficiency and consumption of the built environment, this literature review focuses only on transport and spatial planning dimensions. Figure 2.1. depicts a graphical representation of the research avenues taken into consideration in this chapter. It aims to be a review of recent research, highlighting the most important results and discoveries of the past decade, and provide insights on what could be the focus of future research in the spatial and transport planning energy dimensions of the urban built environment. For more reviews regarding the different topics presented in this chapter, please see [62–69]. The term built environment can also refer to buildings, but these are not the focus of this review. Authors suggest MDPI Energies Special Issue "Thermal Behaviour, Energy Efficiency in Buildings and Sustainable Construction" [70] and the review from Quan et al. [71] for a deep dive on buildings energy consumption and efficiency.

Figure 2.1. Graphical representation of research avenues in review.

2.2. Transport and the built environment

Transport has a crucial role in the development and daily life of our societies [72]. However, it remains an essential source of harmful air pollutants [53,54], surpassing one-fifth global CO_2 emissions in 2021 [73–75] (21-23%, depending on source). The urban form and built environment directly influences the travel mode choice of dwellers, with consequences on transport energy consumption [49,76–81]. Numerous studies over the past decades looked at the relationship between the urban form and CO_2 emissions and transport energy consumption [82–97]. Reducing fuel consumption and associated emissions is possible by focusing on three main areas: fuel type, fuel efficiency, and vehicle miles travelled [98–100]. While the first two areas are not directly related to the built environment, the latter is, as research shows that land use and urban form policies can help reducing motorised modal share and transport energy consumption in the urban environment [17,18,101–104]. The high modal share of private motorised transport is one of the main causes of high transport energy consumption in cities [105]. Urban regeneration policies must be part of the solution by creating new infrastructure and foster a jumpstart of active mobility (walking, cycling), mobility as a service, and zero emissions vehicles [106]. City size and spatial clustering also have a significant impact, as high-density development can help reducing commuting distance and time, as well as fight back urban sprawl and its long-term negative consequences [78].

Understanding which factors can improve travel patterns, reduce energy consumption and promote an urban environment with low-carbon and sustainable development has been, and remains, an active research topic for urban planners [86].

2.2.1. Commuting and urban trips

The relationship between the built environment and commuting trips has received continuous interest, as research shows [82,107–112]. Recently, Wang et al. [113] demonstrated a potential for commuting trips to significantly increase CO_2 emissions on two major cities of China and India. Economic growth and motorization in those cities are inducing fast urbanization and urban sprawl, leading to an expected increase of the annual average CO_2 emissions per person from 0.22 t in 2012 up to 1.6 t in 2030, a 727% rise if "business as usual" conditions are maintained.

A study on Vehicle Miles Travelled (VMT) in the Baltimore area (USA) confirmed that the built environment affects commuting trips, but also that its influence extends to non-commuting trips [114]. For commuting trips, employment density, street connectivity, and accessibility are statistically significant regressors for reduced VMT, as closer jobs and more job opportunities, smaller blocks, and denser intersections provide shorter paths and alternative travel modes. For non-commuting trips, mix land use and street connectivity were found to be positively significant, as higher street connectivity provides closer opportunities, as does a higher mix land use [114,115]. When comparing residents' density at neighborhood locations with employment density at business areas, [95] the latter has more impact on vehicle miles travelled. This dependence on trip purpose (commuting or non-commuting) was also studied by Yang et al. [116], who examined the effects of built environment on CO_2 emissions for different trip purposes in Guangzhou, China. An important conclusion was that urban planning should consider both types of trips, as some built environment elements may be specific to a particular purpose (e.g., bus stop density, distance to city public centers). The authors also refer that urban growth should avoid the expansion of the urban periphery, and a polycentric development should be advocated for. Higher mix land use is desirable, as it enables shorter trips, a reduction in the number of trips, and higher active mobility levels.

Other studies confirm that polycentric urban conglomeration policies, that aim for a higher road density, even if narrow, are more effective in reducing travel time than wide arterial roads that can encourage urban sprawl [87]. Likewise, population densification was also proven to be an effective strategy to reduce VMT [114,117]. According to a study made in California, a 10% increase in residential density may be able to reduce VMT by 1.9% [118]. Densification also leads to more social opportunities nearby, which is usually also sought-after by inhabitants.

2.2.2. Active mobility

The built environment can impact active mobility in many ways [101,119–121]. Often praised by policymakers and a prominent research topic, active modes are nevertheless still underused while motorized private transport is overused [17,122–125]. In the study on how the built environment can affect physical activity, Handy et at. [40] highlight the importance of the former in increasing the number of pedestrians and cyclists in urban trips, with physical exercise as by-product. Mixed land use, street connectivity and an overall thoughtful design were proven to enhance the attractiveness and feasibility of both active transport modes [40].

Other built environment characteristics can influence active mobility ridership as well [119–121,126,127]. Street aspect ratio and direction [128–137], street vegetation and shade availability [138–142] were found to play a role on pedestrian thermal comfort and overall city walkability. Christiansen et al. [126] confirmed positive associations of active modes for transport with four characteristics: mix land use, residential density, intersection density, and number of parks. However, not all were linear, suggesting that optimum values may exist for each component and that going beyond them will not bring benefits. In particular, residential densities over 12,000 dwellings/km^2 do not seem to improve walking for transport. Also, the physical aspect of the built environment in-fluences citizen perception of neighborhood pleasantness, which in turn affects the propensity to use active modes, as pleasant environments are more likely to be threaded [127,143–148].

Fostering active mobility is one way to reduce transport energy consumption and CO_2 emissions [64,83]. A study from Monteiro et al. [17] analyzed the cycling full potential of Coimbra (Portugal) based purely on trip distances and frequencies; results showed that if the full cycling potential were to be achieved, active mobility (walking plus cycling) would increase by 154%, directly leading to a reduction of 22% on transport energy consumption. A study for the same city showed, by evaluating the exposure to pollutants while commuting, that a reduction of approximately one third in the inhalation of traffic pollutants could be achieved by using a route that is on average only 6% longer in comparison with the shortest route [149].

These studies highlight the importance that the built environment can have on encouraging active mobility. Municipal authorities should provide the necessary walking and cycling infrastructure, with safe and comfortable bike lanes and street furniture (bicycle parking, rest places, etc.), and adopt policies that reward active mobility, such as the coordination with public transport and discouragement of motorized transport.

2.2.3. Public transport

Public transport is an intrinsic part of urban mobility whose impact in transport energy efficiency and GHG emissions is widely recognized [36,150–153]. Increased public transport rideability is necessary to ensure a good public transport service, by decreasing waiting time and increasing lines. Built environment characteristics, such as high population density at residential neighborhoods and high job density at business districts can lead to high rates of traffic congestion and parking difficulties, inducing a widespread use of public transport in lieu of private motorized transport [154], resulting in lower transport energy consumption and emissions. Nevertheless, a study by Li and Zhao [115] that explored car ownership and car use near metro stations in Beijing concluded that proximity to metro stations was not that impactful on reducing car ownership and use. This finding is a reminder that stand-alone policies and strategies to improve transit ridership might not be as impactful as could be expected. Additionally, the effects of the built environment on the reduction of private motorized transport usage can also be limited if, e.g., free parking is provided at destinations [154].

2.2.4. Public electrification

At the time of writing, almost every major car brand offers electric vehicles (EV) in their model range and has committed to an entire model range of just EVs in the foreseeable future [155,156]. International and national authorities are showing signs of commitment on ensuring zero-emission new car sales in the next decade [157]. EV market share is also steadily increasing and it is expected that GHG emissions, air pollution and the depletion of natural resources for the production of fossil fuels will slowly decline [72,158].

The growth of EV driving around requires creating adequate charging infrastructure in the built environment [159]. EVs are also being considered for mobility as a service solution and the built environment may need to be optimised for parking and charging stations for this mobility solution, as Gonçalves et al. [160] highlights. A study by Fernández-Rodríguez et al. [161], based on two case studies from Italy and Spain, analysed the potential use of railway and metro power supply facilities to charge EVs, as that would simplify the deployment of charging infrastructure in cities and allow for harvesting a significant amount of braking energy from trains. Karan et al. [162] analysed an integrated building and transportation energy use to design a comprehensive GHG mitigation strategy in Pennsylvania, USA. Initial results showed that, on average, each in-dividual produced around 20 lbs (9.1 kg) of CO_2 per day, of which 62% was from transport. Changing fossil fuel motorized transport for EVs powered by solar electricity, a 12.2% CO_2 reduction per day could be achieved.

Electrification of public transport vehicles can also play an important role [163] and was proven to have economic benefits [164]. Replacing internal combustion engine (ICE) public transport fleets by electric trains and hybrid buses could decrease their share in GHG emissions by 32% [165]. Also, new methodologies to analyse the efficient energy consumption of electric public transport based on the route topology, traffic schedule and vehicle specifications are being developed [166]. Electric buses can additionally provide other environmental and financial advantages, in terms of improved air quality, noise levels and reduced cost of ownership and maintenance. However, their acquisition cost is a significant disadvantage, with a premium of over $100,000/vehicle compared to ICE buses [167].

The future of urban mobility might evolve into massification of EVs, electrification of public transport and micromobility, e.g., bicycles, scooters, in a mobility as a service or increased ownership basis. It is nowadays becoming clear that vehicle electrification is part of the solution, and many researchers and municipal authorities are actively working on promoting a zero-emission urban transport system.

2.3. Urban form: Spatial planning and energy efficiency

This section discusses the relationship between spatial planning and energy efficiency, highlighting the most relevant research and research avenues.

The challenges that the urban built environment faces in the transition to sustainable, low-carbon energy systems are massive [168] and urban form and planning plays an undeniable role in addressing them, by means of implementing policies that privilege energy efficiency [169,170]. However, in the past, energy efficiency and sustainability have not been on the radar of urban planners very often. Take land use as an example: although it is considered a planning tool towards energy efficiency, in many cities the lack of coordination between urban planning and city-wide energy planning led to large patches of single land use, an inefficient solution [48,169,171,172]. Nowadays the relationship between urban and energy planning is largely present in current energy-optimized city planning [38,169,173–177]. For a detailed critical literature review on the importance of coordinating urban and energy planning, see [67]. At a larger scale, initiatives such as the European Commission initiative Covenant of Mayors, Local Governments for Sustainability, and C40 Cities Network (ICLEI) [27,178–180] can bring together municipal authorities to collaborate towards more efficient and sustainable cities.

It is important to note that advances in computer-based technologies provided spatial planners with new resources and tools that can yield quantitative and expedite analyses of energy consumption and sustainability measures [16,181–183]. A study by Ferrari et al. [184] evaluated practical usage of these tools by urban planners.

2.3.1. Eco-districts and clean energy shaping built environment sustainable development

The development of more ecologically based and livable cities has been advocated as a priority when aiming for sustainability [185] Integrating renewable energies into spatial planning, i.e., the creation of eco-districts, was proposed by Roger-Lacan [186] and Marrone et al. [187] as a possible path to achieve this goal. Eco-districts should aim not only for their own energy independence but also to exchange surpluses with neighboring districts [188,189]. However, studies by Lombardi and Trossero [190] and by Bracco et al. [191] showed self-sufficiency may be hard to achieve on a large-scale, as it requires harnessing multiple renewable energy sources locally and the means to deal with their intermittencies.

Solar power is a renewable energy source that can be harvested in the urban environment and a prime candidate for eco-district development. Integrating solar systems into the built environment can have several advantages, e.g., exploiting unused urban surfaces, limiting losses associated with long distance transmission of electricity, and creating a more resilient electric network, capable of supporting extreme weather conditions [192,193]. Incentives to the installation of solar photovoltaic energy and solar energy solutions in cities are a possible policy to foster a transition to eco-districts [194,195]. Indeed, a study on the city of Daejeon, South Korea, found that the citywide deployment of solar energy via rooftop photovoltaic panels could fulfil over half of the city energy needs [196]. A similar study in San Francisco, USA, found slightly lower, but still significant savings, namely 23-38% [197]. For an in-depth review on the deployment of renewable energy sources in urban areas, see [68].

2.3.2. Urban sprawl

Urban sprawl is an extensive low-density, single type land use that creates a lack of continuity and directedly impacts spatial, transport and environmental planning [198–201]. Strong negative correlations exist between urban sprawl, energy consumption and emissions [202,203]. Sprawled city development leads to large commuting distances, which in turn requires extensive roads that inevitably end up congested by excessive private car use. Other consequences are the increase of both air and noise pollution, significant reduction in public transport ridership and negative socio-economic consequences [198,200–202,204–209]. Studies [18,210] show the clear effects of residential location on travelling distances, modal share and transport energy consumption. Dwellers of sprawled suburbs have the worst accessibility and are restricted to motorized transport modes, as walking or cycling is not possible with homes being so distant to destinations. Consequently, transport energy consumption is high, as motorized private transport remains the best (most of the time the only) modal choice option for suburbs dwellers [17,18].

To avoid deepening the negative consequences of urban sprawl, cities must stop planning strategies that can result in sprawled neighborhoods and fight existing sprawl with policies that can infill central urban spaces [18,210]. The solution might be in the past, in the utopian city plans developed by Howard or Le Corbusier [4,17,203,211]. A study by Monteiro et al. [16] compared a real city with sprawled districts with its redraft as a Garden City. Results showed that the Garden City layout improved accessibility to urban facilities and jobs by 41%, which can directly lead to a reduction in transport energy consumption and better public transport planning. This result provides a glimpse on what can be gained by planning cities and their expansions in a more thoughtful way.

An urban compact form is usually seen as a sustainable urban form [212]. Compact development leads to densification and mix land use, which reduces distances and improves accessibility. These efficient land use policies reduce commuting time and private car use, directly impacting transport energy consumption [208,213–215]. A study by Zahabi et al. [165] found statistical significance between built environment variables and transport emissions in Montreal, Canada: a 10% increase in accessibility to public transport, density and mix land use, results in a 3.5%, 5.8% and 2.5% reduction in GHG respectively. Likewise, a study on the Puget Sound region, Washington, USA, revealed that a 100% increase in mix land use, residential and intersection density in urban areas would reduce transport emissions by 31.2-34.4% [216]. Stone et al. [217] found similar results and highlighted the importance of compactness in reducing VMT. Wang and Zhou et al. [218] presented a literature review on the relationship between the built environment and travel behavior in urban China. Authors confirmed a strong connection of high density and mix land use with shorter trips and larger active modal shares. In contrast, residents in the suburbs spend more time communing and have greater motorized transport dependency. Wu et al. [49] used survey data with over 22,000 traffic trip samples from nine streets in Ningbo, China, to analyze transport energy consumption with a regression analysis. With respect to built environment variables, they found that an increase of 1% in population density, mix land use, and road intersection density lead, respectively, to decreases of 0.094%, 0.415%, and 0.079% in total transport energy consumption.

Although several studies show a positive impact of mix land use and sprawl reduction on energy consumption, other aspects may arise. If, on the one hand, mix land use can decrease transport energy consumption, on the other, it can increase overall building energy consumption, making it important to understand the relationship between the spatial arrangement of buildings in a high mix land use zone and their electricity demands [219]. Similarly, densification and infill (see section 2.3.3. for definitions) can compromise perceived neighborhood pleasantness [19]. It is thus important that urban planners and municipal authorities understand and analyze the positive and negative consequences of planning strategies and policies before fully committing to them.

2.3.3. Densification and infill

Densification, i.e., the increase of population density, and infill, i.e., rededication and development of previously derelict or underused land to new land uses or construction, of urban conglomerations may come in many guises and can lead to reductions in transport energy consumption and environmental impacts [18,220–227].

Transit-Oriented Development (TOD) is a medium to highly dense, mixed land use urban form concept in which public transport-based mobility defines the urban planning, with public transport catchment areas below 600 m [102,103,228–232]. A study by Nahlik and Chester [103] on the impact of TOD on VMT showed that residents of TOD areas tend to drive less compared to residents of non-TOD areas. The impact of a TOD solution in Las Vegas was analyzed by Nahlik and Chester [102], authors having concluded that it could decrease GHG emissions by 470 CO_2 equivalent per year, and reduce PM_{10}-equivalents and smog formation by 28-35%. Silva et al. a [233,234] evaluated the energy implications of six urban development alternatives for the city of Porto, Portugal (infill, consolidated development, modern development, multi-family housing, TOD, and green infrastructure), having found that TOD comes on top, with a 15% reduction in transport travel, followed by consolidated development, with 9% reduction.

Concerning infill, Monteiro et al. [18] analyzed the infill potential the city of Coimbra, Portugal, strictly following the Municipal Master Plan and national regulations for buildings. They found an increase of 36% on the potential per capita active modal share and a reduction of 76% on transport energy consumption in comparison to the real city, proving that the infill is a viable strategy to combat urban sprawl.

Different strategies provide different results and local context should always be considered when aiming to densify a city.

2.3.4. The D-variables of compact planning

The D-variables were proposed to guide planners when considering a densification or infill strategy [213,214]. Their impact on transport energy is as follows [213,214]:

D-ensity measures: higher population and job density can reduce the number of trips and trip length, as origins and destinations are closer to one another.

D-iversity measures: high mix land use can reduce motorized transport and encourage active transport.

D-esign measures: network design can reduce motorized traffic. E.g., street networks with a large number of intersections decreases motorized traffic, network distances, and encourages active transport modes.

D-estination accessibility: higher number of urban facilities and employment opportunities reduces trip distances, trip numbers, and increases the viability and conveniency of active transport modes.

D-istance to transit: an adequate coverage of catchment areas for public transport reduces private transport by and incentivizes active mobility.

To measure the impact of these variables, statistical models are commonly used, and results are typically presented in percentage changes between the scenarios being studied [214]. Although these studies provide important prediction data, their practical application is still limited [214]. Stevens [214] highlights that planners and researchers

"...should probably not automatically assume that compact development will be very effective at achieving that goal. If anything, planners should probably assume for now that compact development will have a small influence on driving, until and unless they are given a compelling reason to believe otherwise. At a minimum, planners and municipal decision makers should not rely on compact development as their only strategy for reducing vehicles miles travelled unless their goals for reduced driving are very modest and can clearly be achieved at a low cost."

The above is a warning that infill and densification is not an universal solution to reduce transport energy consumption, due to both local constraints and densification itself [92,235]. A study on perceived neighborhood physical pleasantness showed that, in general, people prefer detached and single-family housing [19]. Indeed, the authors of [236] found that, in response to this market demand, development trends on a dynamic tourist coastal privileged detached urbanism, rather than compact buildings.

As different strategies provide different results, so do different cities behave differently in response to those strategies, further emphasizing the importance of local context when considering an urban layout. As Weisz and Steinberger [237] highlights, distinctions should be made according to urbanization levels and dynamics, history, culture, and social and economic inequalities.

2.3.5. Urban public spaces

Urban public spaces, i.e., outdoor or indoor spaces with free public access where people can gather or pass through (e.g., parks, squares, streets, public shopping malls, streets, walkways) are an essential part of a city's built environment [238–241]. If urban public spaces offer some protection against motorized traffic, people tend to feel more secure, comfortable, and less annoyed [242]. Research suggests that policymakers and municipal authorities should focus on the creation of inclusive and safe urban public spaces [242]. Existing urban green infrastructure (such as parks and urban forests) should be protected, and new ones should be promoted and built [243].

Additionally, retrofitting renewable energy sources in urban public spaces should become a common norm [244]. Passive strategies that use the intrinsic characteristics of the materials composing the built environment are being studied and implemented for higher energy efficiency and CO_2 emissions reduction [245–248]. The use of green areas and vegetation, as well as cool and reflective materials is well documented [249,249–251]. A study by Rosso et al. [245] tested the application of photoluminescent materials on the built environment, for example on sidewalk pavements, and demonstrated that it can be used as a passive strategy to reduce energy consumption, by contributing to public space lighting with no energy consumption. Similarly, Akbari and Matthews [249] evaluated the installation of cool pavements to mitigate summer urban heat islands and improve outdoor air quality and comfort. Nevertheless, although the energy efficiency and thermal comfort capabilities are clear, using cool coatings for buildings and city infrastructure may cause increased glare to pedestrians and increase walking discomfort [252]. Pavement energy harvesting is considered to be a sustainable energy source, with the potential to yield efficiencies around 40-65% [253]. Heat-harvesting pavements and road pavements capable of converting vehicles' mechanical energy into electric energy [254,255] have also been proven as possible energy recovery solutions. However, energy-harvesting pavements require more examination to access their power output, durability and lifetime [256].

2.3.6. Additional challenges in developing countries

In developing countries, lack of infrastructure creates added difficulties and some authors suggested that energy sustainability strategies must go hand-in-hand with sanitation, solid waste management, and food security strategies to eradicate poverty [257,258].

Rapid urbanization and climate change are worsening the vulnerability of undeveloped urban areas of the global south [259]. As societies evolve from the primary sector to the secondary and tertiary ones, more full-time, higher income jobs are created. Given that economic growth is correlated with transport energy consumption and CO_2 emissions [260], urbanization and development is expected to increase emissions in developing countries [261]. Despite wide promotion of built environment sustainability, these countries lack the means and opportunities to make an adequate energy transition and thus this transition remains far from implemented in most developing countries [262,263].

Two studies on African cities show that, even though globalization brought ideas and policies derived from developed countries, those cities still face additional challenges [262,264], making the transition to sustainable energy not as straightforward as research from the global north might suggest. Cities in Africa are very unique and diverse in culture and other contextual issues, requiring different perspectives on how to make that transition [265]. Challenges relate, among others, to insufficient and inconsistent data [266,267], as well as weak governance systems and high percentage of informal economic activities, which hinder the implementation of the necessary strategies [267,268], mostly due to the mismatch between the availability of resources and their fair distribution.

The authors of [262] summarize into two main groups the concerns that African countries are facing: (a) general barriers in developing countries – basic needs, not fully implemented sustainability and inequitable resources distribution; (b) barriers specific to African countries – developing economics, urban poverty, population and poor utilities and the dichotomy between the different countries.

In general, the research [262,264,269] suggest that the widespread use of renewable energy resources and a focus on developing a sustainable built environment would highly benefit developing countries, acting as a step to minimize poverty rates and to overcome current and future environment problems.

2.3.7. Urban geometry and buildings energy consumption

Buildings energy consumption can be evaluated based on four main factors: urban geometry, building design, system efficiency and occupant behaviour [270]. For this review, the focus is on the form of the cities, i.e., the urban geometry, the intersecting factor of urban planning and building energy consumption. Urban geometry and morphology typically relates to the availability of daylight, outdoor temperature, wind speed, and air and noise pollution [270–272], all of which can create microclimates within a certain urban environment, such as urban heat islands (UHI) and street canyons (SC). It [270,273–277] also influences building energy consumption patterns, heat losses and solar exposure. Thanks to computing advances, simulations of built environment and urban form become possible, providing an important theoretical base for the relationship between urban geometry and building energy consumption [270,278].

A study by Silva et al. [279] used a spatially-explicit methodological framework based on neural networks to assess the effect of urban form on energy demand. Results show that urban form can explain around 78% of the variation of energy use, with features such as number of floors and mix of uses as the most relevant. Studies using digital elevation models (DEMs) are also an important part of the research regarding the relationship between the urban environment and building energy consumption [270]. Shaping and grouping buildings is long known [280]; the novelty of recent research is that computer capabilities now enable quantitative analyses and comparisons between different urban forms. A study by Taleghani [273] analysed the energy use impact of thermal comfort in the Netherlands, based on different urban block types. The authors concluded that between single, linear, and courtyard urban blocks layout, the three-storey courtyards presented the best results, with 22% less use of energy and 9% less thermal discomfort in comparison to the single urban blocks layout.

The impact of densification from high-rise construction can also be estimated. Densification has been associated with lower per capita energy use, unlike detached housing, whose heat-energy efficiency is low [281–285]. However, tall buildings that are too close and mutually shade each other, reducing their access to natural light, negatively impacting energy efficiency [286,287], creating a push-pull effect. Building solutions, such as improved thermal insulation of the building envelope, can help mitigate these compactness issues [288]. Actual figures on building energy demands can be estimated from 3D geometric models and data on building construction, as Eicker et al. [289] showed. These authors found that separating buildings can increase energy demand for heating by 10-20% and reduce renewable energy integration by up to 50%, while mutual shading can increase heating energy demand by 10%. Because of the above findings, some authors proposed moderate compactness as a compromise solution between compact and detached development [282,288–290].

Harvesting wind within the urban environment has also been an active research topic recently [291,292]. Gil-García et al. [291] analysed the potential for harvesting urban wind in the region of Cádiz, Spain, and found that over 68,000 kWh/year could be generated, for an investment return rate of just six years.

Passive solar design should also be incorporated into house plans at the design stage, as suggested by Morrissey et al. [293]. Cheng et al. [294] developed eighteen models to assess the solar potential of urban geometric types, based on the built form, site coverage, and land plot ratio. Other estimations of solar potential based on the urban built environment include [295,296]. Urban geometry can also impact the energy collected from facades and roof tops, with a potential to improve thermal comfort of buildings [273].

2.4. Conclusions

Jane Jacobs in *'The Death and Life of Great American Cities'* [7] stressed the importance of the built environment and presented criteria that planners should have in mind: a high concentration of population, buildings of mixed use, shorter city blocks, and an attention to wide-range age gap. These strategies, Jacobs argues, would help retaining diversity, creating better living conditions, and improve quality of life [7].

As urban population grows, so does their energy consumption, making efficiency critical to mitigate emissions and resource use. Thus, spatial and transport planning must include energy efficiency and their strategies, as these are vital to urban sustainability. In this sense, compactness has been shown to have many positive aspects that serendipitously go much in line with Jacobs' ideas. The urban environment is expected to host a growing number of dwellers in the coming decades and compact urbanism is one possible solution to keep energy consumption under control while providing all the benefits of proximity. Lower VMT, higher active modal share, and better public transport service all contribute to lower energy consumption and emissions, in contrast with urban spawl, which increases motorized transport dependency and inefficiencies due to traffic congestion near, and at, arrival at destination. However, to capitalize on proximity benefits policies must also include better accessibility (e.g., higher mix land use), adequate active transport provisions (e.g., infrastructure investments, rights-of-way privileges), improvement of public transport (more/faster lines and stops density), and discouragement of private car use.

Nevertheless, there are many factors that come into play to make a liveable and vibrant urban environment. For example, the perceived physical pleasantness of the urban environment, which can attract or repulse people from cities, seems to decrease with excessively concentrated environments and tall buildings [19,20]. Excessive concentration also creates heat island and canyon effects, inefficiencies from shading, and makes it easier for pandemics, such as the COVID-19, to spread [15]. Polycentric development and moderate concentration development can be good compromise solutions in this respect. In any case, energy efficiency integration within municipal plans and strategies is key for the future development of cities [297]. Land use policies can be more effective if supportive transportation policies are also developed [154].

An extensive list of the multiple aspects found in the built environment research papers related to spatial and transport planning is presented in Volume II Table II.2.1.

2.4.1. Directions for future research

There are many challenges ahead to achieve truly sustainable cities and opportunities are plenty for future research and practical applications in the spatial and transport planning fields towards efficient and sustainable cities. Some major directions include:

I. Find urban forms that compromise between efficiency and pleasantness. Densification provides efficiency but can feel unappealing to inhabitants. Designing and experimenting with new urban forms can lead to new solutions in which people enjoy living while maintaining an efficient and sustainable energy consumption. Classic urban form concepts can also be looked at as development solutions. The Garden City and neighborhood unit development, revamped as the 15-Min City [14], are just two concepts that are now being reconsidered.

II. City expansions. As cities grow, new neighborhoods frequently need to be added. Research should be carried out on how to improve urban expansions based on quantitative indicators and scenario simulations. Expansions can also be a testbed for new urban forms that later provide valuable field data.

III. City infill and sprawl-combating measures. Decision makers deal with problems of real and sprawled cities. Reducing its impact and filling in cities requires developing infill planning methods and policies to bring people closer to the center.

IV. Smart cities and energy efficiency. Big data can provide information on the built environment and evidence mounts that the Internet of Things (IoT) can be used in smart cities to reduce energy consumption [64,298,299]. Research and development are necessary to continue to fulfil this potential.

V. There is a growing research avenue on green energy harvesting in cities. The transition to practical application should be more supported and stimulated.

VI. Research and practical solutions for developing countries. Global north solutions may not fit developing countries. Alternative, tailormade solutions need be researched.

VII. Energy planning integration with both spatial and transport planning. Nowadays urban planning implies cooperation between spatial and transport planning, although in practice, they are still sometimes treated separately. A more integrated urban planning based on spatial, transport and energy dimensions can provide clear strategies and policies towards more sustainable cities.

"City growth has caused climate change, but that growth is also what's going to get us out of it" [300]. The challenges ahead on sustainable cities are numerous and worrying but research for the past decade has shown that spatial, transport and energy planning fields are aware of and facing the problems head-on. It will be up to the politicians to implement the solutions. Many already exist.

3. Planning cities for pandemics: Review of urban and transport planning lessons from COVID-19

"We can't just focus on how we tape everybody back together. We actually have to take advantage of this disruption to really create systemic change in a way that we haven't before." Anika Goss [301]

For the past few years, the world has been facing one of the worst pandemics of modern times. The COVID-19 outbreak joined a long list of infectious diseases that turned pandemic, and it will most likely leave scars and change how humans live, plan and manage urban space and its infrastructures. Many fields of science were called into action to mitigate the impacts of this pandemic, including spatial and transport planning. Given the large number of papers recently published in these research areas, it is time to carry out an overview of the knowledge produced, and synthesising, systematising and critically analysing it. This chapter aims to review how the urban layout, accessibility and mobility influence the spread of a virus in an urban environment and what solutions exist or have been proposed to create a more effective and less intrusive response to pandemics. This review is split into two avenues of research: spatial planning and transport planning, including the direct and indirect impact on the environment and sustainability.

3.1. Introduction

On the last day of 2019, with the new year's celebrations underway, a cluster of pneumonia cases of unknown causes were reported from Wuhan, Hubei province, China [302]. From that moment, societies worldwide faced one of the worst pandemics of modern times. From all over the world and across different areas of knowledge, researchers started looking for solutions to reduce the spread of the contagion while trying to adapt an unaware and unprepared society to a global pandemic. Urban areas became the centre of most outbreaks during these 2 years [303]: with over half of the world's population living in urban areas, most of which easily connect among each other and with each other [22], cities became the main areas of concern for the rapid spread of the virus. This pandemic has impacted, arguably forever, cities, as other pandemics did in the past [304]. As spatial and transport planning certainly influences the spread of a virus in urban environments, in the future, they must become part of short- and long-term solutions to other outbreaks of infectious diseases.

The novel coronavirus disease (COVID-19) first caught the attention of urban and transport planners when a lockdown was declared in Wuhan on 23 January 2020. Words such as 'social distancing' and 'self-isolation' started echoing worldwide at a stage where urban and transport planning was heading in a different, almost opposite direction: cities were becoming denser and more compact, and transport planning policies were aiming for higher public transport mobility and overall mass use. Inevitably, this led to COVID-19 making an enormous impact on cities, as recognised by Krishna and Kummitha [305]. Cities thus face the daunting tasks of mitigating COVID-19 impacts, and spatial and transport planning are becoming frontrunners in this quest, as argued by Ibert et al. and Tešic and Lukic [306,307].

This chapter aims to review the state-of-the-art research produced in spatial and transport planning concerning COVID-19, from its inception to the present, to summarise and analyse the main conclusions and to suggest new avenues of research on the relationships between the urban layout, accessibility, mobility and the spread of a virus in an urban environment. The motivation for this review was to systematise the knowledge in the field, contributing by creating a coherent overview of the research landscape, filling a literature gap on reviews of COVID-19 impacts on municipal engineering. Furthermore, it suggests lines of future research that, as will be observed, address pandemics and also connect that aspect with other essential aspects of the urban environment, society and sustainability. Sections 3.2 and 3.3 highlight the core role that both spatial and transport planning have during pandemic times and how COVID-19 might redirect research and change policies and practice in the short and long terms.

3.2. Spatial planning and COVID-19

Acuto and Ahsan [303,308] have shown that spatial planning can have an essential role in the fight against COVID-19 and future pandemics by adapting to the new circumstances both in the short- and long terms. This section takes a closer look at how the theory and practice of spatial planning evolved due to COVID-19 and previous pandemics, highlighting the importance of green areas and parks in urban areas, how bigger cities have bigger problems and the disparities between developed and developing countries.

3.2.1. What has the past taught us; what does the future hold?

History has taught us about past pandemics, their origins, spread and consequences. COVID-19 did not open a new area of research in this respect, but instead reopened one that had been dormant for many decades. Hays [309] provides an overview of 50 epidemics and pandemics that humans faced, from the epidemic in Athens in 430–427 BC to contemporary malaria and tuberculosis outbreaks. Looking at the timeline of all major pandemics, a worrisome statistic arises: from 430 BC to 2005, a total of 50 pandemics were recorded, whereas from 2005 to 2020, a total of six pandemics made worldwide news, a 25-fold increase in the frequency of pandemics. With the world population climbing, societies evolving and claiming previously uninhabited natural zones, the appearance and spread of new viruses have a higher potential for dire consequences, increasing the need for pre-emptive planning and prompt responses.

Pandemics have already led to changes in how the urban environment is planned and managed [310–313]. For example, when New York, Paris and London had cholera outbreaks, inhabitants searched for open green and sunny areas, which led to the creation and design of buildings and outdoor areas to provide fresher air and sunlight [314,315]. The Garden City Movement is an example of urban planning acting as a tool to fight, among others, poor living conditions, lack of sanitation and the Spanish flu of the twentieth century [316,317]. In fact, several authors encouraged architectural and urban organisations to start including pandemics in disaster management strategies, with integrated containment measures in a seamless way, within the typical city environment [316,318,319]. Bouffanais and Lim [320] urged urban analysts and planners to understand the dynamics of city movement, as urban flows may help explain the spread of COVID-19 within the built environment. Martínez and Short [312] suggested that urban spaces should be rethought and planned for safer and more sustainable cities, starting with parks and green areas in densely populated conurbations.

3.2.2. Green areas as physical and metal safety nets

The COVID-19 pandemic has imposed the necessity to stay home to extremely connected and mobility-based societies. Life in confinement was something that most people were not used to, which led to an increase in the number of people suffering from mental health issues [321]. Psychological health factors that added to economic and social insecurities took an even bigger toll on people's lives [322], with children suffering the most from forced confinement [323].

The claustrophobic nature of many residences in urban environments resulted in an increased use of urban parks and green areas during lockdowns [324]. Urban parks and green areas have proven to be essential to the well-being of residents, creating higher resiliency and overall quality of life for their nearby population [325–327]. In addition, travel patterns emerged that indicated people opt for parks close to their homes with a travel time under 10 min, reinforcing the importance of neighbourhood parks and green areas [327,328]. These authors suggested creating networks of small decentralised parks and green areas accessible for everyone, allowing for easier interactions with nature and providing a place with clear mental and physical benefits. Private gardens were also proven to be important for residents, emphasising the importance of both public and private gardens for improved resiliency [329,330].

3.2.3. Big cities, big problems

Internationally connected cities – that is, cities that host international hubs, industry, and companies – were typically more affected in comparison with smaller urban areas and rural zones. Because big cities directly correlate with international cities, large urban areas and metropolises became the main clusters for the spread of COVID-19 [308]. Wuhan, Shanghai, Hong Kong, London, Milan, Madrid, Barcelona, New York, and São Paulo, among many other cities worldwide, had the largest COVID-19 outbreaks. Even when infections appear in satellite cities or metropolitan areas, the outbreak tends to move towards the city, as was the case in Milan or Oporto.

The idea that population density and urban areas help the spread of COVID-19 has been a possibility ever since the appearance of the virus [331,332]. Salama [319] compared the spread of the previous severe acute respiratory syndrome outbreak in 2003 and the current outbreak, underlining a positive correlation between higher density and rapid spread, which Peng et al. [333] confirmed. Higher densities can relate to low per-capita income, space overcrowding and poor access to healthcare, originating more outbreaks among poorly housed communities [317]. Higher-density neighborhoods are also related to lower well-being during the pandemic, in comparison with lower-density neighborhoods; lower-income neighborhoods and areas of minority concentration with smaller dwellings, less green space and higher reliance on public transport were negatively associated with well-being [334–337]. In contrast, good accessibility to local facilities and better access to amenities and public health infrastructure have been positively associated with well-being and reduced vulnerabilities in high-density areas [337–339]. Lower density resulted in lower infection and death rates, as claimed by Hamidi et al. and Carozzi et al. [340,341]. The incongruity of compact planning transpires once more, suggesting it continuously needs to be addressed and improved, mainly in urban areas where informal settlements are home for most of the residents.

3.2.4. Slums: a COVID-19 playground?

Already known for poor living conditions, slums – that is, dense informal settlements, might be the least prepared urbanised areas to fight this pandemic, with a lack of basic infrastructure such as sewers, waste collection, drainage or even clean drinking water [342,343]. Slums have an already bad situation that has worsened considerably with the onset of the pandemic [344]. Obongha and Ukam [345] analysed different settlement patterns in Nigerian cities, places of serious concern for epidemiologists, virologists and planners. Due to a lack of urban planning policies, buildings are extremely close to each other, making it nearly impossible to have any social distancing. Bearing in mind the lack of space, overcrowding and imminent violence, social distancing and hygienic measures are impractical, leaving millions of people with even less protection from the rapid spread of COVID-19 [312,342,343,346].

Slums are neither a problem caused solely by mismanaged urban planning, and nor are they solvable by urban intervention alone [347]. Its residents are economically vulnerable, and COVID-19 worsened that vulnerability, as Patel [343] argued when looking at slums in Indian cities. Patel also argued that smart cities' solutions to better control the spread of the COVID-19 virus and one-size-fits-all measures will not work for slums. Instead, Patel suggests that providing long-term solutions to reduce the vulnerability of marginalised populations is a prerequisite to making cities more resilient.

3.3. Transport planning and COVID-19

The COVID-19 pandemic had a massive impact on transport patterns, mostly due to the closing of international borders and country-scale lockdowns. Zhang and Zhang and Valenzuela-Levi et al. [348,349] argued that some behavioural pattern changes might be long term or even permanent. Analysing city mobility alterations during a lockdown is the first step to understand how transport planning adapted to this new, unforeseen paradigm. Because cities host mobile populations, transport services and foster social interactions, their intercity and intracity public transport systems increase a city's vulnerability to the spread of contiguous diseases [341,350], both at the hub locations (stations) and inside the transport vehicles, making it important to analyse the role of public transport amidst the pandemic. By contrast, active mobility has a small associated risk of contagion, which contributed to the reinforcement of its position on the urban transport agenda. Additionally, ripple effects in air pollution emerged, due to changes in mobility patterns, which must be mentioned.

3.3.1. Mobility during lockdown

With the number of cases on the rise, cities worldwide underwent lockdown measures, enforced either by local or nation-wide government decisions [351]. With severe restrictions, urban transport significantly reduced. Several studies analysed the impact that the pandemic had on mobility, with public transport suffering from a drastic decrease in ridership, due to people preferring to use private transport, both motorised and nonmotorised, for a reduced chance of contagion [352–355]. Nevertheless, people still needed to move, either to work, restock food or for services, so not all trips could be curtailed [356].

Parr et al. [357] showed that by 22 March 2020, during the state-wide lockdown in Florida, traffic volumes dropped to an average of 47.5% in comparison with the homologous value in 2019, with urban areas all around the state exhibiting an earlier and more significant decline in traffic volumes in com- parison with rural areas. Osservatorio Audimob [358] analysed the impact of the COVID-19 lockdown on general trips in Italy, having found that during the worst pandemic stage, all-purpose countrywide mobility declined from an average of 85% in 2019 to just 32%. Parr et al. also concluded that proximity mobility – that is, walking trips taking < 5 min, rose from 6 to 17%, while commuting and leisure trips dropped from 91 to 49%. Fatmi [359] found similar figures, with out-of-home activities in the Kelowna region of British Columbia, Canada, dropping over 50% during the COVID-19 pandemic. Aloi et al. [352] presented a detailed analysis for Santander, Spain. Overall results show that mobility plunged by over 76%, with the private car being the least affected and public transport being the most affected, with a staggering 93% reduction. A noteworthy by-product was the reduction of up to 67% of traffic accidents. That study also revealed an interesting change in modal share between pre- and post-pandemic times, with a rise from 48 to 77% of the private car and a reduction of 7.8 to 2.3% of public transport trips. Commuting trips became the main reason for people to leave their homes, rising from 35 to 74% during the pandemic.

The pandemic also impacted commuters and the future of commuting. Singh et al. [360] found a significant impact on how people view and perceive safety when travelling, with metro, carpool and buses observing a decline in modal share, whereas walking and the private car rose their share. Choosing a mode of transport was mostly based on travel time, cost and overall convenience, and the inconvenience of wearing masks or social distancing also became valid arguments [361]. Rubin et al. [362] conducted an international online survey among individuals who regularly commuted to their workplace and concluded that 69% of the respondents miss at least some aspects of commuting, such as the commuting itself (53%), spending some time on their own (25%) or feeling independent (24%). People do not all miss commuting equally: those who frequently commute by private cars are the least affected, with over 50% not missing commuting at all. As for public transport users, 75% did not miss commuting. Active transport users – for example, (e-)cyclists and pedestrians, are the ones who missed commuting the most comprising 91%. Another interesting conclusion of Rubin et al. [362] was that the more time a person had to spend commuting, the less that person would miss it.

Perhaps the most important question concerning the reduction in travelling and lockdowns is whether it impacted the spread of COVID-19. According to Gargoum and Gargoum [351], it did: countries that were faster to respond had significantly lower mortality rates per 100,000 people and managed to implement less strict lockdown strategies. Furthermore, the study highlighted that there is a potential positive correlation between (a) taking early action and lower mortality rates; (b) taking early actions and being able to maintain a higher level of mobility and (c) taking early action and the potential of observing an early recovery onset, thus setting a benchmark on disaster relief actions.

3.3.2. COVID-19 and mobility patterns

The hypermobile society enhanced the virulence of the contagion [363]. The virus quickly entered big international cities, rapidly spreading to the rest of the country, helped by the fact that people infected with COVID-19 become contagious before showing any symptoms or even being completely asymptomatic [364]. A study by Badr et al. [365], based on daily mobility data from mobile phones, has shown a strong correlation between mobility patterns and COVID-19 cases, with the lockdown resulting in lower mobility and consequently a decrease in the growth of COVID-19 cases for those same areas. Additionally, changes in mobility patterns were only perceptible after 9–12 days of COVID-19 transmission, consistent with the incubation time of the virus [365]. Similarly, Cartenì et al. [366] conducted a quantitative estimation through a multiple regression model to prove a connection between mobility and overall trips made within Italy and new COVID-19-positive cases.

3.3.3. Environmental flip of side of standing still

High levels of air pollution in cities are a serious environmental issue that most cities worldwide have been facing over the past few decades [367]. Several authors have found a positive correlation between air pollution levels and COVID-19 incidence and severity [368–370]. The positive correlation between urban transport and air pollution is also well documented [371,372], and indeed a reduction in travelling from lockdowns had a direct impact on pollution and air quality, despite the increase in the private car modal share. Lockdowns were, in fact, the first time in modern history where societies radically reduced global greenhouse emissions and improved both air and water quality [339,373–382]. With most of the cities in the world on lockdown, according to data from National Aeronautics and Space Administration and European Space Agency, pollution lowered by up to 30% in COVID-19 epicenters such as Italy, Spain, Wuhan or the USA [383]. It is however unclear whether this new evidence can change the willingness and capability of worldwide governments to promote policies and changes in transport planning to improve air quality and overall sustainability [381,384].

3.3.4. Public transport mid a pandemic

Several researchers agreed that public transport, as it was before COVID-19, was a prime space for person-to-person transmission [363,385–387]. Commuters are confined in small and limited spaces, which are more prone to virus transmission [302]. If there is active contagion on public transport, it is impossible to identify the passengers who might have been in proximity to the person infected [363]. Both public transport vehicles and stations have multiple surfaces that are constantly used by several people: leaving seats, handrails, doors and ticket machines prone to easy virus transfer surfaces [388]. Due to this, public transport was the most affected of all modes, both in terms of ridership and rider trust. Indeed, ridership plummeted all over the world, with examples such as Switzerland (90% decrease), Sweden (40–60% across regions), Curitiba, Brazil (80% decrease) or Santiago, Chile (reduction in subway trips of 55% and 45% in bus trips) [388–394].

COVID-19 temporarily brought to a halt the ongoing endeavours by municipal authorities to promote and raise public transport ridership, creating new challenges for both authorities and commuters [385]. Fear on the commuter side might take over, making it plausible that public transport is traded for other means of transport, as some reports have evidenced [395–397]. In fact, Thombre and Agarwal, and Das et al. [394,398] found an increase in car dependency, with people willing to shift towards the private car. Such a shift is, however, not desired; as Dong et al. [399] state, in a health crisis, public transport should protect passengers while still meeting travelling demand, improving their operational modes by increasing service frequency and ensuring physical distance among passengers. At this stage, it is still uncertain what the ramifications and long-term impacts of the pandemic truly are for public transport. However, the fostering of higher ridership levels has become more problematic.

3.3.5. Walking and cycling: towards a post-COVID-19 future?

As lockdowns were enforced, walking and cycling were observed by many as resilient and reliable modes of transport with a small risk of contagion. Cities observing this phenomenon started promoting cycling by creating new and additional bike lanes, reducing the prices of bike-sharing systems, restricting car circulation and creating incentives for bicycle purchases [400–402]. Zhang and Zhang [348] argued that the disruptions in spatial and transport planning might make it the right time for active mobility to seize the opportunity and gain even more momentum. This trend was also supported by recent research relating COVID-19 and active transport, which advocated for greater support and implementation of active transport solutions [350,360,362,363,401,403,404]. On the field, local and international entities are prompting green solutions aiming for the decline in car-based transport infrastructure in exchange for adequate cycling infrastructure [346].

Research by Teixeira et al. [405] has shown that despite decreasing ridership, bicycle-sharing systems have higher resiliency in comparison with public transport, and compelling evidence surfaced of a modal shift from public transport to bicycle ridership [387,406] and active mobility in general [407,408]. This is a positive sign for low- and middle-income countries, where public transport is often overloaded. Higher shares of walking and cycling can be beneficial by reducing public transport pressure [409].

More and more cities are including active mobility in their agendas, and this pandemic brought an opportunity for higher commitment alongside new and improved solutions. Cities in Italy, such as Turin, Naples, Milan, Bari and Palermo, are actively working on post-COVID mobility solutions [400]. England and France also recognised the opportunity and created investment packages for a new era of cycling [410,411]. Findings by Thombre and Agarwal [394] indicate that building new infrastructure can increase bicycle share from 31% to approximately 44% in India. Openness to new transport policies in favour of new car restrictions, more pedestrian space and a switch to more sustainable mobility gained more acceptance during the pandemic compared with normal circumstances [412]. The lockdown period drove a collective reflection on sustainability, which on its own, provides an important window of opportunities for change [339,412–419], and more attention to the promotion and implementation of active transport mobility [420,421]. It is now imperative to develop temporary and permanent new policies [346,411], which, if successful, might generate between $1 and $7 billion in health benefits annually [402]. A study by Buehler and Pucher [422] analysed and compared bicycle levels between 2019 and 2021 from 14 different cities and concluded that cycling levels generally increased from 2019 to 2021, mostly due to recreational and exercise trips, whereas cycling trips to work and education declined.

To achieve higher levels of sustainability in a post-COVID-19 era, urban transport policies must aim for higher resiliency, social equity and reduce the carbon dioxide emissions [349]. The authors show that some of these objectives may be achieved by combining adequate housing location and cycling promotion in an integrated policy. This suggestion was corroborated in recent research, which used quantitative arguments to argue that planned urbanism is a possible path to achieve equity and reduce the carbon dioxide emissions [16].

3.4. Conclusions and future research

Cities face new and daunting challenges in the post-COVID-19 era, with spatial and transport planning in the spotlight of a society that needs and must change [306,307]. Difficult and unusual decisions had to be taken during the pandemic, with limited knowledge by those taking them. Two years of dealing with the pandemic has resulted in publication of numerous papers concerning COVID-19 and pandemics in general, including those dealing with urban and transport planning issues. This review showed that the consequences of pandemics are now better understood at that level, and clear city planning implications begin to emerge. It was also observed that research at the beginning of the pandemic was mostly theoretical since little to no field data were available and that current research is starting to take a more practical approach. Concomitantly, new avenues of research have been opened for both academics and practitioners. Table 3.1. summarises the main findings of this review and suggests directions for future research concerning planning cities for pandemics. Figure 3.1 presents a visual framework for the findings, noting that the suggested links should be taken with a grain of salt since in an urban environment everything is interconnected; the links show only what are arguably the strongest relationships. An extensive description of the multiple aspects found in COVID-

19 research papers related to spatial and transport planning is presented in Volume II Table II.3.1.

Table 3.1. Conclusions and research opportunities.

Conclusion	Research Opportunities
C1. Disaster management plans for urban environments should include provisions for pandemic health crises.	R1. Design efficient and seamless lockdown areas based on spatial and transport planning procedures to prevent mass contagion.
C2. Large and dense built environments propitiate disease contagion.	R2. Deepening the link between contagion and compact development/high density living.
C3. Proximity-based parks and green areas mitigate lockdown effects.	R3. Development of methodologies which combine active accessibility to parks and green areas with contagion risk when those areas are small.
C4. The different and harsh reality of informal settlements does not fit in the typical solution for developed countries urban areas.	R4. Develop specific solutions for contagion mitigation in informal settlements. Monitor the efficacy of the solutions in the field.
C5. Lockdown-induced traffic reduction directly led to a reduction of air pollution and air quality improvement. A world-scale impact that would otherwise not be experienced.	R5. Use of data collected during lockdown for transport planning, mobility, and air quality analyses.
C6. COVID-19 added a health safety dimension to the choice of transport mode.	R6. Scrutinize the impact that this new perception has on commuters.
C7. Public transport experiences ridership losses during pandemics due to fear of contagion. The task of promoting and improving public transport became harder.	R7. Investigate effects of social distancing and respiratory etiquette on contagion within public transport. Issue recommendations to transport authorities.
C8. Active mobility, e.g., walking and cycling have proven to be safe and resilient modes of transport in urban areas.	R8. Use active accessibility studies to optimize the deployment of urban facilities. Work together with municipal authorities to design and implement cycling and pedestrian network infrastructure.

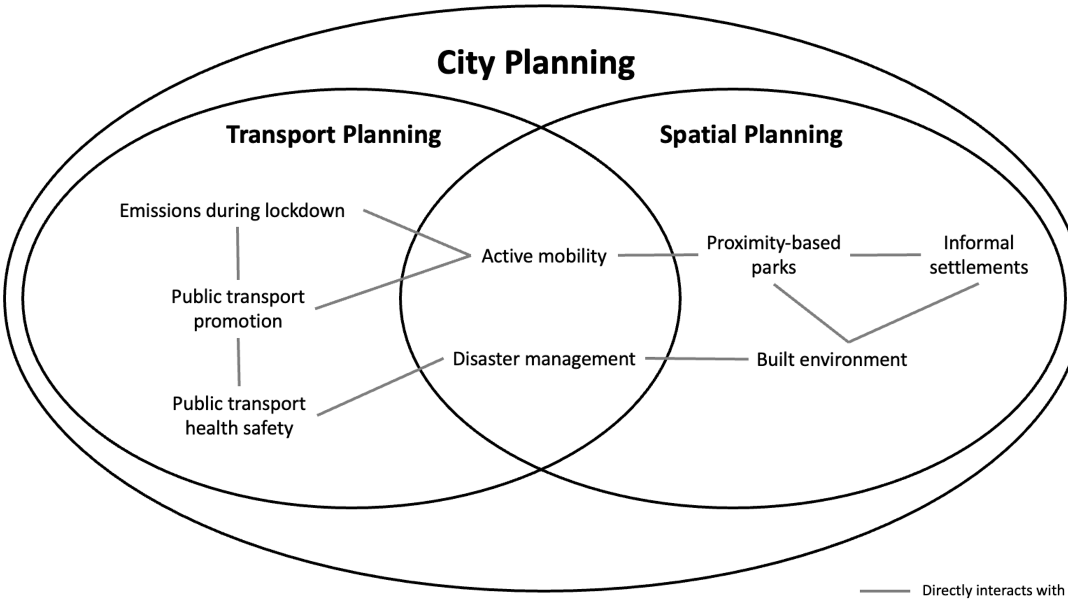

Figure 3.1. Findings framework.

Researchers are aware that there would be more pandemics in the future, however, societies need to be prepared. As Rojas-Rueda and Morales-Zamora [423] also concluded in their literature review:

"COVID-19 offers an opportunity to rethink the built environment and transport infrastructure with the aim to support short-term mitigation strategies and reduce long-term urban health inequities."

Research may look in a holistic manner at the future of society, cities, mobility and high interconnectivity, learning from this pandemic the mistakes and the right calls. If done properly, spatial and transport planning can mitigate mass disease dissemination, possibly even helping epidemiologists trace high-risk contacts while simultaneously catering for other urban and societal needs in the perpetual quest of achieving higher resiliency and sustainability for all.

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4. Benchmarking city layouts – A methodological approach and an accessibility comparison between a real city and the Garden City

"Beauty of nature, social opportunities, fields and parks of easy access, bright homes & gardens, no slums, freedom and co-operation" - Ebenezer Howard [4]

This chapter presents a comparative accessibility study between a real city and its redraft as a Garden City. The benchmarking methodology involves defining and evaluating a location-based accessibility indicator in a GIS environment for the city of Coimbra, Portugal, and for the same city laid out as a Garden City, with the same number of inhabitants, jobs, and similar number of urban facilities. The results are derived as maps and weighted average distances per inhabitant to the facilities and jobs, and show that, for the Garden City, average distances drop to around 500 m for urban facilities and 1500 m for the combination of facilities and jobs, making much of the city accessible by walking and practically the whole of it accessible by cycling, with positive impact on transport sustainability and accessibility equity. The methodology can be extended to other benchmarking indicators and city layouts, and the quantitative results it yields make a valuable contribution to the debate on the ideal layout of cities. Moreover, it gives directions on how to improve real cities to address current and future sustainability concerns.

4.1. Introduction

Cities are the main engines driving our economies, with over half the world's population living in urban areas [424]. Cities attract people by offering job opportunities, better education, healthcare, and living standards in general [3]. Due to their enormous complexity and importance in the modern society, modelling cities to achieve reliable quantitative predictions, contemplating their evolution and behaviour, and assessing and improving their sustainability, has become a major challenge for the modern world [425,426].

The ideal spatial layout of cities has been an active theme of debate for scholars, organizations concerned about the evolution and sustainability of urban areas, and municipal entities aiming to improve the living conditions of their citizens [427,428]. The past century has been prolific in such debates, with city concepts being proposed and studied, such as the Garden City, the *Ville Radieuse*, the Linear City, and the Transit-Oriented Development or Polycentric Cities [429]. Theoretical debates, however, lacked adequate quantitative analysis tools that could point out objective advantages of the different urban form ideas and provide comparisons, either between the concepts or between those concepts and real cities.

Current computer capabilities opened the possibility of putting theories and city concepts to the test. The bulky quantitative analyses needed to benchmark the various concepts are now possible using geographic information systems (GIS). Because urban layout, or form, is arguably the most strategic aspect of a city, with deep, lasting impacts at many levels, the capacity to obtain, from those layouts, quantitative figures on relevant indicators is an ability which provides meaningful evidence and guidance on how to plan and develop the city. It also paves the way for further analyses which rely on knowing those quantitative figures. This research makes use of the GIS capabilities of today, proposes a methodology to derive such figures using solely geographic characteristics of the spatial layout of the urban areas, and demonstrates it in a case study. It constitutes a first step towards a comprehensive comparative analysis between real and ideal cities based on the hypothesis that such analyses can provide a better understanding of the advantages of planned urbanism and transpose some of the learnings to practical contexts.

4.2. Review of research

Literature discussions on classic and contemporary city concepts have mostly focused on just one layout, addressing its virtues and shortcomings [235,430–432]. Some of these debates included quantitative measures, usually the evaluation of the impact of a particular idea, without implying major changes in the city structure [229,433,434].

Comparative studies between different city layouts were performed almost exclusively in a qualitative way. Classic debates include [435–437], whose impact in spatial planning influenced urban planning trends. The comparison made by Frey [436] stands out, concerning the potential performance of six city concepts: Core City, Star City, Satellite City, Galaxy of settlements (nowadays evolved into Transit-Oriented Development), Linear City, and Polycentric Net. The evaluation and comparison were made in terms of sustainability indicators and involved several assumptions. The results show that all concepts scored similarly, which can be justified by the inaccuracy and assumptions made during the process, as Frey himself recognizes.

Comparative analyses based on quantitative evidence are very scarce. In fact, only one such example was found in the literature, namely Yuan et al. [438], who compared accessibility to green areas between a real city, Zhujiajiao, China, and an urban form based on the Garden City, having found that the Garden City concept had better overall accessibility to those areas.

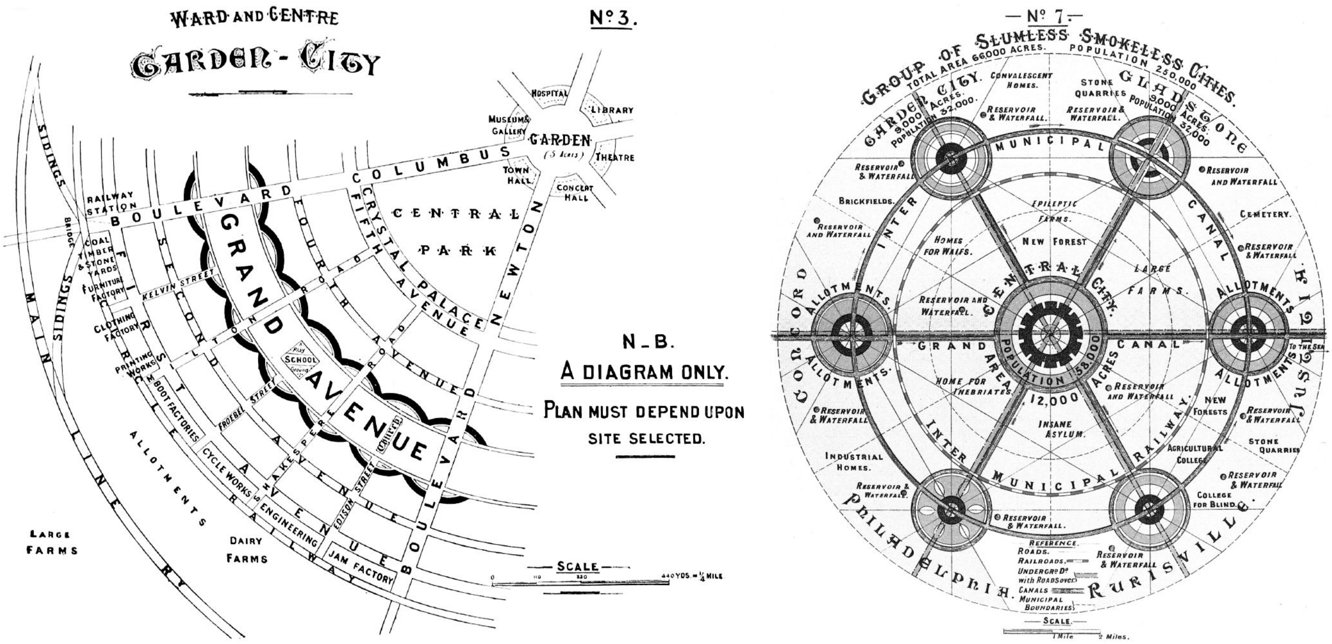
This chapter expands on previous research by combining quantitative aspects of the urban layout with comparative analyses between multiple layouts, providing new, quantitative arguments to the debate on the ideal city form. To do so, a methodology is proposed, based on the idea of considering the geographic elements of a real city, redisposing them in the layout of a classic or contemporary city concept, and using GIS to evaluate benchmarking indicators for the different layouts. The approach contributes to the literature on city concept benchmarking by providing a means to carry out comprehensive comparative analyses between real and ideal cities based on quantitative indicators, which depend solely on the urban spatial layout. Taking accessibility as an indicator, the methodology is applied to the real city of Coimbra, Portugal, and its redraft as a classic city concept, the Garden City. This case study shows that quantitative benchmarking of city concepts is a promising idea, which can open new avenues of research and contribute to the long-standing debate of the ideal layout of cities and its sustainability and planning implications.

4.2.1. Overview of real cities and the Garden City

Real cities evolved and grew based on different ideas and concepts, incorporating many influences along the years, and leading to organizing layouts that reflect these multiple trends and interests [439–441]. A few decades ago, priority was put on big avenues to sustain motorized transport, whereas nowadays those same avenues are receiving bigger sidewalks and cycleways at the cost of traffic lane space, aiming to promote sustainable and active mobility. The city of Coimbra is one such case of long-term evolution, accumulating changes over one millennium, with an urban form influenced by different trends and urbanistic pressures [442].

The Garden City was proposed by Ebenezer Howard over a century ago [4] as a city concept that would combine the attractions of city life, affordable housing, and a pleasant environment. Kremer et al. [443] considered it one of the origin theories of urban sustainability, and it remains inspiring in many aspects [203]. The Garden City was chosen for demonstrating this research because it is one of the most debated city concepts in academia and frequently used as a paradigm in sustainable urban and spatial planning [429]. It is presented as a theorical example of an alternative urban layout. No claim is made on it being a goal of urban expansion or a natural endpoint of it.

The Garden City would hold around 30,000 inhabitants in its hallmark circular shape. Ringlike concentric zones of specific land use alternate between urban facilities, residential areas, roads, green spaces, and an exterior railway. Radial boulevards connect the outskirts to the center and divide the city in six wards (Figure 4.1a). In Howard’s vision, city expansion would be accommodated by establishing new garden cities with connections such as those in Figure 4.1b, forming a cluster of “Social Cities”, a polycentric city layout. Enlarged versions of Figure 4.1 can be found in volume II (Figure II.4.1).



(**a**) (**b**)

Figure 4.1. (a) Layout of a Garden City ward; (b) and Social City [4].

The Garden City remains an active topic of research in urban planning and cities been built based on this concept, such as Letchworth and Welwyn (UK) or Almere (Netherlands) [444]. Modern adaptations were used in city expansions of La Coruña (Spain) and Brøndbyvester (Denmark). Some features of the Garden City, e.g., the abundance of green areas, were adopted in the contemporary concepts of Eco-Cities [429] or Smart Cities [445]. Despite this, Yuan et al. [438] points out that Howard's theory has only been considered qualitatively, and Morris et al. [446] recognized that few studies have been devoted to confirming the validity of the concept, making it important to revisit the concept, especially considering today's sustainability concerns.

4.3. Methodological approach

The main idea of the methodology is as follows: consider the geographical location of the building blocks of a city (buildings, road network, etc.) and evaluate how well they serve the population using a quantitative benchmarking indicator (or several). Then, in a GIS, geographically redistribute those building blocks so that the city assumes the form dictated by the urban layout(s) one wants to compare with one another. The redistribution should be conducted maintaining the same number of inhabitants and a similar number of urban facilities. Finally, recalculate the benchmarking indicator(s) for the different urban layouts under comparison. The layouts can then be compared using the values obtained for the indicators.

4.3.1. Benchmarking indicador

In the case study's Section 4.4, accessibility was taken as the benchmarking indicator. Other indicators could be used as well, provided they can be calculated on a GIS. This point is essential, as even small cities have very high amounts of geographic data associated with them. The choice of accessibility to demonstrate the methodology was made because it is a very important concept in transport and urban planning [447,448] and recognized as a path in achieving sustainable development [449]. Other benchmarking indicators will be researched in the near future (see Section 4.6.2).

Accessibility is a wide concept related to urban spatial layout, qualities of the transport and land-use systems, and economic and environmental goals [450], which can be interpreted and calculated via different approaches. This research uses the classic definition of accessibility as the ease, or more widely, the cost of reaching destinations [451]. Cost-based approaches to accessibility use time or distance measures and are frequent in the field of spatial and transport planning, as acknowledged by several authors [452–456]. Specific examples are: Apparicio et al. [457], who used a range of accessibility measures (including cost based) to compare discrepancies in accessibility to healthcare services; Gutiérrez and Urbano [458], where a weight-averaged impedance, i.e., generalized cost of going from origin to destination, usually time or distance, was used to evaluate the impact of the trans-European road network; Ryan and Pereira [459], on which travel time was employed as impedance to estimate accessibility to grocery stores and healthcare centres; and Shen et al.

[460] and Zhou et al. [461], which used direct home–facility network distance as accessibility measure. The measure of accessibility used here is based on origin–destination (OD) network distances and was chosen because of its flexibility and ease of interpretation, an important point because for planning purposes accessibility measures must be understandable to policy makers [462]. Other measures or formulations of accessibility could be used as well, without any loss of generality, provided their evaluation in a GIS is feasible. In Vale and Pereira [463], a review on other measures was carried out focusing on exponential, power-law, Gaussian, and cumulative Gaussian probability decay functions, which have impedance as argument. Accessibility was then evaluated as trip probability times the number of opportunities at the destination zone.

The accessibility indicator selected was inspired by the above references and is akin to that used in [464]. It is given by:

$$A_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} d_{ij}^k}{\sum_k L_{kj}}, \tag{4.1}$$

where
i: 1, … , I number of origins;
j: 1, … , J number of facility types (includes jobs);
k: 1, … , K number of closest facilities (when it applies), and in this thesis, $K = 3$;
A_i: accessibility score of origin i;
d_{ij}^k: network distance from origin i to the k-th closest facility of type j (or job zone centroid).
w_j: weight of facility type j (destination attractiveness);
L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

This indicator can be interpreted as the average distance from origins to destinations, weighted by destination attractiveness and by choice factor. Its interpretation as a distance allows for important conclusions to be readily derived, which was the main reason this indicator was selected. Other accessibility indicators could be used, such as the decay functions of [463] or log-logistic decays. These are programmable in GIS but would require parameterization of the decay functions. Moreover, their A_i output values would be harder to interpret. The $L_k(j)$ can be interpreted using $L_k(j) = \{70,20,10\}$, as an example, a 70% preference for the closest facility, 20% preference for the second closest, and 10% preference for the third closest. The reason for including this factor is related to the cost nature of accessibility as measured by Equation (4.1) and is discussed further below.

4.3.1.1. Building blocks for evaluating accessibility

The origins are residential locations and destinations are jobs and urban facilities, segregated by type and weighted by attractiveness. A street's network connects origins and destinations, and distance is evaluated along this network. Attractiveness weights need to be considered when evaluating accessibility [448,464] and are assigned by the decision maker for each destination type based on trip frequency. Table 4.1. shows the weights chosen for this research, with higher weights meaning trips to the corresponding destinations are likely to be more frequent. For urban facilities, these weight values are consistent with trip frequencies per facility type found by the UK Government [465] and were also used in [466,467]. For jobs, the percentage of commuting trips was considered, and a weight was assigned accordingly. For Coimbra, this percentage is 37% (survey data), leading to $w_j = 22, j$: jobs, as for this value, one has $\frac{w_{\text{jobs}}}{\sum_j w_j} = \frac{22}{60} \approx 37\%$.

Table 4.1. Facility types and jobs weights.

Weight 1 Facilities $w_j = 1$	**Weight 2 Facilities** $w_j = 2$	**Weight 3 Facilities** $w_j = 3$	**Jobs** $w_j = 22$
Post offices [1]	High Schools	Kindergartens [1]	Average job locations (Section 4.3.1.2)
Sports facilities	Shopping centers	Primary schools [1]	
Cultural organizations	Entertainment sites	Middle Schools [1]	
Universities and institutes	Primary healthcare services [1]	Grocery stores	
Elderly care centers	Pharmacies [1]	Supermarkets	
Churches	Restaurants	Bakeries and pastries	
	Parks and green areas		

[1] Type 1 facility.

Multiple facilities (opportunities) should be considered in accessibility [453]. However, when accessibility is a distance, higher values of A_i are generated as more destinations are considered, leading to the degradation of the indicator. Thus, instead of considering all facilities of a given type, the OD distance is calculated for the *k*-closest facilities of that type and weighted by the $L_k(j)$ factors. These factors are monotonously decreasing in *k* because the further a facility is, the less likely it is to be visited. This approach, also used by Brimberg et al. [468], models demand for multiple facilities while preserving the interpretation of accessibility as a distance.

However, for some facility types only the closest one is relevant (type 1 facilities, j_1, marked in Table 4.1). Type 1 facilities always have $L_k(j_1) = \{100,0,0\}$ and for other facilities (type 3, j_3), three sets of L_k were used: $L_k(j_3) = \{100,0,0\}$, $L_k(j_3) = \{70,20,10\}$, and $L_k(j_3) = \{50,35,15\}$ (ascending order of k).

4.3.1.2. Accessibility to jobs

Accessibility to jobs requires a different treatment for two reasons. First, jobs are at fixed locations: there is no "closest job". Second, knowing where the people from each origin work requires large scale surveys, which are in general not available. To deal with these issues, the following approach was used, inspired by Traffic Analysis Zone [454,469]: identify job locations and employee count, divide the city into zones, count jobs in each zone, and find the geometric average job location of each zone. Finally, for each origin, calculate distance to each average job location and ponder it by the percentage of jobs in the respective zone. Equation (4.2) summarizes this.

$$d_{ij}^1 = \sum_z p_z d_{iz}, \qquad j\text{: jobs} \tag{4.2}$$

where
d_{ij}^1 (j: jobs): distance from origin i to jobs.
z: $1, \dots, Z$ number of job location zones.
p_z: percentage of jobs in zone z.
d_{iz}: distance from origin i to average job location in zone z.

Jobs are type 1 destinations, and d_{ij}^2 and d_{ij}^3 are defined as zero. High distances to jobs affect the choice of residence location, so p_z job percentages may need to be corrected by decay factors, depending on the origin. However, average job distance in Coimbra is around 5 km, which is below the 6–10 km thresholds presented by de Vries et al. [470] and Goel [471] for that effect to start, so no corrections to p_z were needed. Alternative treatments to job accessibility include, e.g., simulation-based methods [472,473].

4.4. Case study

The case study consists of a comparison between the city of Coimbra, Portugal, as it stands and its redraft as a Garden City, using Equation (4.1) as the benchmark. The building blocks considered for the two layouts were those of Section 4.3.1.1, namely origins, destinations, and the road network. Details on the methodology implementation are now described. All the operations were carried out in the ESRI ArcGIS 10.7 environment.

4.4.1. The city of Coimbra

4.4.1.1. Origins

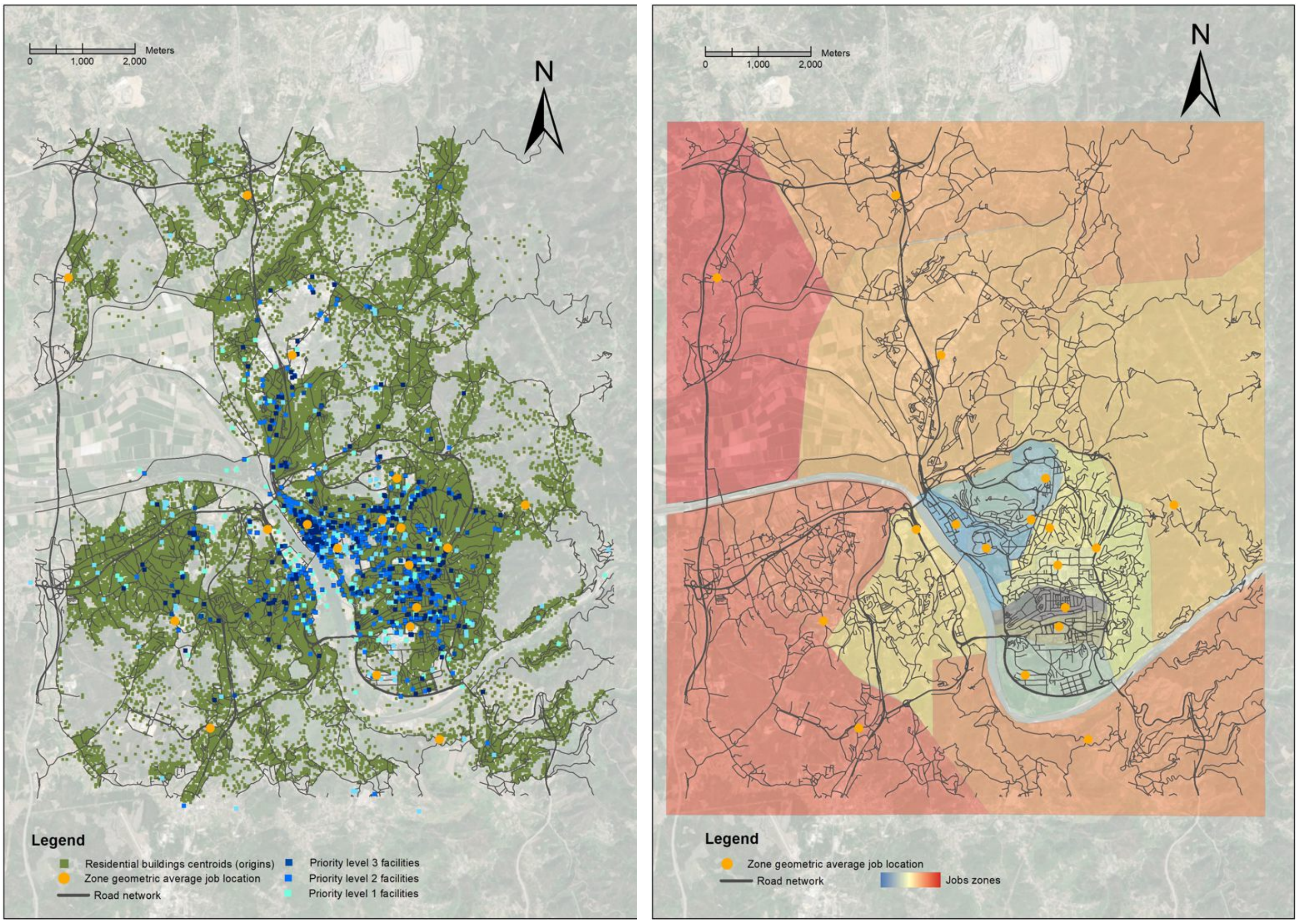
Origins represent demand (for trips) and are the residential centroids over the study area. Official Portuguese GIS databases were used. The residential centroids are the set of origins i (Figure 4.2a).

4.4.1.2. Destinations: Urban facilities and job locations

The location of and type urban facilities of Coimbra was obtained (Figure 4.2a), as well as job locations and employee count. Average job locations are depicted in Figure 4.2b. Zones were drawn considering population density, buildings, jobs, and existing administrative divisions.

4.4.1.3. Road network

The detailed road network of Coimbra was obtained from OpenStreetMap and is displayed in Figure 4.2a.



(**a**) (**b**)

Figure 4.2. (a) Coimbra origins, urban facilities, and road network; (b) Coimbra job zones and geometric average job locations.

4.4.2. Coimbra as a Garden City

To redraft Coimbra as a Garden City, the description and blueprints of Howard [4] were followed, with adaptations stemming from Coimbra being a city of services, with healthcare and higher education as main activities. Since Coimbra has 104,000 inhabitants, in the redraft, Coimbra was extended from a Garden City to a Social City of three interconnected garden cities, placed in overlap with the main urban zones of real Coimbra. This was performed so that the two layouts would be closer to each other.

4.4.2.1. Origins

Residential buildings were located in the two circular rings allocated to this land use in each garden city. Area calculations show that each inhabitant has around 61.5 m^2 living space, which compares with 47 m^2 in real Coimbra (see Volume II Section 4 for details).

4.4.2.2. Destinations: Urban facilities

Facilities were distributed by the four ringlike areas corresponding to their land use, with the necessary adaptations, following Table 4.2. The number of facilities of each type, dimensions, and construction areas were defined using information for Coimbra and the space available in Coimbra as a Social City. The Social City has more post offices and parks than Coimbra but fewer neighborhood facilities because it is more compact and requires fewer of these facilities to be distributed. The location of some larger facilities was based on their homologous location in Coimbra: regional hospitals were placed in the outerings, close to the same place where they sit in the real city.

Table 4.2. Facility distribution in Coimbra as a Garden City.

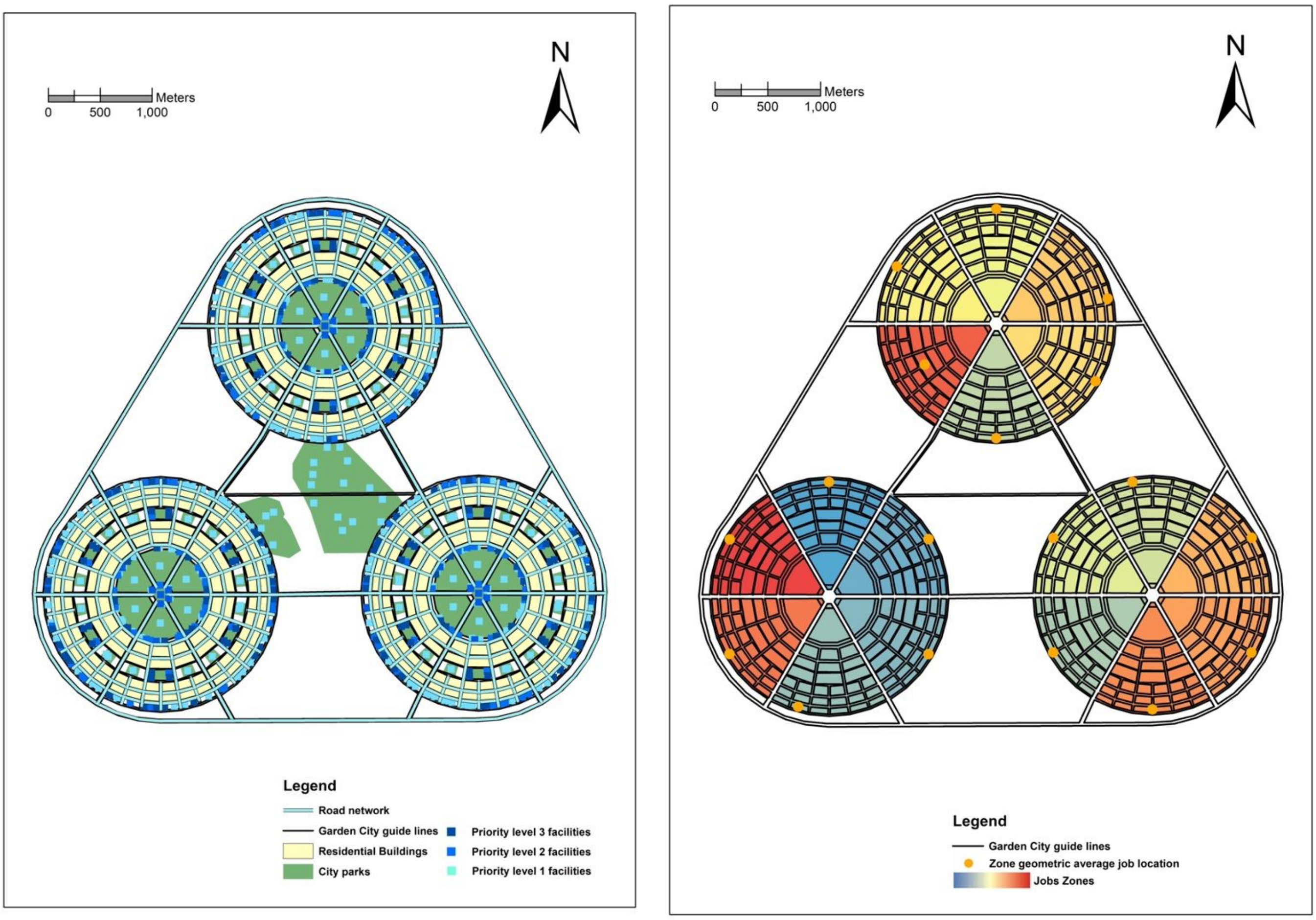
Area	Function [439]	Facilities on Coimbra as a Garden City
Inner Ring	Civil service, healthcare, and cultural buildings	Civil service, healthcare, and cultural buildings
Crystal Palace	Cultural and recreational areas and small shops	Small shops, cultural spaces and associations, post offices, pharmacies, restaurants, and pastries/bakeries
Grand Avenue	Green spaces, schools, and places of cult	Parks, schools, and places of cult
Outering	Industry	Shopping centers, supermarkets, entertainment sites, sports facilities, cultural organizations, restaurants, bakeries, regional hospitals, and elderly care centers
Green Belt	Agriculture	Parks, cultural spaces, and sports facilities

4.4.2.3. Destinations: Jobs locations

Top job locations of Coimbra (100+ employees) totalize 41% of jobs. Some of these correspond to large urban facilities with precise location (e.g., hospitals and universities), others to private companies which were placed in the outerings. The remaining 59% of jobs were placed in the ringlike areas of the Social City, distributed according to ring area. The job zone division coincides with the wards (6 per garden city, 18 total).

4.4.2.4. Road network

The road network was drawn based on Howard's specifications, and all streets are two way. The result, Coimbra as a Garden City, is seen on Figure 4.3. Real Coimbra has circa 11 km size (Figure 4.2), which compares with 5 km for the more compact Garden City. See volume II section 4 (Figure II.4.2). for a side-by-side comparison. The urban sprawl of Coimbra suggests higher average distances to facilities and jobs, but since the city center has high population density and the suburbs have neighborhood facilities, it is not clear beforehand what the differences will be.



(**a**) (**b**)

Figure 4.3. (a) Coimbra as a Garden City; (b) job zones and geometric average job locations.

4.4.3. Accessibility analyses

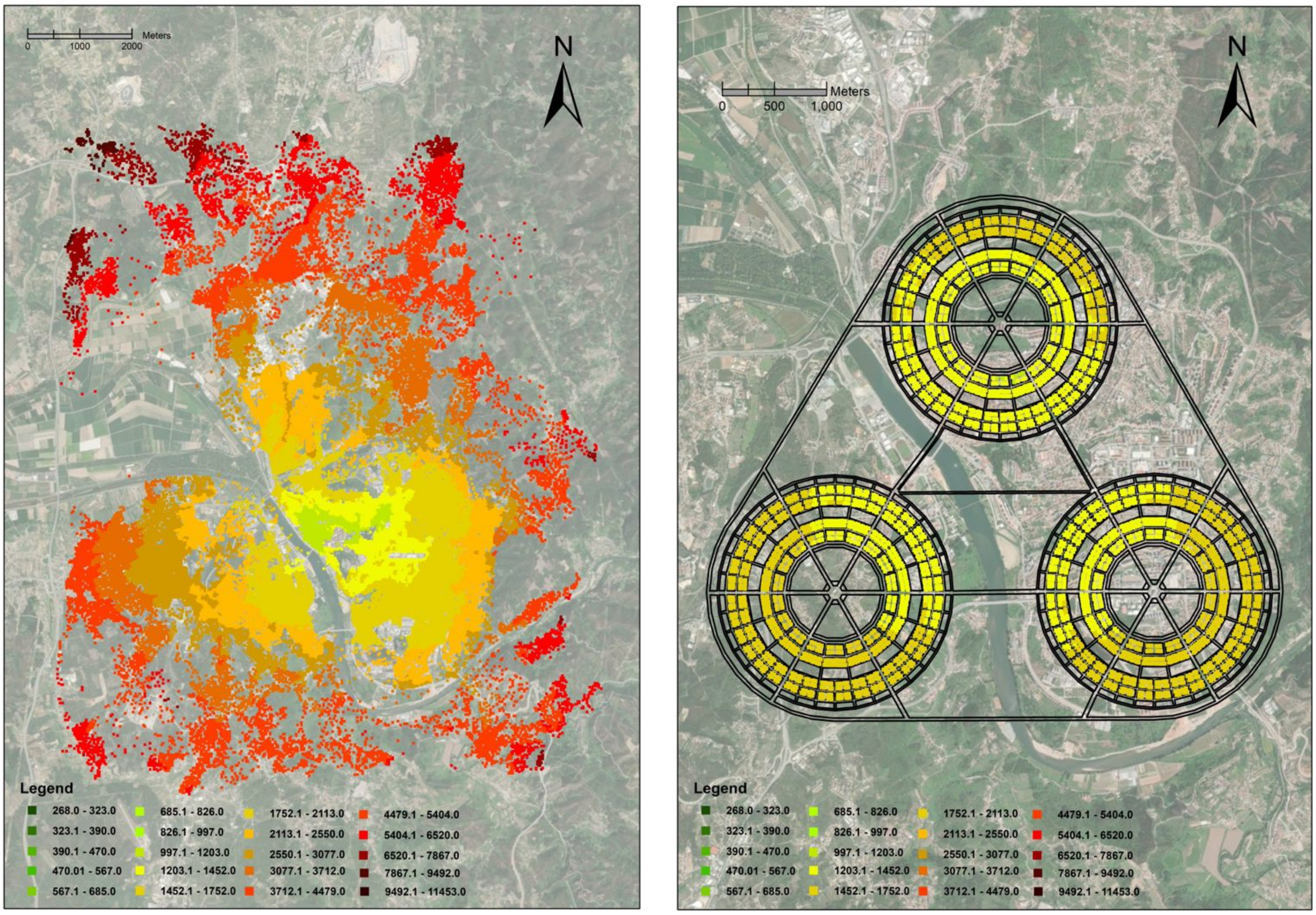
Network distances to the closest facilities and average job locations were obtained in ArcGIS for every origin. A base scenario with $L_k(j_3) = \{70,20,10\}$ was considered, and three sets of results for A_i were derived for each layout implementing Equation (4.1): accessibility to (*i*) urban facilities; (*ii*) jobs; and (*iii*) facilities and jobs (overall accessibility). Analysis (*i*) is justified because a significant fraction of the population is retired or not in the job market. In addition, people who live in Coimbra but work outside the study area are mostly interested in accessibility to facilities only. Analysis (*ii*) was made for completeness. A sensitivity analysis for the other sets of $L_k(j)$ was also carried out.

4.5. Results

Base scenario maps for overall accessibility are shown in Figure 4.4. Full maps for all results are given in the Volume II (Figures II.4.3–II4.9). Table 4.3. displays summarizing statistics for all analyses. The statistical measures are calculated over the set of A_i values, except for "average per inhabitant", which was calculated from $\frac{\sum_i h_i A_i}{\sum_i h_i}$ with h_i the population of origin *i*. The bold highlighted values are the main result for the base scenario.

Table 4.3. shows that the Garden City layout provides better accessibility scores in all cases, proving that urban sprawl has a large impact on accessibility, in line with similar results in the literature [474]. This difference is especially relevant when only the urban facilities are considered, as inhabitants in the Garden City would be, on average, almost one-third the distance to those facilities, as compared with Coimbra (530 m vs. 1440 m, three significant digits; see Figure II.4.3 for a map). This result shows that for most trips to facilities, inhabitants of the Social City stay within their garden city of residence. When jobs are considered, this drop in distance also appears, with the Garden City exhibiting on average 59% of the distances of Coimbra for overall accessibility (1490 m vs. 2530 m) and 71% for jobs only (3160 m vs. 4420 m; Figure II.4.4). The average distances for jobs show that, more often than not, inhabitants commute between different Garden Cities of the Social City, making it important to provide for adequate mass transit systems in the social city. As the Garden City is more compact, the result of shorter trip distances is not surprising and is expected hold for other compact layouts. However, the actual value of the difference is important and novel, as it required making the methodological calculations using the

benchmark, Equation (4.1). Travel distance reduction also means a reduction in travel time and can impact quantities beyond accessibility, such as energy consumption or GHG emissions, which are not linear with travel distance because, as distances shorten, active mode trips (efficient and emissions-free) become more likely. Active modes may also lead to better travel satisfaction [475], so the Garden City has the potential to become a more pleasant and energy-efficient city concept.



(**a**) (**b**)

Figure 4.4. (a) Overall accessibility (facilities and jobs) for $L_k(j_3)$ 70/20/10, Coimbra; (b) and Coimbra as Garden City.

Table 4.3. Accessibility summarizing statistics.

Average accessibility per inhabitant (m)		Urban facilities		Urban facilities and jobs (Overall Accessibility)		Jobs only	
$L_k(j_3)$	Measure	Garden City	Coimbra	Garden City	Coimbra	Garden City	Coimbra
100/0/0	Min	332	223	1143	1041	2403	2427
	Max	629	7908	1884	9208	4100	11,453
	Average per inhabitant	462	1352	1452	2478	3161	4421
	Average	461	1833	1451	3023	3159	5078
	Standard deviation	57	1321	173	1461	440	1766
	Coefficient of variation (no unit)	0.12	0.72	0.12	0.48	0.14	0.35
70/20/10	Min	411	268	1194	1063	2403	2427
	Max	705	8099	1914	9329	4100	11,453
	Average per inhabitant	**529**	**1440**	**1487**	**2533**	**3161**	**4421**
	Average	528	1936	1486	3088	3159	5078
	Standard deviation	56	1352	171	1483	440	1766
	Coefficient of variation (no unit)	0.11	0.70	0.12	0.48	0.14	0.35
50/35/15	Min	461	295	1228	1076	2403	2427
	Max	761	8230	1934	9412	4100	11,453
	Average per inhabitant	573	1498	1511	2570	3161	4421
	Average	572	2003	1510	3130	3159	5078
	Standard deviation	58	1374	170	1497	440	1766
	Coefficient of variation (no unit)	0.10	0.69	0.11	0.48	0.14	0.35

To quantify this potential, note that the average distance per inhabitant to facilities in the Garden City ranges from 460 m to 570 m. This is slightly above traditional guidelines of a quarter mile (400 m) for walking distance but is below recent research that points to 800 m [476] and 700 m [477] as acceptable distances. So, with respect to facilities, Coimbra as Garden City is mostly a walkable city. This conclusion is also important, as commerce and service activities available close to home are likely to be more important than a short commute [478,479]. Concerning cycling, Huang [472] reported average cycled distances of 3800 m in the USA, while Mouratidis et al. [475] mention 3890 m averages for commuting trips, with 3070 m median, in Canada (figures are similar in Europe). The maximum overall accessibility travel distance for the worst-located inhabitants in the garden city sits between 1890 m and 1930 m, well within cycling range. With trip distances of 5 km between far away points in the Social City, the bicycle is a viable option for most trips within the social city and a strong candidate for commuting trips. The high number of green spaces in the social city may also foster cycling [480,481].

The situation for Coimbra is quite different. With average distances per inhabitant to facilities ranging between 1350 m and 1500 m, Coimbra is far from walkable for everyone. Looking at overall accessibility, average distances sit around 2530 m and maximum distances raise to 9330 m. For jobs, these climb to 4100 m and 11,450 m. The bicycle may still be a viable mode for the average citizen of Coimbra, but the worst-located inhabitants clearly live outside cycling range. With 83/52/29% of inhabitants living more than, respectively, 3070/3890/5000 m away from their job (GIS calculations), the potential for commuting by cycling is significantly more limited than that of the Garden City, whose homologous percentages are 53/7/0%. This is an important conclusion, as it shows that motorized transport modes are almost inescapable for many inhabitants of Coimbra, with the inevitable consequences of increased GHG emissions, rush hour traffic jams, and parking space use. While some neighborhoods in the outskirts of Coimbra have grown to the point where small businesses and local facilities started to appear, results show this urbanization of the suburbs was insufficient to provide for all the services needed.

Another insight that is very visible from Figure 4.4 is that the Garden City provides much more accessibility equity than the real city. This social impact is confirmed by Table 4.3., which exhibits much lower values of dispersion measures for the Garden City, in striking contrast with Coimbra, where a clear difference exists between those who live close to most facilities and those who live far away from just about everything.

4.5.1. Impact on the environment and sustainability

In what concerns transport sustainability, the Garden City is arguably a more sustainable layout than the real city, due to reduced sprawl and higher potential for active travel, as argued above. More sustainability aspects exist, however, and further research is needed to know how Coimbra compares with the Garden City in those aspects. Transport-related aspects are, however, important given that cities consume 78% of the energy and emit 60% of greenhouse gases [482], so any action which can reduce urban energy consumption and emissions has a large impact on the environment and sustainability. The fact that the methodology provides quantitative measurements makes it possible to estimate that impact in terms of miles travelled, which can then be translated into energy and emissions savings, and reduction in air pollution.

The ringlike regular geometric layout of Garden City also makes it easier to plan for public transport. Natural two-way bus lines flow through the circular avenues and across radial directions within each Garden City and the Social City. With adequate scheduling, it is conceivable that more passengers use mass transit rather than a private car, leading to further energy efficiency and benefits to the city and its inhabitants.

4.5.2. Sensitivity Analysis

The three $L_k(j)$ cases analysed yield similar results for all measures, as Table 4.3. shows. The differences can be explained as follows. As per Equation (4.1), as accessibility indicators degrade, $L_1(j)$ decreases. For accessibility to urban facilities, this degradation is about 14% for Coimbra and 27% for Coimbra as a Garden City, slightly hinting that the Garden City is more geared towards having *some* facility of a given type nearby, rather than a variety of choices of facility type. For the overall accessibility, this degradation drops to 3–4% in both cases because of the impact of jobs, a fixed location effect. See supplementary materials for maps.

4.6. Discussion

The past few decades brought forth new perspectives on sustainability, and urban areas should be prepared for the future [483,484]. Such paradigms include better accessibility and overall proximity [485–487], compacting cities and fighting back urban sprawl [488,489], citizen equity [490], and a rising importance of public green spaces and recreational areas [491,492]; the latter having an impact on quality of life, city pleasantness, and the environment. A good urban form also leads directly to better transport planning opportunities [493–496] and, currently, one of the main focuses of transport planning is the active modes, its health benefits, and potential for lower energy consumption [125,497–501]. The accessibility comparison between Coimbra and its redraft as a Garden City provides quantitative evidence which can help judge the pros and cons of the two layouts considering those new paradigms. The better accessibility of the Garden City layout arguably puts it as the frontrunner in some of them, while not being excessively compact, a characteristic which research mentions as desirable only up to a point [235]. Nevertheless, trends exist which advocate that the city is akin to a living, self-evolving organism, much reflecting the people who live in them [502], and whose growth is not likely to follow predefined theoretical layouts. This research presents quantitative elements for all to judge, foresee, and ultimately make decisions, regardless of what the future may bring. The Garden City scores well in accessibility and equity, but other aspects exist which determine whether an urban layout becomes successful or is abandoned. These also need to be looked at in urban planning and, all things considered, it may turn out that the Garden City is not ideal or has a limited scope of appeal.

4.6.1. Impact in city planning

Despite the good accessibility and equity scores of garden cities, it is not expectable that real cities are rebuilt in a more efficient manner, as the costs and resource spending would be prohibitive, as well as the associated inconveniences. Still, practical applications of the results found in this research may come in two ways.

4.6.1.1. Cities expansion programs

Social movements from the countryside to cities and among cities make city growth the main trend nowadays. This inevitably leads to the development of new city areas. This research suggests the Garden City is one possible way of planning city expansions if the sought-after emphasis is on efficiency, sustainability, and promotion of active travel modes and healthier lifestyles. This layout is being considered for the expansion of the suburbs of London to the greenbelt [503], as well as all around England [504,505]. The methodology also enables decision makers to analyze past layouts of expansions and compare them with new proposals to make predictions about the future of cities, a point Günaydin and Yücekaya [506] deemed as very important.

4.6.1.2. Building new cities

Albeit rarer than expansions, examples exist of new cities sprouting up, mainly in Asia and Africa [507], offering a natural stage for implementing new city concepts based on purposeful long-term planning. The challenges faced decades ago are vastly different from today’s challenges, but the priorities are still the same: quality of life, economic growth, and a clean and green environment. The present study shows that old ideas such as the Garden City remain current and worthy of attention by decision makers. China in particular has developed a national Garden City program, aiming at building pilot low-carbon cities [508].

4.6.2. Future work

Future developments involve researching quantitative indicators that go beyond accessibility, as transport-oriented benchmarks tend to favor city compactness. Other measures are necessary for a wider, holistic view. For instance, people tend to avoid excessive concentration, so a benchmarking indicator should be sought after that relates the urban layout and its compactness to how satisfied citizens might be with the city where they live, i.e., an urban pleasantness indicator. A mix land-use indicator can also be used as benchmark.

Transport-oriented benchmarks remain nonetheless important, and more indicators that go beyond network distances could be developed based on the methodology, such as, e.g., the active modes share or the quantification of the potential impact of this share on energy expenditure and GHG emissions, the latter exhibiting a double effect as distances shorten: less distance per se and more active travel. Two mobility-related indicators can also be developed and tested for: network directness [509], i.e., the quotient of network distances by Euclidean distances, and a benchmark of the road hierarchy. The latter could be evaluated by looking at the route profiles of accessibility-related trips and checking to what point they may promote traffic flow, prevent jams, and avoid rat-running, i.e., the use of local access roads by long distance traffic.

All these indicators can then be tested using Coimbra and Coimbra as a Garden City as prototypes, as well as others in classic and contemporary city concepts (e.g., TOD, compact city, or transect planning) with an aim at creating a complete city concept benchmarking methodology.

4.6.3. Limitations

While the application of the methodology to multiple cities (real and/or classic and contemporary concepts) and benchmarking indicators may shed light on the debate of ideal city layout and provide quantitative elements for decisionmakers and the public, its application at a practical level is limited by the fact that real cities' layouts are typically very static or evolve slowly and are unlikely to change based solely on benchmarking results. This is the main limitation of the methodology because it restricts its practical use to the situations of Section 4.6.1 (city expansions and new cities), and even then, driving forces may exist that are stronger than planned urbanism.

From a more theoretical point of view, methodology limitations stem mainly from the assumptions on how the indicators are modelled and evaluated. For example, the accessibility indicator used in this research requires some parameterization and does not cater for chained trips, i.e., round trips which include stopovers at multiple facilities (jobs included or not). Moreover, it does not consider orography, floodplains, and other geographic facts, which are nontrivial determinants of city growth and may constrain constructive solutions. Finally, for large cities, job distance decay functions need to be considered, complexifying the analysis.

4.7. Conclusions

In this chapter, a quantitative comparison between the accessibility of a real city and its redraft as a Garden City was made. The benchmarking methodology took the building blocks of the real city of Coimbra, Portugal, and redisposed them geographically in a Garden City layout with three centers in a GIS environment. After defining a distance-based accessibility measure, the two layouts, real Coimbra and Coimbra as a Garden City, were then compared. The benchmarking methodology and the accessibility comparison are the two main and novel results of this research.

The results show that accessibility of the Garden City is superior to that of Coimbra, with average distances to urban facilities dropping from 1500 m in Coimbra to circa 500 m in the Garden City, a walkable distance. When jobs are considered, average commuting distance drops from 4500 m to 3000 m and the overall accessibility (facilities plus jobs) drops from

2500 m to 1500 m. The distance reduction is mostly due to the Garden City having less urban sprawl, showing this layout is mostly walkable and fully cyclable, thus exhibiting a high potential for a shift to active transport modes. These provide for more efficient, sustainable, and healthier lifestyles that are also environmentally friendly. The extent to which a real city could be organized in a walkable/cyclable way is a nontrivial result and could only be reached by performing the bulky calculations mandated by the methodology.

This study shows that benchmarking real cities versus classic and contemporary city concepts is possible with the proposed methodology, which can (and should) be extended to other benchmarking indicators and city layouts. This would open new windows of research on the debate on the ideal form of cities, as well as allowing for a better understanding of how to plan upcoming city expansions.

5. The potential impact of cycling on urban transport energy and modal share: A GIS-based methodology

"By being sweet to the pedestrian and the cyclist you hit five birds with one stone – you get a lively city, you get an attractive city, you get a safe city, you get a sustainable city, and you get a city that's good for your health. These are all things we are very concerned about at this time in history." - Jan Gehl

This chapter presents a methodology to estimate the maximum potential impact of a well-built and conserved cycling infrastructure, measured as modal share for accessibility trips, as well as the associated transport energy that can be saved in those trips. The methodology uses Geographic Information Systems (GIS) to estimate active trip probabilities, from which the output variables can be obtained. It was applied to a case study of a mid-sized city in Southern Europe, and results show that an adequate cycling infrastructure can achieve cycling mode share in that city on par with the world's most cycling-friendly cities. Concerning transport energy, a full-cycling scenario is estimated to reduce fossil energy intensity by approximately 20%, mainly by inducing a mode change for residents on the closest outskirts. It is also argued that cycling investment in commuting routes will have the most impact on reducing fossil transport energy.

5.1. Introduction

Rising concerns over traffic congestion in cities, greenhouse gas emissions (GHG), transport energy spending, and related health issues have led to a surge of interest in active mobility from academics, practitioners, and policymakers [123–125,499,500,510–513]. Cycling, in particular, has been a prominent research topic in both transport and spatial planning, with many studies highlighting its importance and benefits as a means of transport and commuting solution. Cycling is a promising mode of transport for urban mobility, ideal for trips up to 5 km [514,515], has low energy intensity and near-zero emissions, and thus has been increasingly recognized as a cleaner, healthier, and overall more sustainable mode of transportation [422,515–519]. Cycling is also an affordable, low-congestion, and readily available mobility option, which can cover large areas and daily movements when urban areas are dense enough [520]. Commuting by bicycle also has important indirect health benefits for surrounding inhabitants [497,521].

The benefits of cycling prompted major international authorities, such as the Organization for Economic Co-operation and Development (OECD), the European Commission (EC), and national and municipal authorities, to promote, invest in, and create the necessary infrastructure for it to become a viable daily means of transport [411,520,522–532]. Furthermore, the unexpected SARS-CoV-2 (COVID-19) pandemic has also played an important role in the last years, with climate-friendly transportation solutions that indirectly enforce social distancing starting to be seen as pandemic-resistant solutions as well [402,422,533]. This realization led to an even bigger push for cycling as a means of transport in urban areas, with cities such as London, Paris, Barcelona, Milan, Brussels, Bogotá, Berlin, Seoul, and Budapest promoting cycling and improving and creating infrastructure at a faster rate [534–537].

Nevertheless, cycling infrastructure needs to be properly implemented, as evidence has emerged that failure to meet cyclists' concerns highly deters people from choosing that transport mode [538]. Moreover, because the investment needed to promote, create, and adequately maintain cycling infrastructure is typically high, it is an arduous task to achieve, especially in consolidated cities which, over the last decades, prioritized motorized transportation. Therefore, to properly analyze the cost–benefit relation of cycling infrastructure investments, the need arises to estimate the maximum potential impact of those investments. This chapter proposes a methodology to provide an initial estimation of that impact, measured by modal share and transport energy use. It relies on evaluating active trip probability for accessibility trips to urban facilities and jobs, which constitute a high percentage of all urban trips [465] and uses Geographic Information Systems (GIS) to execute the city-scale calculations required.

The methodology allows for a comparison between a base scenario, where cycling is not considered as a feasible means of transport (i.e., it has near-zero modal share), and a scenario in which cycling infrastructure has been implemented in the best possible way, following all engineering codes of practice and along pleasant environments. Such implementation means segregation of the cycle mode from other modes (pedestrian and motorized), with cycle tracks of adequate lane width, quality and well-maintained pavement, cycle parking facilities, safety measures against motorized traffic, and placement of mechanical aid devices for the case of hilly cities. Codes of practice for cycle tracks can be found in Parkin [539] and placement of aid devices in Tralhão et al. [540]. For quality and maintenance issues (including safety), see, e.g., [541,542]. The methodology output gives municipal authorities valuable preliminary data to analyze the cost–benefit relationship of retrofitting their cities to include large-scale provisions for the cycling mode. The city of Coimbra, Portugal, a city with considerable urban sprawl and almost nonexistent cycling modal share, was used as a case study to demonstrate the concept. Results show that with adequate cycling infrastructure, Coimbra can aspire to have active modal shares on par with top-tier cities, such as Amsterdam or Copenhagen. To the best of the authors' knowledge, this is the first quantitative methodology to estimate the potential impact of a full-cycling scenario at various levels and one of the first case studies thereof.

Note that while an adequate cycling infrastructure removes the most important barriers to cycling (see, e.g., [543–545] for a list), promotional measures may be needed. These can be, for example, implementation of bike-sharing systems, institutional advertising, provisions for bicycle storage in public transport (multimodal approach), incentives to bicycle acquisition, or the creation of congestion taxes and restricted access areas. These factors may increase cycle mode share, but the study of their effect is beyond the scope of this thesis.

5.2. Literature review

The large-scale impact of cycling on an urban area can be studied and evaluated in various ways. Modal share and transport energy spending are commonly used measures in transport planning as evaluators of mobility [546–549] and indicators of the impact of the creation or redevelopment of infrastructure [402,526,550,551]. Likewise, those indicators were used to evaluate the effects of new cycling-related policies or the reform of old ones [526,549,551–553], the implementation of various mobility-related services, e.g., bike-sharing [405,554,555], and combinations of policies and services [556,557]. Modal shift towards cycling has, in turn, socio-economic, travel behavior, and overall mobility impacts [558–560]. At a more general level, modal share and transport energy spending were also used as evaluators of the momentum towards renewable and non-polluting sources of energy [220,561–566].

The various studies mentioned above focused on the impact of one or two cycling- fostering policies or services, or infrastructural improvements of limited scope. None estimated the potential impact that a full-scale intervention on the cycling infrastructure could have, one which would leave citizens with no excuse not to opt for the cycling mode, except trip distance. It is to fill this literature gap that the present research is presented. The only study in the literature that is similar in objective to this chapter is that of Raustorp and Koglin [546]. However, those authors studied only commuting trips, at a different, regional level, and focused on health benefits. No trips to urban facilities were considered, and energy impacts were not estimated.

It is worth noting that during the COVID-19 pandemic, factors came into play which created fluctuations in cycle use [567]: lockdowns decreased overall ridership, but recreational/exercise trips increased. Cycling commuting trips also rose when economic activities resumed, feeding mostly from a modal shift of public transport users to cycling [387,406]. Being a low-contagion mode, the need to quickly create cycling infrastructure led to the appearance of dedicated planning tools [568] and the subsequent investments were made on the field infrastructure, which is likely to generate sustainable increases in the cycling modal share into the future [402,454], possibly to levels not expected so soon, had the pandemic not occurred. The present chapter presents a way to estimate what the maximum expectable share might be.

5.3. Materials and methods

The methodology is based on the ideas below. These describe the procedure in broad brush strokes, after which finer details are given.

1. An urban area is selected for study. Three datasets are collected and curated into a GIS environment: origins (O), destinations (D), and road network. Origins represent demand (for trips) and are the centroids of residential buildings over the study area. Destinations represent supply and consist of urban facilities and centroids of job zones. The road network connects origins to destinations.

2. For each origin, network distances are evaluated in GIS to (*a*) the nearest urban facilities of each kind and (*b*) the centroid of each job zone.

3. The following transport modes are considered: walking, cycling, private motorized transportation, and public transport. For each OD pair, trip probabilities for all those modes are obtained. The cycling mode is, however, considered only in one scenario (see #4 below). If it is considered, the trip probability for walking and cycling modes is evaluated as a function of distance and combined into a single active modal probability.

4. Two scenarios are evaluated: a first scenario, where cycling is not considered as a means of transport (i.e., cycling modal share set to 0%; only three transport modes are considered), and a second scenario, where cycling is included. Modal share distribution and the associated transport energy spending are calculated for each scenario.

The four transport modes indicated above are comprehensive categories. This division has been considered in recent urban mobility analyses [569–571] and simulations [16]. The cycling mode includes any type of cycle, including pedelec cycles. However, for simplicity, this research considered only the most common type, the bicycle. Private motorized transportation refers to private vehicles which do not require human muscular energy for locomotion, such as cars, motorcycles, scooters, etc. Public transport refers to any form of public transportation. Again, for simplicity, this research considered only the car for private motorized transportation and assumes this has an internal combustion engine (ICE). Likewise, for public transport, only ICE busses were considered.

The trips considered in the methodology are accessibility-related, with accessibility defined in the classic sense of the ease to reach destinations, i.e., interaction opportunities. Accessibility trips constitute the majority of trips in the urban environment and can be modeled in GIS as one-way or round trips to predefined destinations, subject to supply attractiveness and demand intensity.

The subsections below present implementation details and their rationale. Some GIS details are presented using the ArcGIS 10.8 tools language, but any other GIS environment can be used, provided its toolset can execute the operations described herein.

5.3.1. Defining the datasets

As to what concerns dataset definition and curation, the methodological approach follows previously validated work by Monteiro et al. [16].

5.3.1.1. Origins

Centroids of residential buildings are given population information in their associated table. For large study areas, where route computational times might be too large, the alternative is to create a square mesh over the study area. The mesh size is tuneable, usually between 25 × 25 m and 100 × 100 m (smaller sizes yield greater precision but lead to longer computational times). Implementation involves creating the mesh and their centroids feature classes and then erasing centroids which lie a certain distance away from the road network, e.g., 50 to 100 m, together with their associated square polygons. Each mesh centroid is then given population information in its associated table using GIS Join tools. Finally, mesh squares and mesh centroids with zero population are erased.

5.3.1.2. Destinations: Urban facilities

Destinations of the urban facility type consist of point feature classes. Facilities are divided into types, according to Table 5.1. below, and a feature class is created for each type. The points represent either building centroids or main entries. Destination attractiveness or weight needs to be considered when studying accessibility [448,464], and facility weights depend on their type. Following Monteiro et al. [16], this research proposes an empirical 1-2-3 Likert scale for weights, based on trip frequency, where 3 denotes the most frequent. Higher weights mean trips to the corresponding destinations are likely to be more frequent. For urban facilities, the above weights are consistent with the trip frequencies per facility type found by Gov.UK [465]. Some trips to facilities are naturally two-way trips, i.e., round trips, where the person returns to the origin soon after reaching the destination (e.g., supermarkets or post offices), while others are one-way, implying a long stay at the destination (e.g., entertainment). Because of the feeling of a longer distance when permanence time at a destination is short, distance to facilities which are likely to generate two-way trips is doubled in active trip probability calculations. Another point is that multiple opportunities should be considered in accessibility [453], as a person usually wants to have the option to reach, for example, several nearby restaurants or shopping centers. However, for some facility types, the person usually goes to the closest one, e.g., pharmacies or post offices. Consequently, multiple facilities need to be considered only for facility types for which freedom of choice is relevant. As an example, Martínez and Viegas [572] considered freedom of choice to the five closest facilities, as well as facilities without such freedom. Table 5.1. below shows the facility types considered in this research and summarizes the above considerations. In the case study section a map is shown with the spatial distribution of those facilities over the study area.

Table 5.1. Facility types.

Weight 1 facilities	**Weight 2 facilities**	**Weight 3 facilities**
Post offices *,2	High schools 1	Kindergartens *,2
Sports facilities 2	Shopping centers 2	Primary schools *,2
Cultural organizations 1	Entertainment sites 1	Middle schools *,1
Universities and institutes 1	Primary healthcare services *,1	Grocery stores 2
Elderly care centers 1	Pharmacies *,2	Supermarkets 2
Churches 1	Restaurants 1	Bakeries and pastry shops 2
	Parks and green areas *,1	

* Closest only, 1 One-way facility, 2 Two-way facility.

5.3.1.3. Destinations: Jobs

Destinations of the job type require a different approach; as a person usually has only one job, the concept of "nearest job" does not apply. In addition, precise job destination figures require knowing where the people from each origin work, which, in turn, requires large scale surveys, which are, in general, unavailable. Thus, this research uses traffic zone analysis [573,574] to approach job accessibility. This is implemented as follows [16]: identify job locations and employee count; assign these to a 'jobs' point feature class; divide the city into zones and create a 'job zones' polygon feature class; count jobs in each zone (intersect 'jobs' and 'job zones'); and find the geometric average job location of each zone (GIS *Mean*

Center spatial statistics tool). Finally, for each origin, calculate the distance to each job zone geometric average. Jobs are considered one-way facilities and their weight is proportional to the percentage of commuting trips within the study area. All job zones centroids are considered as destinations, and a ponderation by the fraction of jobs in each zone is later applied (see section 5.3.4 below for details).

5.3.1.4. Road network

The road network is the one existing on the field, with the addition of walking and cycling dedicated infrastructure, where it exists. Because of dedicated infrastructure, distance to facilities may depend on the transport mode, although the differences are usually small.

5.3.2. Obtaining GIS distances

For deriving distances to facilities, the ArcGIS *Closest Facility* tool is used. The maximum snapping distance, i.e., straight-line distance from the network to a destination (or origin) point is the same used to remove faraway origins (usually 50–100 m). If a destination lies inside the study area but sits more than the snapping distance away from the network, then the snapping distance can be increased for that facility type. Motorized, walk, and cycle OD distances are obtained by solving *Closest Facility* problems for each facility type and transport mode. For facilities where freedom of choice is relevant, the distance to the K-closest facilities is calculated. For other facilities and jobs, K is always 1. For two-way facilities, OD distances are multiplied by two (if many one-way streets exist, separate towards and away distances can be calculated separately and added). All the OD distances obtained are stored in the origins feature class associated tables.

5.3.3. Estimating modal split

5.3.3.1. Individual walking and cycling trip probabilities

On the basis of the OD distance, a probability for carrying out the trip in active mode (walking or cycling) is calculated as follows. First, trip probability for individual walking and cycling modes is modelled via a log-logistic distribution:

$$p(x) = \frac{1}{1 + \exp(a + b \ln x)} \tag{5.1}$$

where a and b are parameters, and x the network distance for the respective travel mode. The log-logistic function was chosen because it provides a good fit to experimental data, as recognized by Hilbers and Verroen [575] and Geurs and van Wee [453], and is not sensitive to small x instabilities that other trip probability models exhibit. However, log-logistic parameters for the walk and cycle modes are, in general, not available so for this research, they were obtained indirectly from the results of Yang and Diez-Roux [576] for the walk mode. Those authors presented walking trip frequency as a function of distance and trip purpose using a negative exponential law. Evaluating the distances for which the Yang and Diez-Roux law yields 10% and 90% walk probabilities, equating these benchmarks to Equation (5.1), and solving for a and b allows the log-logistic to be calibrated for the walk mode and for each destination type. This yields the parameters shown in Table 5.2. below:

Table 5.2. Log-logistic parameters for walking.

Destination Type	a_j (Distance: Km)	b_j (Distance: Km)
Post offices	1.19225	1.83021
Sports facilities	0.05574	1.83013
Cultural organizations	1.00344	1.82990
Universities and institutes	1.07775	1.82989
Elderly care centers	1.19225	1.83021
Churches	1.00344	1.82990
High schools	1.07775	1.82989
Shopping centers	1.19225	1.83021
Entertainment sites	1.00344	1.82990
Primary healthcare services	1.19225	1.83021
Pharmacies	1.19225	1.83021
Restaurants	1.46215	1.83009
Parks and green areas	1.00344	1.82990
Kindergartens	1.46215	1.83009
Primary schools	1.46215	1.83009
Middle schools	1.46215	1.83009
Grocery stores	1.19225	1.83021
Supermarkets	1.19225	1.83021
Bakeries and pastry shops	1.46215	1.83009
Jobs	0.89627	1.83017

For the cycling mode, users typically spend a similar time buffer in cycling trips as in walking trips [571]. However, the distance ridden by a bicycle is greater due to its higher speed. Walking speed can be modelled by, for example, Tobler's hiking function [577], and cycling speed is available from Parkin and Rotheram [578]. Similar speeds, albeit slightly smaller, were found [579–581]. For zero slope, the Tobler walking speed is 1.4 m/s, whereas cyclist speed sits at approximately 6.0 m/s. The ratio of the two is approximately 0.233, which can be used as a multiplier for x for cycling trips while keeping the same a and b values of Table 5.2. A very similar ratio of walk/bike average distance was also found by Ton et al. [571].

The second step in obtaining an active trip probability requires combining walking and cycling probabilities into one single probability. This can be accomplished considering two *ansätze*: #1 for short distances, one has the choice either to walk or to use a bicycle. Thus, the probability p_{A} of making the trip using an active mode can be modelled by the probability of walking (p_{W}) or cycling (p_{C}) to the destination. Mathematically, this can be expressed by

$p_{\mathrm{A}} = 1 - (1 - p_{\mathrm{W}})(1 - p_{\mathrm{C}})$, where p_{W} and p_{C} are obtained by applying Equation (5.1) for distances x and $0.233x$, respectively. The above reasoning can be extended to all x, but active trip probabilities modelled by distance–decay functions can be optimistic at large x, and, therefore, p_{A} above could lead to even more optimistic probabilities, possibly excessive, unrealistic ones (see Ton et al. and Risjman et al. [571,582] for examples regarding long distances lead to no use of active modes). For this reason, *Ansatz* #2 comes into play; for long enough distances, it is assumed that all active mode trips are of the cycling type. Defining what constitutes short and long distances is subject to decision-maker judgment; in this research, the following guideline is proposed: short trips are those for which $p_{\mathrm{W}} \geq 0.50$, and long trips have $p_{\mathrm{W}} \leq 0.10$. Trips in between are modelled by a linear interpolation between the two *ansätze*. The mathematical expression for the unified active trip probability is then:

$$p_{\mathrm{A}}(x) = \begin{cases} 1 - (1 - p_{\mathrm{W}})(1 - p_{\mathrm{C}}) & p_{\mathrm{W}} \geq 0.50 \\ p_{\mathrm{C}} + \dfrac{1 - (1 - p_{\mathrm{W}})(1 - p_{\mathrm{C}}) - p_{\mathrm{C}}}{0{,}5 - 0{,}1}(p_{\mathrm{W}} - 0{,}1) & 0.10 \leq p_{\mathrm{W}} \leq 0.50 \\ p_{\mathrm{C}} & p_{\mathrm{W}} \leq 0.10 \end{cases} \tag{5.2}$$

Recall that p_W and p_C depend on destination type j, so the active trip probability may read $p_{\mathrm{A}j}(x)$ to reflect this dependence. Equation (5.2) can be implemented in ArcGIS using the *Field Calculator* tool. Figure 5.1 below shows a graphical depiction of the trip probability curve for post-office access as a function of distance, x. In it, the p_{W} (blue) and p_{C} (red) curves are shown, along with the curve for walking or cycling following *Ansatz* #1 (dashed gray). The green curve is the interpolation result, Equation (5.2). The intersection of gray lines with the walking curve indicates the distances for which the walk probability is 50 and 10%.

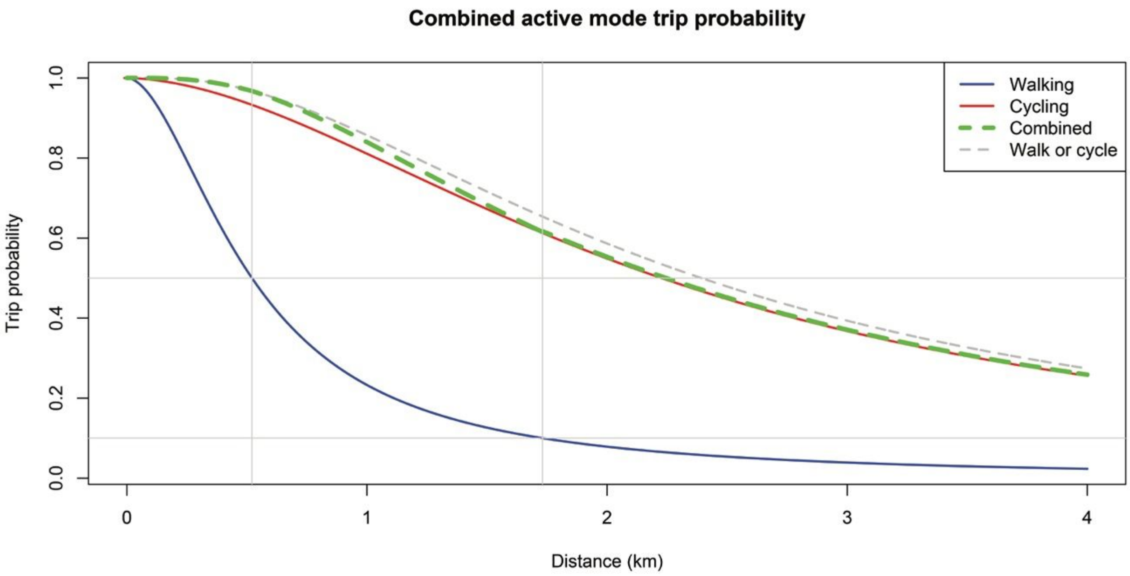


Figure 5.1. Combined active mode trip probability function for accessibility to post-offices.

5.3.3.2. Motorized modal split

Whenever a trip is not carried out actively, the person is assumed to resort to a motorized mode, which has consequences in terms of fossil energy spending and GHG emissions. The remaining probability is split between the private car and public transport (this split is equal for both scenarios). This research proposes a split based on the actual modal share for the study area, but other estimations of the modal split can be applied. Once the split is defined, fossil energy spending is evaluated. Walking and cycling are considered to spend zero fossil energy, and for private car and public motorized transport, average values per person can be assumed. In evaluating fossil energy spending, motorized trips are all two-way, as they in reality are.

5.3.4. Scenario evaluation

Two indicators are obtained for comparing the no-cycling and full-cycling scenarios, namely active mode share and fossil energy spending.

5.3.4.1. Active modal share to all destinations

The first indicator, active modal share, is obtained for every origin i by weighting active trip probabilities from that origin to all destinations by frequency and facility choice. This is accomplished using:

$$M_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} p_{\mathrm{A}ij}^k}{\sum_k L_{kj}}, \tag{5.3}$$

where
M_i: active modal share of origin i;
$p_{\mathrm{A}ij}^k$: active trip probability from origin i to the k-th closest destination of type j, with
$p_{\mathrm{A}ij}^k = \sum_z f_z p_{\mathrm{A}iz}$ for *j*: jobs ($p_{\mathrm{A}iz}$: active trip probability from i to average job location of zone *z*).

The $p_{\mathrm{A}ijk}$ are obtained by applying Equation (5.2) for facility type j. Note that facilities of the "closest only" type have $L_{kj} = 0$ for $k > 1$. The normalization factors in the denominator ensure that M_i values sit between 0 and 1 and can be interpreted as the doubly weighted average probabilities of performing accessibility trips with an active mode. The M_i values can then be displayed on a map.

For jobs, $p_{\mathrm{A}ijk}$ is obtained by a weighted-sum procedure over all job zones:

$$p_{\mathrm{A}ijk} = \sum_z f_z p_{\mathrm{A}iz}, \qquad j\text{: jobs} \tag{5.4}$$

where
z: $1, \ldots, Z$ number of job zones;
f_z: fraction of total jobs in zone *z*;
$p_{\mathrm{A}iz}$: active trip probability from origin i to the z-th job zone centroid.
As for $p_{\mathrm{A}ijk}$, the $p_{\mathrm{A}iz}$ are obtained by applying Equation (5.2).

5.3.4.2. *Fossil energy spending*

Equation (5) is used to estimate the fossil energy spending associated to origin i:

$$E_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} \left(1 - p_{\mathrm{A}ij}^{k}\right)\left(f_{\mathrm{car}} F_{\mathrm{car}} + f_{\mathrm{pub}} F_{\mathrm{pub}}\right)\left(d_{ijk}^{\rightarrow} + d_{ijk}^{\leftarrow}\right)}{\sum_k L_{kj}}, \qquad (5.5)$$

where
E_i: average fuel consumption of accessibility-related trips originating in i;
f_{car}: fraction of motorised trips made using the private car;
f_{pub}: fraction of motorised trips made using public transport;
F_{car}: private car average fuel economy (MJ/passenger.km);
F_{pub}: public transportation average fuel economy (MJ/passenger.km);
$d_{ijk}^{\rightarrow}, d_{ijk}^{\leftarrow}$: one-way distances from origin i, respectively, towards/away the k-th closest destination of type j.

The value $1 - p_{\mathrm{A}ijk}$ represents the left-over probability that an accessibility trip is carried out by motorized modes, which is then split into private and public transport. The normalization denominator results in Equation (5.5) the interpretation of the (again, doubly weighted) average fuel spending in accessibility trips, as measured in MJ/passenger-trip. As with M_i, the E_i values can be displayed on a map.

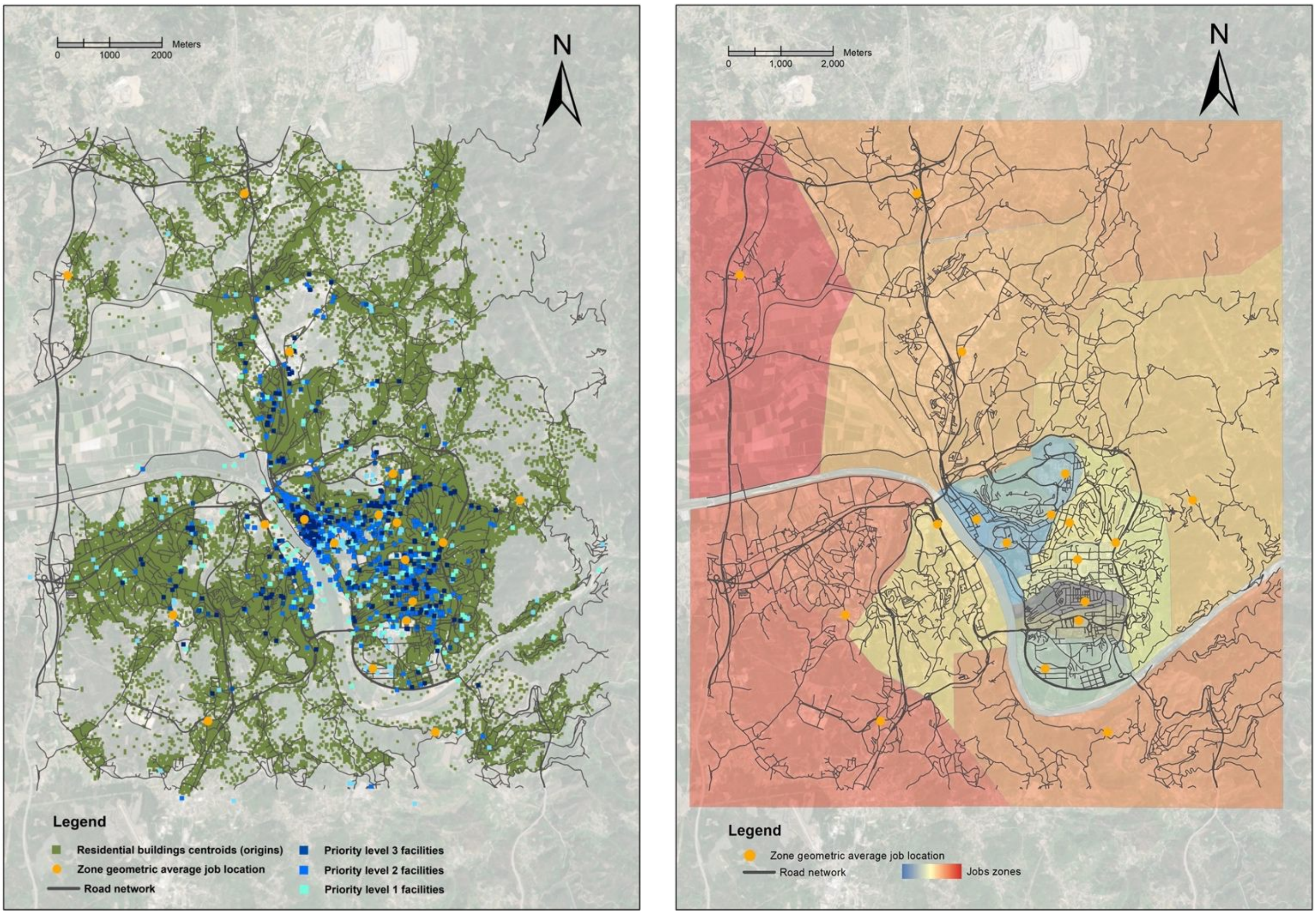
5.3.4.3. *No-cycling vs. full-cycling scenarios*

Equations (5.3) and (5.5) represent the full-cycling scenario. For the no-cycling scenario, it is sufficient to replace $p_{\mathrm{A}ijk}$ by $p_{\mathrm{W}ijk}$, the latter representing walk probability from origin i to the k-th closest destination of type j, a quantity that is directly available in GIS from intermediate steps (likewise, $p_{\mathrm{A}iz}$ is replaced by $p_{\mathrm{W}iz}$). Equations (5.3) and (5.5) and their no-cycling counterparts can be implemented in the ArcGIS environment using *Field Calculator*, and the results are stored in the origins feature class associated table.

5.4. Case study

The methodology was applied to the city of Coimbra, Portugal, a mid-size city with approximately 104,000 inhabitants [583]. Data from Metro Mondego [584] disclose that the active modal share is approximately 22%, of which an abysmal 0.2% is cycling. The empirical motorized share splits as $p_{\text{car}} = 0.7$ and $p_{\text{pub}} = 0.3$, and the share of commuting trips is 37% (survey data), leading to $w_j = 22, j$: jobs. Concerning fuel economy, IEA [585] averages were used, namely 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport. For non-closest facilities, a choice parameter of $K = 3$ was considered, and two sets of L_{kj} were used for sensitivity analysis, namely $L_{kj} = \{70,20,10\}$ and $L_{kj} = \{50,35,15\}$. Results concerning the latter are presented in the supplemental material.

For generating datasets, residents' centroids could be used as origins, so there was no need to create a mesh feature class. The location and type of urban facilities in Coimbra were obtained from existing datasets, as well as job locations and employee count. Job zones were manually drawn in GIS, considering population density, buildings, job density, and orography. The detailed road network of Coimbra was obtained from OpenStreetMap. Figure 5.2a depicts the mesh centroids after empty and faraway polygon removal, facility locations, and road network. Figure 5.2b depicts job zones and their geometric average job locations. All maps were derived in the ArcGIS environment, with background imagery provided by that platform (*World Map Layer*).



(**a**) (**b**)

Figure 5.2. (a) Coimbra origins, urban facilities, and road network; (b) Coimbra job zones and geometric average job location per zones.

5.5. Results and discussion

Applying the methodology to the case study data yielded the results of Tables 5.3. and 5.4. and Figures 5.3. and 5.4. In Tables 5.3. and 5.4., the statistical calculations were carried out over mesh centroid data, except for the Average per inhabitant row whose statistics are related to centroid population, h_i, via the formulas $\frac{\sum_i M_i h_i}{\sum_i h_i}$ and $\frac{\sum_i E_i h_i}{\sum_i h_i}$ and are the main result of this chapter. The outcome shows that realizing the full cycling potential of Coimbra has a large impact on the cycling share for accessibility trips, more than doubling it, both for facilities and facilities plus jobs, putting it at the level of the world's most cycling-friendly cities, such as Amsterdam (61% active share) or Copenhagen (47% active share) [570]. Interestingly, the model–theoretical walking share for no cycling is 16.8%, which sits below the observed 22% [584]. This may be due to Coimbra having higher education as one of its main economic activities, which attracts many young people who typically resort to walking more often than older people. It may also be related to the effects of chained trips, i.e., trips to multiple destinations, and trips not related to accessibility, which were included in the survey [584] but which the present research could not consider.

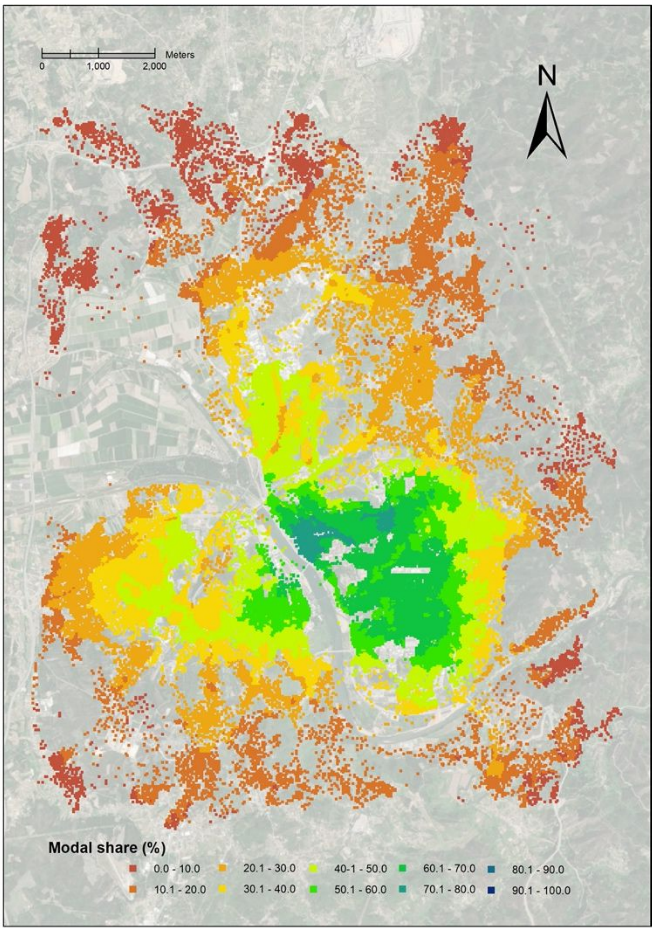
Table 5.3. Active modal share summarizing statistics.

Active Modal Share Per Inhabitant (%)		Urban Facilities		Urban Facilities and Jobs	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	3.3	0.5	3.5	0.4
	Max	94.3	71.8	73.7	48.0
	Average	45.8	18.6	35.6	12.7
	Average per inhabitant	55.3	24.7	42.6	16.8
	Standard deviation	24.9	15.9	18.7	10.6
	Coefficient of variation	54%	90%	52%	87%

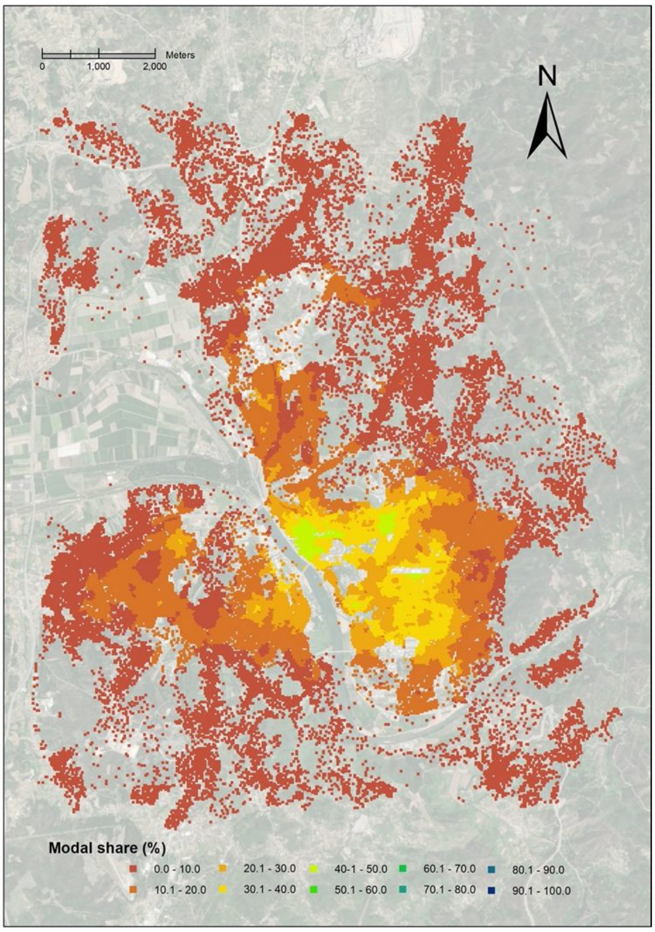
With respect to energy spending, the impact of full cycling is a reduction of approximately 23% for accessibility to urban facilities and of 18% for facilities plus jobs. This impact is not as high as that for the modal share because Coimbra has a high urban sprawl. Fossil energy spending comes mostly from long-distance trips and faraway inhabitants, which are the biggest contributors to this spending, and have little chance to exercise a modal shift towards cycling. On the other hand, inhabitants near the center have better conditions for a shift towards cycling, but those inhabitants were already meager fossil fuel spenders. That full cycling has a high potential for modal shift but a lesser one for energy spending can also be seen from Figures 5.2 and 5.3, which graphically exhibit a larger discrepancy for the former. The differential maps of the volume II supplemental material (Figures II.5.7a and II.5.7b) add visual insights: the modal share differential map shows that the most potential for a change towards active travel lies in the central regions, up to 2–3 km away from the city center, whereas for transport energy, the most savings appear in a ring-like area around that center.

Table 5.4. Fossil energy spending summarizing statistics.

Fossil energy spending (MJ/passenger-trip)		**Urban Facilities**		**Urban Facilities and Jobs**	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	0.19	0.69	3.29	5.32
	Max	35.37	36.34	46.16	47.59
	Average	6.70	8.18	13.54	15.88
	Average per inhabitant	4.53	5.90	10.69	13.01
	Standard deviation	6.17	6.21	7.97	7.69
	Coefficient of variation	92%	76%	59%	48%

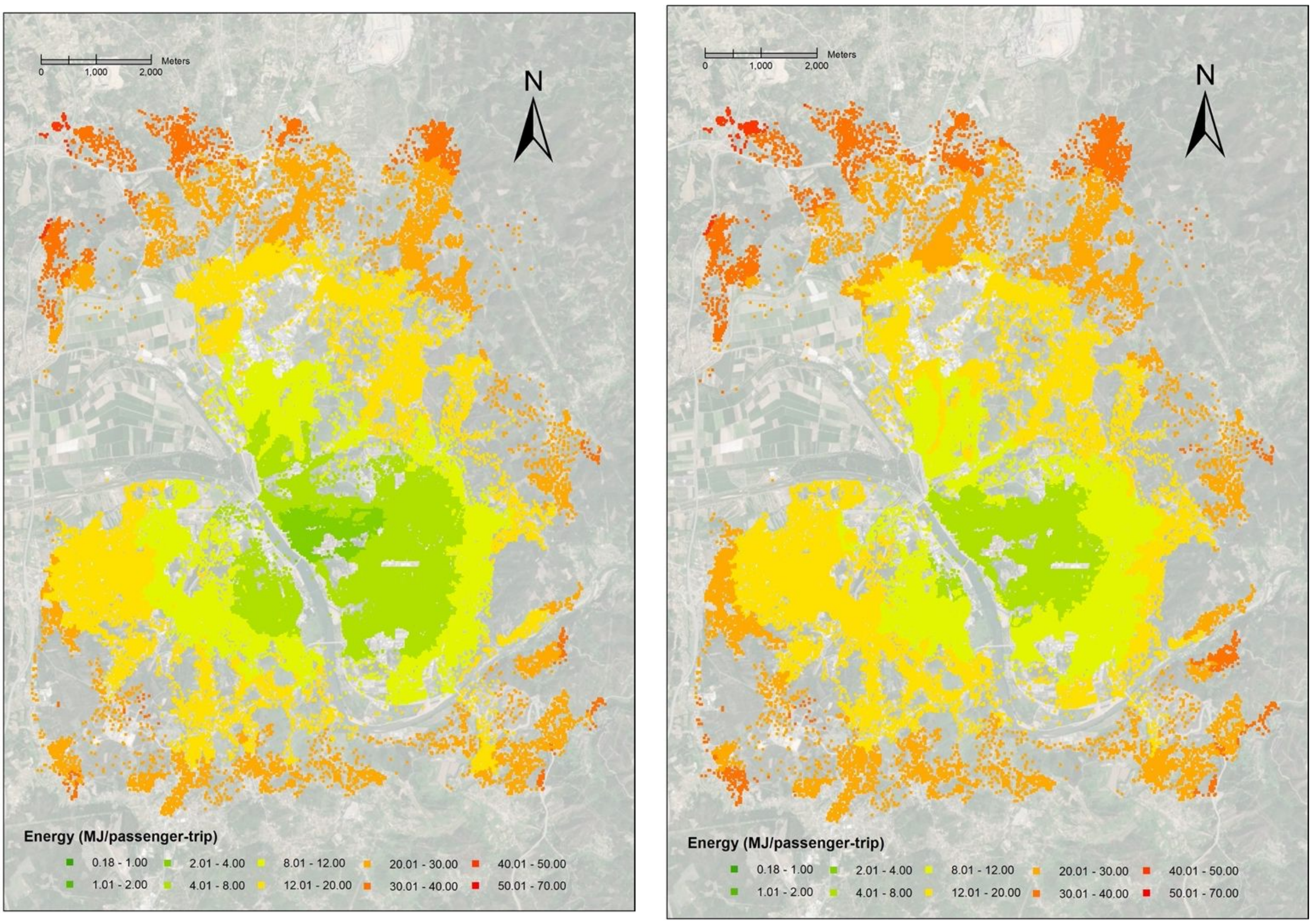


(**a**)



(**b**)

Figure 5.3. (a) Active modal share for full cycling: facilities and jobs; (b) Active modal share for no cycling: facilities and jobs.



(**a**) (**b**)

Figure 5.4. (a) Fossil energy spending for full cycling: facilities and jobs; (b) Fossil energy spending for no cycling: facilities and jobs.

Referring back to Table 5.4., for transport energy spending, the full/no cycling differential is larger for facilities plus jobs (2.32 MJ/passenger-trip) than for facilities only (1.37 MJ/passenger-trip), revealing that a significant portion of fossil energy spending comes from trips to jobs. This is due to longer average distances to jobs and their high daily frequency and is confirmed by Table II.5.3. of the volume II supplemental material, which shows a differential of 4.22 MJ/passenger-trip if job-only trips are considered. Such importance of commuting trips suggests municipal authorities should first concentrate financial efforts in constructing good commuting routes which can foster bicycle use for this type of destination.

Another noticeable insight from Tables 5.3. and 5.4. is that the full cycling scenario has lower dispersion measures, thus reducing the differences between those who live close to most facilities and jobs and those who live far away from those opportunities. This suggests cycling has a positive impact on equity in urban areas.

Despite the positive impact that cycling can have on both active modal share and transport energy spending, results show that urban sprawl still has a large impact, in line with similar results in the literature [474]. While cycling is known to be competitive compared with the private car in terms of time up to 5 km [514], this sprawling distance is inferior to that of the faraway regions of Coimbra, reducing the cycling potential for inhabitants of the outskirts and pushing them to the motorized modes. For these inhabitants, a way to reduce energy spending could be to promote a multimodal approach, e.g., transport of cycles on public transport, cyclists switching to busses when near the center.

A sensitivity analysis with $L_{kj} = \{50,35,15\}$ for non-closest only facilities was also carried out, statistical results being presented in the supplemental material. As per Equations (5.3) and (5.5), modal share and transport energy spending indicators degrade as L_{1j} decreases, but other than that, results do not significantly deviate from those of Tables 5.3. and 5.4.; hence, no additional maps were generated.

5.5.1. Impact on city planning

The above discussion leads to some conclusions with respect to city planning for the cycling mode. First and foremost, it was seen that even relatively sprawled urban environments (as Coimbra is) can aspire to high active modal shares, comparable to the world's top cycling-friendly cities. However, achieving a full cycling scenario is not an easy task [586], as there are several strong deterrents to cycling that need to be addressed, with safety from motorized traffic and hilliness as the top concerns [587–592]. Hilliness is a topographical limitation and cannot be easily overcome, but mitigation measures exist, such as the placement of mechanical assistance devices in critical locations [593] or electrical assistance of the cycles themselves (pedelec cycles). Safety from traffic can be achieved with the construction of dedicated cycling infrastructure or adequate retrofitting of existing roads. Indeed, the correct implementation of a cycling network will greatly mitigate safety concerns. However, due to the financial costs of such endeavors, it is not realistic to expect a quick change from the no-cycling scenario to the full-cycling one. This is where the evidence gathered in this research becomes relevant, as the expected fossil energy savings suggest that authorities should prioritize a cycling network for commuting routes. Several proposals exist in the literature regarding how to obtain the best routes [594–598], which can be implemented by municipal decision-makers.

Another conclusion is that urban sprawl considerably limits the potential energy savings of a full-cycling scenario. This suggests that compactification of urban space is a possible way to reach that scenario, or at least come closer to it. Compactification can be achieved in practice, for example, by urbanizing unused space within cities or regenerating derelict zones. Such actions typically appeal to the private sector, which sees to their execution. If conducted in a cycling-friendly way, compactification increases cycling network connectivity and directness, which was recognized by Dingil et al. [599] as a factor which may persuade users to shift to this mode.

It should be noted that constructing or retrofitting complete walking and cycling networks, following all engineering, safety, and level of service requirements, is typically very expensive and requires many years of execution. To maximize the return on investment, municipalities will want to prioritize certain routes, especially cycling ones, as these are more expensive to implement. Recent research on route selection includes [600], which proposed an infrastructure building information model (I-BIM) for cycle path design, and [601], where a cycling traffic model was presented, aiming at sustainable urban mobility planning. This model was applied to a case study where optimal improvement locations were identified.

5.6. Summary and future work

In this chapter, a methodology to evaluate the potential impact of cycling on cities on the basis of active trip probability to urban facilities and jobs is presented. This impact is measured by comparing active modal share and fossil energy spending in two scenarios; one where urban areas have yet not adopted cycling and another where cycling is a well-established means of transport. However, providing cycling with all the prerequisite conditions requires a collective effort from municipal authorities, from creating the adequate infrastructure for cycling to promoting cycling as an alternative. The methodology outputs are important preliminary data to evaluate the cost–benefit relationship of undergoing such constructive and financial efforts.

The methodology was applied to the city of Coimbra, a mid-sized city exhibiting considerable sprawl, that has an almost nonexistent cycling modal share. Results showed the distanced-based potential of cycling in Coimbra, with the full-cycling scenario having an expected increase of active modal share between 25.8 and 30.6% and a reduction of transport energy spending between 1.37 and 2.32 MJ/passenger-trip. These provide clear evidence of the impact that cycling can have on urban areas, creating better mobility conditions, less automotive traffic, improved health conditions, and overall higher sustainability. A finer-grained analysis revealed interesting planning insights, such as the recommendation to prioritize commuting routes or compactification of the city (if/where possible). Although the latter conclusions are based on the case study alone, the authors expect them to be general enough to constitute planning guidelines in their own right. The model has the limitation that it considers only accessibility-related trips. However, since these constitute a very significant fraction of urban trips, the results should not differ considerably from reality (i.e., all trips).

Applying the methodology to other cities or urban neighborhoods and comparing results with Coimbra is a natural first step for future work. Other extensions of this work include analyzing the effect of chained trips on the results, whereby multiple destinations on each *sortie* are considered (e.g., home–work–shop–home), evaluating how effectively hilliness can be mitigated by pedelec cycles or mechanical aid devices, investigating the effects of weather on the results [602], or considering a multimodal approach (e.g., cycling plus public transport). On the technical side, the methodology requires some assumptions for estimating the active modal share and overall GIS parameterizing. In this chapter an *ansatz* for estimating the active modal share and a mean citizen approach for parameters were followed. It would be interesting in the future to validate the *ansatz* and to conduct a sensitivity analysis by segmentation of the population, e.g., by age group or socioeconomic status, which could affect destination weights and/or $p_{\mathrm{A}}(x)$ parameters to investigate what differences might arise. It is also worth noting that the active mode probabilities do not consider issues of interaction with motorized transport supply/demand, e.g., high motorized congestion might increase active trip probability. Investigating the impact of such interactions is another possible follow-up. We hope to pursue some of these lines of research in the near future.

6. FILLING IN THE SPACES: COMPACTIFYING CITIES TOWARDS ACCESSIBILITY AND ACTIVE TRANSPORT

"Per concepire la città come la nostra casa, dobbiamo conoscerla e viverla lentamente"
Monteiro et al. [18]

Compactification of cities, i.e., the opposite of urban sprawl, has been increasingly presented in the literature as a possible solution to reduce the carbon footprint and promote the sustainability of current urban environments. Compact environments have higher concentrations of interaction opportunities, smaller distances to them, and the potential for increased active mode shares, leading to less transport-related energy consumption and associated emissions. This chapter presents a GIS-based quantitative methodology to estimate on how much can be gained in that respect if vacant spaces within a city were urbanized, according to the municipal master plan, using four indicators: accessibility, active modal share, transport energy consumption, and a 15-minute city analysis. The methodology is applied to a case study, in which the city of Coimbra, Portugal, and a infill version of itself are compared. Results show the infill layout improves all indicators, with averages per inhabitant improving by 20% to 92%, depending on the scenario assumed for cycling, and is more equitable.

6.1. Introduction

Cities are the driving forces of local and global economies, generating over 80% of the world's wealth and consuming a fraction of 60–80% of all the energy produced on the planet [10]. Cities attract people by offering better housing standards, multiple job and interaction opportunities, better education, and higher health standards [3]. As a result, more than 56% of the world's population currently resides in urban areas [8], with a continuous growth trend that calls for new policies for the optimisation of territorial resources (more than 2.2 billion new urban residents are expected by 2050 [424]). Urban areas must be prepared for the future, with clear perspectives on sustainability [483,484]. The agenda includes improving accessibility and overall proximity [485–487] as well as fighting back urban sprawl by promoting a more compact urbanism [488,489].

Urban form is an essential element of urban planning that either can lead towards sustainability or unsustainability [204]. The post-war decades witnessed urban transformations due to technological and economic changes that led to urban dispersion [603]. Rapid transport, road investment, and low rents in city suburbs led to a metropolitan expansion onto suburban low-density areas [205], ultimately creating a lack of continuity and separating areas of housing, industry and offices, retail, and recreational use, i.e., urban sprawl [199–201]. Urban sprawl impacts transport and the environment due to trip distances, traffic pollution, extensive roads, excessive private car use, and low public transport ridership [200,206]. It has also negative social and economic consequences [199,200,204–207].

In the pursuit of more sustainable cities, urban compactification and densification policies have been widely promoted and adopted [207,604,605], as they counteract urban sprawl and provide tentative solutions to accessibility and walkability challenges [488,489,606,607] and avoid countryside urbanization [488,489,607]. A good urban form leads directly to better transport planning opportunities [494–496,608], and other high-density urban strategies such as mixing land-use, urban diversification, sustainable transport, development of green spaces, and higher population density have been suggested as means of planning for sustainability [604,607,609–612].

Together with efficiency and sustainability considerations, citizens want cities to provide them with a sense of place. "Home sweet home" is a brief sentence that summarises the importance of being able to live in a place that protects us, with the people we love. Leon Battista Alberti in his treatise *La Architettura* [613] compared the city to the house and equally compared rooms to urban blocks and corridors to streets. With this comparison, one could reformulate, following Leon Battista Alberti, for the concept of "city sweet city". To conceive the city as our home, we must get to know it and live it slowly. Slow city, 15-minute city, or an urban space that we can experience and get to know like a large and comfortable home: this is the meaning authors give to the infill city in the third millennium. Knowing built parts, and equally knowing empty parts, means reflecting on how to recreate the compact city. In *L'estetica della città europea*, Marco Romano [614] recalls two entities that make up cities: Civitas, which represents a spiritual entity or population with its desires and with pride of belonging to that specific city, and Urbs, made up of the buildings that create the image of the city. For Urbs and Civitas to cooperate in the formation of what could be called the soul of the city, or the interpretation that inhabitants have given to a certain place, citizens, buildings, and empty spaces must live together and belong to each other. Modernity has untied this union, the creed of zoning denying any value to this blend, and the futurist exaltation of speed and of the machine broke the alliance between man and his ability to design and build spaces, buildings, for himself and for others. In the compact city, habit means living knowing the city well and being certain that one's behaviour ensures the proper functioning of the city.

Modern techniques enable us to measure, interpret, and understand where and how the compact city is interrupted. The use of geographic information systems (GIS), algorithms, and the powerful tool of datafication allows us to deeply investigate those lacerations of the urban fabric that interrupt the relationship of union between the city space and citizens. Investigating the simplest and cheapest way to fill these gaps in space and communication and restore the city to its compact harmony means giving cities back to citizens.

Thanks to social media, modern communication systems, and the Internet, speed is no longer the only value, as one can travel while remaining in the same place, making the once futuristic concept of speed outdated and now replaced by the concept of connection. The compact city does not need fast means of travel but efficient travelling. Efficient public transport and its infrastructure network became more desirable than individual means of transport. Models of interpretation and study demonstrate it: urban sprawl is responsible for the segregation and gentrification that excludes, divides, and opposes citizens to each other. The infill city includes the re-use of spaces within historic cores that exist but are not known because they are not properly valorised, and this constitutes a new way of conceiving town planning.

Powerful possibilities of simulating effects and benefits of the redesign of the city, in the direction of a compact city, allow us to possess effective tools for economic and political strategies. The future cities passes through governance of these surveys and these simulations, which are indispensable tools for understanding social dynamics and for making the best use of potential energies of creativity, entrepreneurship, and citizen cooperation. Modelling cities to obtain reliable quantitative predictions is one major step in that direction and a key challenge of the modern world [425,426]. Accordingly, this research proposes one such modelling tool, a quantitative methodology, based on GIS, to estimate the impact that compactification can have on accessibility and active transport. Starting with the city of Coimbra, Portugal, a sprawled city that has expanded in a low-density pattern, and turning it onto a infill version of itself by filling in vacant spaces of the urban fabric while respecting the municipal master plan. Quantitative indicators are proposed and evaluated for the two layouts, yielding comparative figures that give a precise notion of what can be gained from the compactification procedure.

It should be mentioned that several studies have argued that, overall, compact urban environments provide better accessibility, encourage public transport, and lead to reductions of transport energy and associated emissions [493,615–617]. However, to best of the authors' knowledge, the present research one of the first quantitative efforts to measure the effects of compactifying a real city, thus filling an important a gap in the field of urban planning. Other quantitative studies include the work of Mouratidis [489], which relates the degree of compactness with neighbourhood satisfaction, which is a different topic.

Compact urban development is not without downsides, and some positive outcomes such as less traffic, less environmental problems, or social liveability, have been questioned over the past decades [235,488,618–620], making it all the more important to have quantitative figures, which can help people decide in what way they want their city to develop.

6.2. Materials and methods

The proposed methodology pivots on a comparative analysis between the city of Coimbra as it is, henceforth designated simply as "Coimbra" or "real Coimbra", with its compact counterpart, i.e., "Infill Coimbra". That is to say, the urban layout of real Coimbra is compared to a hypothetical, compact layout, in which Coimbra is reorganised by moving residential areas, urban facilities, and job locations from the outskirts onto vacant spaces in the real city, following municipal regulations. The comparison is carried out using four quantitative indicators: accessibility, active transport modal share, transport energy consumption, and the degree by which a city layout can be considered a 15-minute city. In transforming, or redrafting the city, the principle is followed that it should not distort the number of actors in play (inhabitants, destinations, etc.).

6.2.1. Indicator motivation

The four indicators above were selected mainly because of their importance for city planning. A brief motivation for them now follows.

6.2.1.1. Accessibility

Accessibility is a wide-ranging concept, related to urban spatial layout, qualities of the transport and land-use systems, and to economic and environmental goals [450,621,622]. Providing a binding factor of urban structure key components: people, mobility, and social activities [623], accessibility is being increasingly incorporated into metropolitan transport plans and national planning guidelines [447,487,624]. It is recognised as one of the possible paths to sustainable development: by putting more emphasis on proximity rather than speed, daily living is facilitated without creating a dependency on long distance, fast, and energy-intensive transportation [449,460,486,625].

6.2.1.2. Active mobility share

Active transport, e.g., walking, cycling, requires human muscular input for locomotion, thus providing health benefits, and is non-polluting [626–629]. It is currently one of the main focuses of transport planning also due to energy efficiency, local context, and socioeconomic factors [125,497,498,500,501,558–560,626]. Active travel has been strongly promoted worldwide [630–634] as a sustainable form of urban mobility that is also equitable, affordable, and inclusive [456,635–640]. Strategies that encourage the replacement of short-distance car trips by active travel are becoming more popular [125,641,642], e.g., redesigning streets to accommodate for pedestrian, cycling, and public transport infrastructure [643].

Active modal share is an outcome of those promotional policies but also of planning policies and urban features such as density and mixed land-use [40,643–649]. Albeit active mobility is important to today's urban society [606,650] recognise it to be a striking challenge for contemporary cities, making it important to evaluate to what degree compactification may help in this respect.

6.2.1.3. Transport energy consumption

An individual's transport energy consumption is a product of the travel modes used, i.e., trip distances and frequency, that in turn are directly correlated to the built environment [651]. Consumption from motorised travel is especially impactful, mainly due to greenhouse gas emissions (GHG) but also due to fuel supply issues and urban congestion [87,105,652–654]. Measures towards energy conservation and emissions reduction are becoming critical [220,611], and the urban form and land-use policies are powerful tools to achieve them. Since more compact urban forms are associated with lower consumption and emissions, and fragmentary urban forms (e.g., urban sprawl) are associated with higher consumption and emissions [66,87,220,653,655–657], it becomes important to have quantitative estimates of energy consumption for those urban layouts.

6.2.1.4. The 15-Min City

The 15-Minute City is a contemporary holistic concept for urban planning developed by Carlos Moreno, a modern interpretation of the neighbourhood unit concept and the work of le Corbusier [14,658,659]. Motivated by chrono-urbanism, i.e., that quality of life is inversely proportional to transportation time [14], it suggests an urban form that enables residents to carry out their daily activities within distances that would not take more than 15 min by walking or cycling [14,660,661]. The aim is not to bring people to activities but rather bring activities to people, in particularly work. It seeks to localise workplaces near people, considering that commuting represents the main and most inelastic of everyday trips [661]. The 15-minute city represents a shift in traditional urban planning, which often spatially separates city functions of residence, work, leisure, and circulation [658] towards local living [662].

It is argued that implementing the concept of the 15-minute city need not imply a complete city overhaul; some urban areas might already meet the general criteria, as studies in Barcelona, Naples, or Bogotá evidence [660,663,664]. Other cities such as Paris are making plans to adapt it [14,665]. Evaluating to what degree compactification can lead to a 15-minute city becomes an indicator of whether the methodology can achieve such objective in practice.

6.2.2. GIS implementation

The bulky quantitative analyses required to calculate indicator values are carried out in a GIS environment using solely the geographic characteristics of the spatial layout of the urban areas. The GIS component of the methodology can be summarised as follows:

1. An urban area was selected for study. Three datasets are collected and curated into a GIS environment: origins (O), destinations (D), and road network. Origins represent demand (for trips) and are the residential centroids (endowed with inhabitant number information). Destinations represent supply and are urban facilities and centroids of job zones (see Section 6.2.4.1. for details on job zones). The road network connects origins to destinations. Origins and destinations are point feature classes, and the road network is a polyline feature class;

2. In a copy of the datasets, new buildings and facilities are positioned in vacant urban spaces, job zones are remade, and connecting roads are drawn. The buildings house population from the outskirts and are endowed with inhabitant information;

3. For every origin of each layout, network distances are evaluated in GIS to (a) the nearest urban facilities of each type and (b) the centroid of each job zone;

4. Four transport modes are considered: walking, cycling, private motorised transportation, and public transport. For each OD pair, trip probabilities for all those modes are obtained;

5. Indicator values for each origin are then calculated for both the real and the infill layouts based on OD distances and trip probabilities;

6. From the indicator values, statistical measures and maps are derived for the two layouts.

Steps #3 to #6 are similar to Monteiro et al. [16,17]. Some further notes are as follows:

- The methodology considers only accessibility-related trips, which constitute most trips in an urban environment and can be modelled in GIS as one-way or round trips to predefined destinations, subject to supply attractiveness and demand intensity, two attributes which need be considered in accessibility [448,464];
- If the methodology is applied to a very large city, computational complexity can be reduced by defining origins as centroids of a square mesh over the study area, with associated inhabitant number given by the intersection of building centroids with mesh polygons;
- Urban facility types and respective destination attractiveness are here represented by weights as given in Table 6.1. below. An empirical 1–2–3 Likert scale for weights was used in the research, based on trip frequency, with three the most frequent. Higher weights mean trips to the corresponding destinations are likely to be more frequent. These weights are consistent with trip frequencies per facility type found by GOV.uk [465];
- For some facility types, only the closest facility is relevant (e.g., primary healthcare, parks), whereas for others (e.g., restaurants), inhabitants usually want to choose between multiple facilities [453]. The closest-only facilities are marked with an asterisk in Table 6.1.;
- If the return trip to a facility is made soon after reaching the destination, the person may experience a feeling of walking or cycling a longer distance. Therefore, in evaluating active transport probabilities (which are a function of distance), a one-way distance is considered for facilities that imply a long stay at the destination (e.g., schools, restaurants), whereas for the other facilities, a two-way distance is considered instead. One- and two-way facilities are indicated in Table 6.1. by the I or II;
- The four transport modes are comprehensive categories; e.g., for cycling, they include all types of cycles and not just bicycles. Likewise, public transport includes buses, subway, etc.

Table 6.1. Facility types and weights.

Weight 1 Facilities	Weight 2 Facilities	Weight 3 Facilities
Post offices *II	High schools I	Kindergartens *II
Sports facilities I	Shopping centres II	Primary schools *II
Cultural organizations I	Entertainment sites I	Middle schools *I
Universities and institutes I	Primary healthcare services *I	Grocery stores II
Elderly care centres I	Pharmacies *II	Supermarkets II
Churches I	Restaurants I	Bakeries and pastries II
	Parks and green areas *I	

(*) Closest only, (I) one-way facility, and (II) two-way facility.

The Section 6.2.3. to Section 6.2.6.1. present implementation details and their rationale. Some of these details are presented using the ArcGIS 10.8 language, but any other GIS environment can be used provided its toolset can execute the operations described herein.

6.2.3. Compactification procedure

Compactification is done in accordance with the existing municipal master plan. These plans define authorised construction zones and set rules in terms of soil impermeabilization coefficients, usable building area, gross floor area, number of floors, and zoning rules (i.e., zone land use), which must be respected in the compactification procedure. Authorised (but still construction-free) zones usually form the largest share of vacant space to be occupied. Other spaces include derelict areas and brownfields, as those zones are likely to be regenerated at some point [666–673]. No green areas are reassigned to residential or commercial use. Identifying the vacant spaces is the first step in the compactification procedure. These zones can be strictly residential, non-residential (e.g., commercial, industrial, other public facilities, etc.), or have mixed land use.

The second step is to determine how many people can be moved onto the vacant spaces that allow for residential use. From the soil impermeabilization coefficients, it is possible to determine the usable building area for each vacant space (the area that a building occupies when seen from directly above). Multiplying this area by the number of floors yields the gross floor area. After discounting 15% for building communitarian spaces (e.g., main entrance, stairways, etc.), the resulting area is what is available for apartments, i.e., private gross floor area. Apartment typologies and respective inhabitants are then distributed by the private gross floor area. This can be done following the empirical statistical distribution for the country's typologies [674] or by any other means (e.g., minimizing building unused space or maximizing number of inhabitants). As an example, Table 6.2. below shows the characteristics of building typologies in Portugal and can be used for the purpose.

Table 6.2. Building typologies in Portugal.

Apartment Typology	Fraction	Minimum Private Area * (m^2)	Average Inhabitants
T0 (studio)	2%	35	1
T1 (one bedroom)	9%	52	2
T2 (two bedrooms)	32%	72	3
T3 (three bedrooms)	36%	91	4
T4 (four bedrooms)	13%	105	5
T5+ (five+ bedrooms)	9%	122	6

(*) See ref. RGEU, 1951 [675].

Having determined how much of the population can be moved into the residential buildings, the new buildings are drawn in GIS in the vacant spaces as follows:

1. Locate the point with best accessibility in the real city, point P;
2. Define a 100 m radius circle centred on P and draw all the possible new buildings within that circle. Assign the population farthest from P to those buildings and remove the buildings originally containing the moved population from the origins dataset;
3. Define a ring-like area 100–200 m away from P and repeat the assignment of #2;
4. Add 100 m to the ring-like area edges of #3 and repeat #3 until resulting new buildings can no longer be fully populated.

For vacant areas with mixed land use, i.e., residential and commercial, the commercial space is deducted from the private gross floor area. The deduction amount is determined by the municipal master plan. After moving the population, urban facilities that ended up away from residential buildings are moved, starting from the farthest away, to the ring-like zones centred around P and onto vacant spaces that allow their land use and as close as possible to P. Note that some facilities can be moved onto buildings with mixed use, subject to area restrictions.

The third step is to move job locations. Jobs and job zones that already existed inside the new urban perimeter remain in their location. Employers with over 100 employees (e.g., hospitals, shopping centres) that can be moved are, and their employee count is added to the job zone they are moved to. Those that cannot be (e.g., stone quarries, chemical industries) remain in their original position, and a dedicated job zone is created for them. Smaller employers are allocated to job zones inside the new urban perimeter according to the percentage of population moved to those inside zones; e.g., if a job zone in the outskirts held 1000 jobs and the population of that zone was moved 70/30% onto inside zones A and B, then A gains 700 jobs in its centroid, and B gains 300. Edge zones, i.e., zones that have a part (but not all) of their population and jobs moved, are redrawn and centroids recalculated based on the jobs that remained inside. Note that job zone centroids are geometric averages of actual job locations of that zone, weighted by employee count (see Section 6.2.4.1.).

The final step is to add road strips alongside new buildings and non-residential land-use plots that become occupied with facilities or jobs.

6.2.4. Accessibility

This research uses the classic definition of accessibility as the ease or, more widely, the cost of reaching destinations [451,485], measured as averaged distances from origins to destinations (OD). Recent examples of cost-based approaches to accessibility include [459–461]. The use of distance is justified because of its flexibility and ease of interpretation, an important attribute for planning purposes since measures need to be well understood by policy makers [462] and also because distance can be used as a proxy to other measures, as will be seen below.

The accessibility measure selected in this research is similar to that used in Monteiro et al. and Sousa et al. [16,466]. It is given by the following:

$$A_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} d_{ij}^k}{\sum_k L_{kj}}, \qquad (6.1)$$

where

i: 1, … , I number of origins;
j: 1, … , J number of facility types (includes jobs);
k: 1, … , K number of closest facilities (when it applies), and in this thesis, $K = 3$;
A_i: accessibility score of origin i;
d_{ij}^k: network distance from origin i to the k-th closest facility of type j (or job zone centroid).
w_j: weight of facility type j (destination attractiveness);
L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

This indicator can be interpreted as the average distance from origins to destinations, weighted by destination attractiveness and by choice factor. Formally, freedom of choice factors for closest-only facilities can be defined as $L_{kj} = \{100,0,0\}$.

6.2.4.1. Accessibility to jobs

Accessibility to jobs requires a different treatment because people have fixed job locations; hence, the concept of "closest job" does not apply. In other words, contrary to facilities where people can choose where to go, for jobs, employees must go where their job is located. To deal with this issue, a zone analysis is carried out instead, as follows in Monteiro et al., Jiao et al. and Wang [16,469,676]: identify job locations and employee count, divide the city into zones (considering population density, buildings, job density, and orography), count jobs in each zone, and find the geometric average job location of each zone. Finally, for each origin, calculate distance to each average job location, and ponder it by the percentage of jobs in the respective zone. Mathematically, this can be expressed by the following:

$$d_{ij}^{k} = \sum_{z} f_z d_{iz}\,, \qquad j\text{: jobs,} \tag{6.1}$$

where
$z: 1, \dots, Z$ number of job zones;
f_z: fraction of total jobs in zone z;
d_{iz}: distance from origin i to the z-th job zone centroid.

Jobs are of "closest-only" nature, and their weight can be set by, e.g., the percentage of commuting trips on the study area.

6.2.5. Active modal share

This research estimates the walk/cycle/car/bus modal split by the methodology of refs. [17,570,662,677], which is based on the following ideas:

- The active mode share is estimated from transforming accessibility-related trip distances onto active trip probabilities using log-logistic distributions. Separate walk and walk/cycle probabilities are obtained, the latter by combining walk and cycle probabilities, yielding two types of analysis;

- After discounting the active trip probability, the remaining probability corresponds to motorised trips, which are split onto bus/car trips according to the empirical percentages.

The above analysis is applied to each origin and OD pair. The modal split for origin *i* is then as follows:

$$M_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} p_{\mathrm{A}ij}^k}{\sum_k L_{kj}}, \tag{6.3}$$

where
M_i: active modal share of origin i;
$p_{\mathrm{A}ij}^k$: active trip probability from origin i to the k-th closest destination of type j, with
$p_{\mathrm{A}ij}^k = \sum_z f_z p_{\mathrm{A}iz}$ for *j*: jobs ($p_{\mathrm{A}iz}$: active trip probability from i to average job location of zone z).

The separate scenarios for walk and walk/cycle is justified because many cities do not provide adequate support for the cycling mode (e.g., lack of bikeways and/or lack of mechanical aid devices in hilly cities [466]), causing users to steer away from this mode. Because of this, two $p_{\mathrm{A}ij}^k$ actually exist, each corresponding to an active mode scenario. Methodological details on the active mode estimation are lengthy and are thus presented in the volume II Supplementary material, chapter 6, for the interested reader.

6.2.6. Transport energy consumption

Transport energy consumption is defined as fossil fuel usage on motorised trips. It is estimated for each origin and OD pair and can be obtained from the motorised modal split using the following:

$$E_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} \left(1 - p_{\mathrm{A}ij}^k\right)\left(f_{\mathrm{car}} F_{\mathrm{car}} + f_{\mathrm{pub}} F_{\mathrm{pub}}\right)\left(d_{ijk}^{\rightarrow} + d_{ijk}^{\leftarrow}\right)}{\sum_k L_{kj}}, \tag{6.4}$$

where
E_i: average fuel consumption of accessibility-related trips originating in i;
f_{car}: fraction of motorised trips made using the private car;
f_{pub}: fraction of motorised trips made using public transport;
F_{car}: private car average fuel economy (MJ/passenger.km);
F_{pub}: public transportation average fuel economy (MJ/passenger.km);
$d_{ijk}^{\rightarrow}, d_{ijk}^{\leftarrow}$: one-way distances from origin i, respectively, towards/away the k-th closest destination of type j.

The E_i is measured in MJ/passenger-trip (at the tank). Note that in Equation (4), trips are always considered as two-way regardless of facility type.

6.2.7. 15-Minute City

Rather than checking which origins belong to a 15-Minute City, the attainable fraction for each origin is calculated instead. For this purpose, network arcs are endowed with walk and cycle speed information (walk speed: 1.14 m/s [678]; cycling speed: 5.00 m/s for facilities [579]; 6.01 m/s for jobs [578]) and network junctions with delay (turns) information. New OD routes are derived, minimizing time and accumulating this variable (call it t_{ij}^k). Then, for each OD pair, a binary score is applied depending on whether the trip is (or is not) achievable in 15 min. The OD pairs are then doubly weighted and summed using the following:

$$C_i = \frac{\sum_{jk} w_j L_{kj} B_{ij}^k}{\sum_j w_j \sum_k L_{kj}}, \tag{6.2}$$

where
C_i: attainable fraction of 15-minute city for origin i;
B_{ij}^k: 1 if the trip from origin i to the k-th closest destination of type j is possible within 15 min using active modes $\left(t_{ij}^k \leq 15\right)$; otherwise, 0. For jobs, $B_{ij}^k = \sum_z f_z B_{iz}$ (B_{iz}: 15-min binary score from i to job centroid z).

Again, two sets of C_i exist depending on whether or not cycling is considered in the active modes. If it is, the trip time t_{ij}^k refers to cycling time. Both walking and cycling times are calculated not considering terrain slope. Hilly cities reduce active mode speeds; considering the effect of hilliness is possible, but it requires having network datasets with altimetry information and is left for future research.

6.3. Case study results

Coimbra is a mid-sized city with 104,000 inhabitants located in the centre region of Portugal [583]. Founded in the Roman age, Coimbra grew mostly in an unrestricted way, owing to its long history of occupation by different cultures, ideals and needs. Coimbra had a compact layout during its origin and medieval times and up to the twentieth century, having then developed onto a sprawled, low-density, and low-mix pattern of land use, with long and wide streets to accommodate the motorised traffic that came in the wake of the cheap fuel boom of the second half of the twentieth century. This spatio-temporal trend left plenty of unused urban space, which the city can now reclaim. Figure 1 shows the evolution of Coimbra urban perimeter and population; Table 6.3. summarises the associated sprawl. The figure was based on data from refs. [679,680] and the table on data from refs. [679–683].

Table 6.3. Population and area of Coimbra.

Year	Population	Population Increase	Area (ha)	Area Increase	Population Density (inhab./km^2)
17th Century	Circa 12,000	N/A	43	N/A	27,907
1930	36,021	200%	170	295%	21,189
2021	104,464	190%	8700	5018%	1201

As can be seen from the table, sprawl increased throughout the centuries, with area increases being greater than the homologous population increases.

Detailed Coimbra datasets were available from previous projects, and Infill Coimbra datasets required only minor changes of the former, carried out manually on GIS. Survey data show circa 19% of trips use active modes, of which only 0.2% are cycling [584], mostly due to poor cycling network suitability (i.e., lack of cycling infrastructure and overall safety) [542] and high inclines [451]. Motorised trips are split 30/70% between public transport and private car, respectively [584]. The low cycling share is, however, expected to rise significantly if the cycling network were upgraded and deterrents mitigated, again justifying the two-scenario approach [17]. The commuting trip sharing of Coimbra is 37% [542], which translates to $w_j = 22, j$: jobs, and all the analyses used $L_{kj} = \{70,20,10\}$ for non-closest-only facilities. Parameterization of active-mode trip probabilities can be found in the Supplementary Materials, Section 1. Motorised fuel consumption was assumed to be 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport [585].

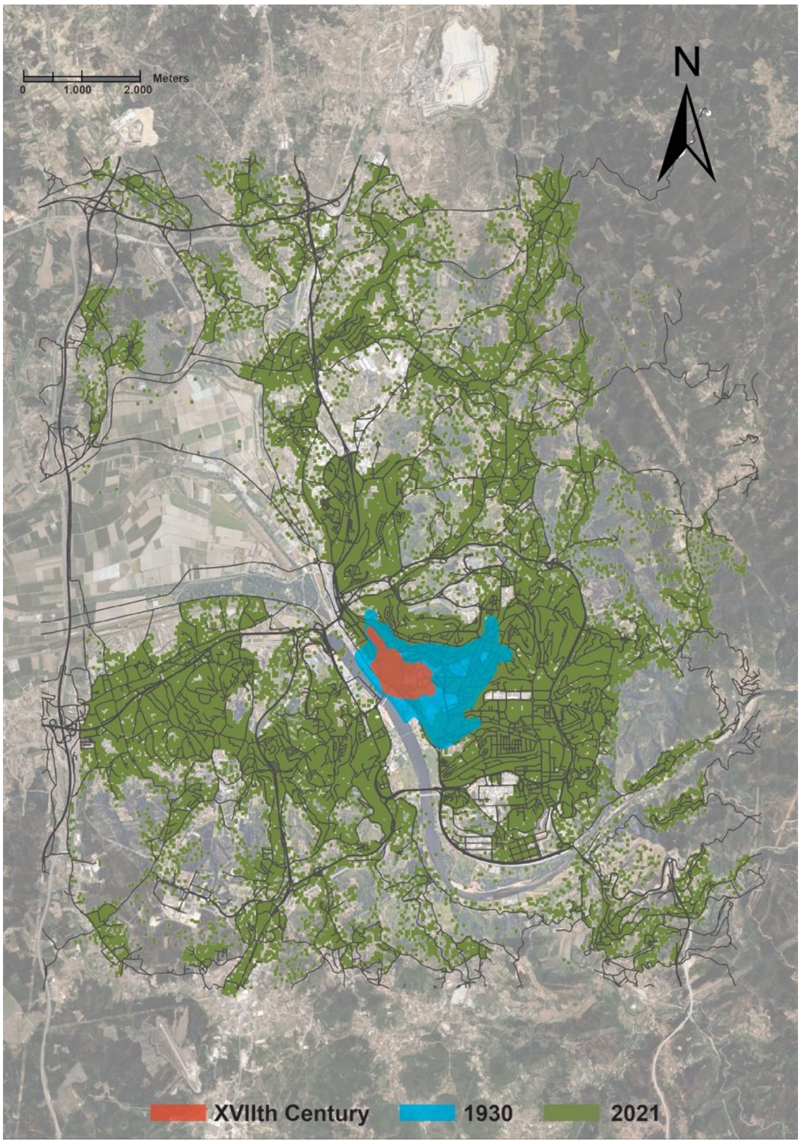


Figure 6.1. Evolution of Coimbra's urban perimeter and population.

6.3.1. Compactification of Coimbra

As mentioned above, Coimbra's urban sprawl left many spaces unurbanized, and others that were once occupied became derelict. New buildings occupying the vacant spaces were drawn in GIS in full compliance with the current regulations of the municipality of Coimbra using the up-to-date municipal master plan, as prescribed by the methodology. Compliance with those plans makes it possible to operationalise the compactification, should municipal authorities and civil construction contractors wish to do so.

After applying the municipal regulations to new buildings, a layout of flats per floor was chosen that maximised the available surface area for the number of inhabitants accommodated. This gave rise to T1 to T4 typologies in percentages of 0.1/45.8/46.5/7.6, respectively. In total, 196 new land plots were idealised, and 636 buildings created that were able to house 54,469 inhabitants, meaning that around 40% of the Coimbra's population would be moved. With respect to urban facilities, each relocated facility would be given the same area it currently occupies.

Figure 6.2 depicts the arrangement of new buildings that are needed to realise an Infill Coimbra, and Figure 6.3 shows the location of buildings, facilities, job zone centroids, and the road network pre- and post-compactification. Volume II supplementary materials Figure II.6.1 shows the full job zones.

At the end of this compactification process, the total urbanised area of the city was reduced from 141,720 m^2 to 16,732 m^2, a reduction of about 88%, as Figure 6.3 and Table 6.4. show. The living space per inhabitant in the new buildings is rather small (24 m^2): about half the actual value. However, it should be noted that some dwellings of real Coimbra have very generous areas, which biases the result towards large average areas.

Table 6.4. Compactifying procedure statistics.

Indicator	Infill Coimbra	Notes
City area	16,732 m^2	Coimbra: 141,720 m^2
New buildings	636	New land plots: 196
New building area	296,910 m^2	Gross floor area: circa 1,300,000 m^2
Moved population	54,469 inhab.	52% of total population
Average residents per building	86	
Average building floors	4.5 floors	
Living space per inhabitant	24 m^2	Coimbra: 47 m^2

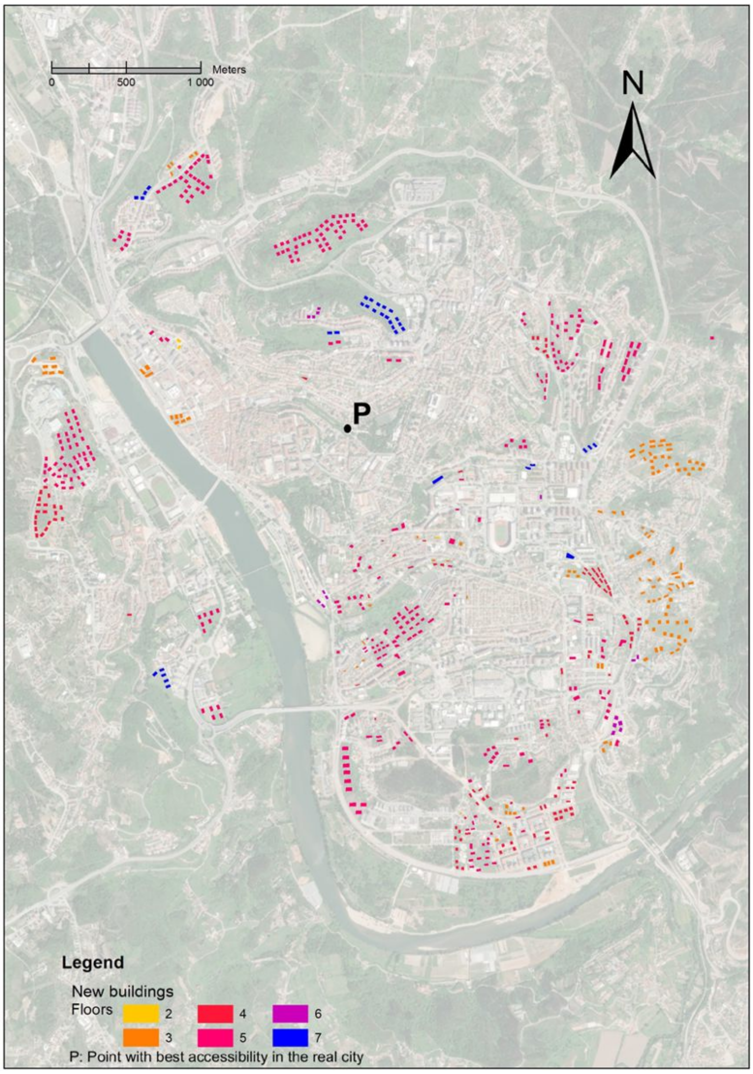
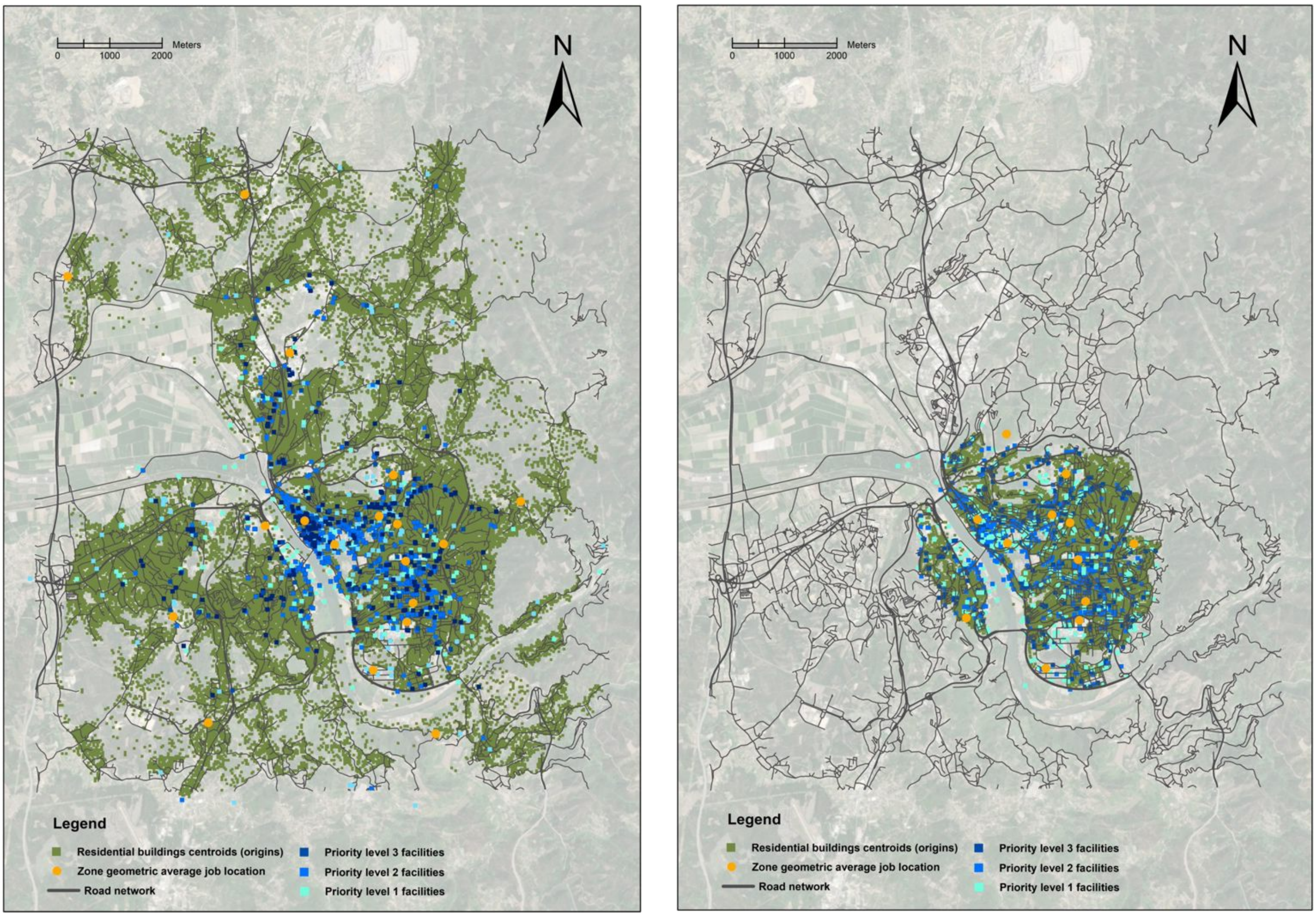


Figure 6.2. New buildings arising from compactification (in full compliance with the current municipal master plan).



(**a**) (**b**)

Figure 6.3. Origins, destinations, and road network. (a) Layout of Coimbra; (b) layout of Infill Coimbra.

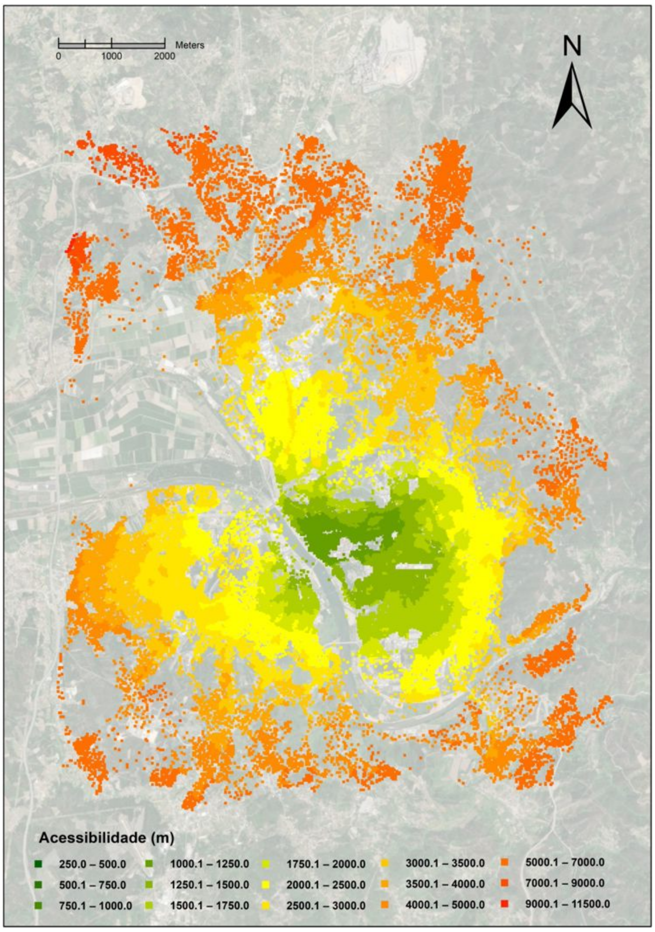
6.3.2. Accessibility and the 15-Minute City

Applying the methodology to obtain the accessibility and 15-Minute City indicators yields the results of Figures 6.4 and 6.5 and Table 6.5. In all results tables, statistics are carried over the set of origins i except for the average per inhabitant line, which is weighted to origin population (h_i), i.e., $\frac{\sum h_i A_i}{\sum h_i}$. As seen from Figure 6.4, and as expected, compactification increases the accessibility scores. That increase is felt overall and is substantial even in the more central areas, which already had good scores before compactification. Accessibility scores also become more homogeneous as the city becomes denser and more compact. Statistically, Table 6.5. shows a reduction in the average OD travel distance per inhabitant of 38%—from 2533 m to 1570 m on average. If jobs are taken out of the equation, that difference reaches 56%—from 1440 m to 638 m on average. It is interesting to note that the average per-inhabitant distances of Infill Coimbra are actually higher than the per-origin averages. This happens because much of the population is moved into zones with slightly subpar accessibility, but this effect is very small.

Table 6.5. Accessibility (m) and 15-minute city statistics (%).

Accessibility (m)	**Urban Facilities**		**Urban Facilities Plus Jobs**	
	Coimbra	**Infill Coimbra**	**Coimbra**	**Infill Coimbra**
Min	268	252	1063	948
Max	8099	1746	9329	3092
Average	1936	594	3088	1491
Average per inhabit.	1440	638	2533	1570
Standard deviation	1352	188	1483	280
Coeff. of variation	70%	32%	48%	19%

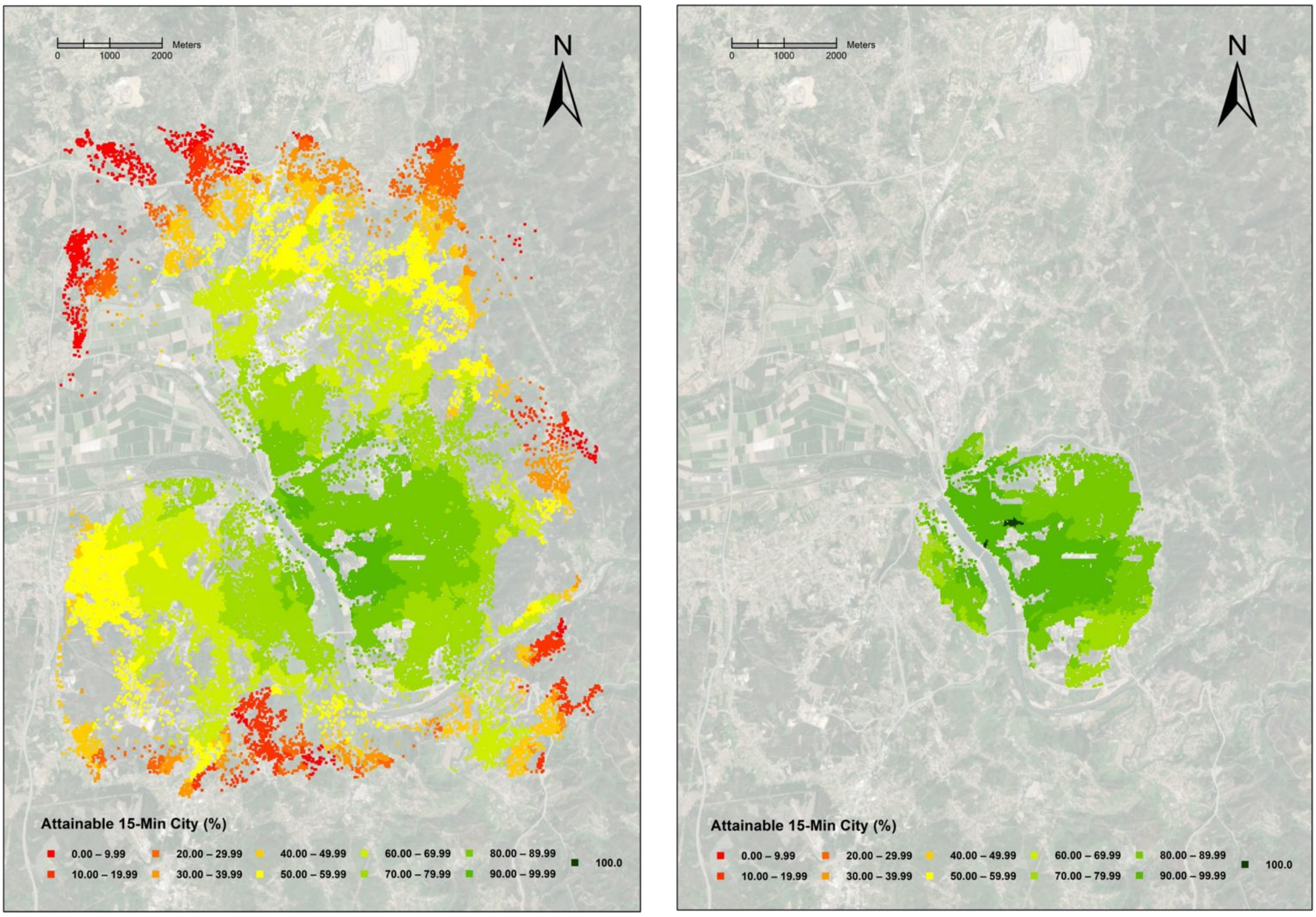
15-Min City (%)	**Walking**		**Walking and Cycling**	
(Facilities Plus Jobs)	**Coimbra**	**Infill Coimbra**	**Coimbra**	**Infill Coimbra**
Min	0.0	6.7	0.0	69.1
Max	71.3	76.3	91.8	100
Average	22.5	61.6	66.3	88.5
Average per inhabit.	30.2	58.0	71.1	85.0
Standard deviation	20.1	8.9	19.7	5.7
Coeff. of variation	95%	15%	30%	7%



(a)

(b)

Figure 6.4. Accessibility to urban facilities plus jobs (m): (a) Coimbra; (b) Infill Coimbra.



(a) (b)

Figure 6.5. The 15-minute city for walking/cycling to urban facilities plus jobs (%): (a) Coimbra; (b) Infill Coimbra.

Assuming walkable distances of 700 m [476,477] or 800 m [576], Infill Coimbra is largely a walkable city, especially if only facilities are considered. This is in sharp contrast to real Coimbra, whose average distance per inhabitant to facilities of 1440 m, 2533 m if jobs are added, makes it far from walkable. As for cycling, assuming cyclable distances in the range of 3800 m [476], both cities are cyclable for the average inhabitant. However, while Infill Coimbra is clearly cyclable for all its inhabitants, in Coimbra, that cyclability is restricted to the more central areas.

Figure 6.5. and Table 6.5. present the results in a 15-Minute City perspective. Average walking and cycling speeds mean that for 15 min, a person can walk up to 1026 m or cycle up to 4500 m, which are slightly higher values than the current literature standards.

Looking at Figure 5a reveals that Coimbra achieves a reasonable fraction of being a 15-Minute City but only on its central region and only if cycling is considered. Outskirts are heavily penalised, and in practice, cycling is marginal. The volume II supplementary material Figure II.6.6a, which considers only walking, is thus a more precise picture of the current situation: only a few select locations in the centre achieve 50%+ of being a 15-minute city. In contrast, as shown by Figure 6.5b, a cyclable Infill Coimbra manages attainability scores of over 70% almost everywhere, with percentage averages in the high eighties. Considering only walking greatly decreases those scores (Figure II.6.6b., Table 6.5.), once again highlighting the importance of cycling in an urban environment and the opportunities that it creates.

However, from the theoretical viewpoint of a 15-Minute City, defined as a city with 100% active travel, the locations of Infill Coimbra that reach the paradigm are very few (Figure 6.5b), proving that the 15-Minute City may be an extremely difficult objective to achieve in practice, at least within the current municipal master plan. This result makes it tempting to speculate that, in general, achieving a 15-Minute City is likely to remain a utopia except for, perhaps, by using very aggressive compactification forms (possibly requiring a change in the municipal master plan) or extremely dense, purposedly built urban layouts. However, such a claim needs quantitative validation, e.g., by developing and applying a modified version of the present methodology.

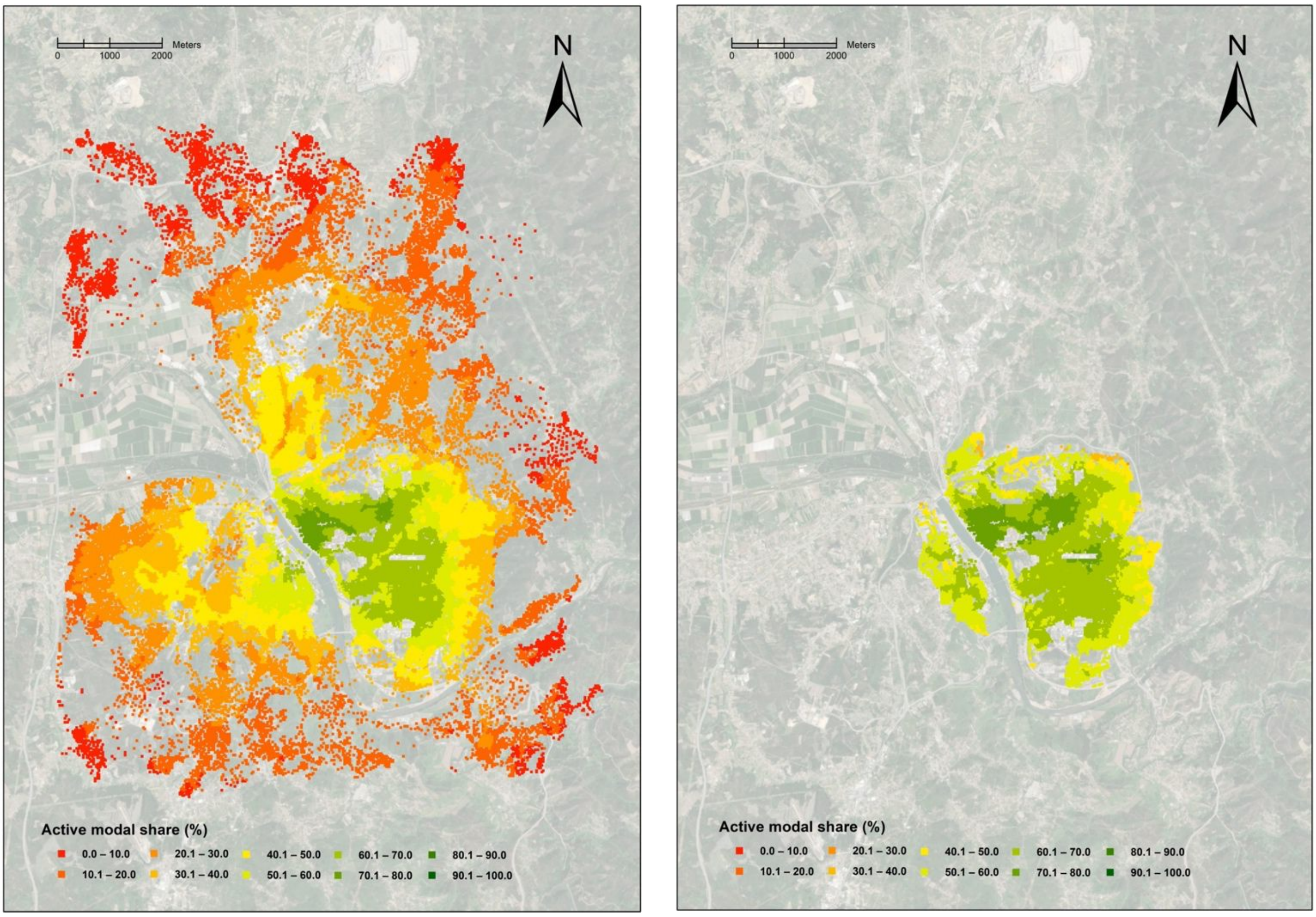
It should be noted that Coimbra is a hilly city, and although in situ observations confirm feasibility of a walking speed averaging 1.14 m/s [684], cycling speed did not reflect slopes. Still, the appearance of affordable pedelec cycles [685–687] and public aid devices [466] can mitigate this effect, making it reasonable to assume that, given adequate cycling infrastructure, slopes can be overcome. Ongoing research to evaluate slope impact on bicycle ridership in Coimbra is being developed by the team.

6.3.3. Modal share

Figure 6.6. and Table 6.6. display the active modal share results.

Table 6.6. Active modal share (%) statistics.

Active Modal Share (%)	Walking		Walking Plus Cycling	
(Facilities Plus Jobs)	Coimbra	Infill Coimbra	Coimbra	Coimbra Infill
Min	0.5	5.6	3.5	28.9
Max	48.0	48.7	73.7	76.3
Average	12.7	28.1	35.6	61.6
Average per inhabit.	16.8	25.6	42.6	58.0
Standard deviation	10.6	7.4	18.7	7.2
Coeff. of variation	83%	26%	53%	12%



(a) (b)

Figure 6.6. Active modal share (%): (a) Coimbra; (b) Infill Coimbra.

The impact on active modal share of compactifying Coimbra is significant, and if all the necessary conditions to cycle are provided, that impact is even greater. Considering all trips, i.e., facilities plus jobs, compactifying Coimbra can increase the modal share by 35% to 50%. For real Coimbra, while it is possible that the bicycle can still be a valid means of transport for the average citizen, the farther-away inhabitants are clearly outside the cycling range for many trips. The outskirts are low-density areas with insufficient connection to the city's public transport network, forcing the resident population to use private cars, another problem that compaction can help solve.

6.3.4. Transport energy consumption

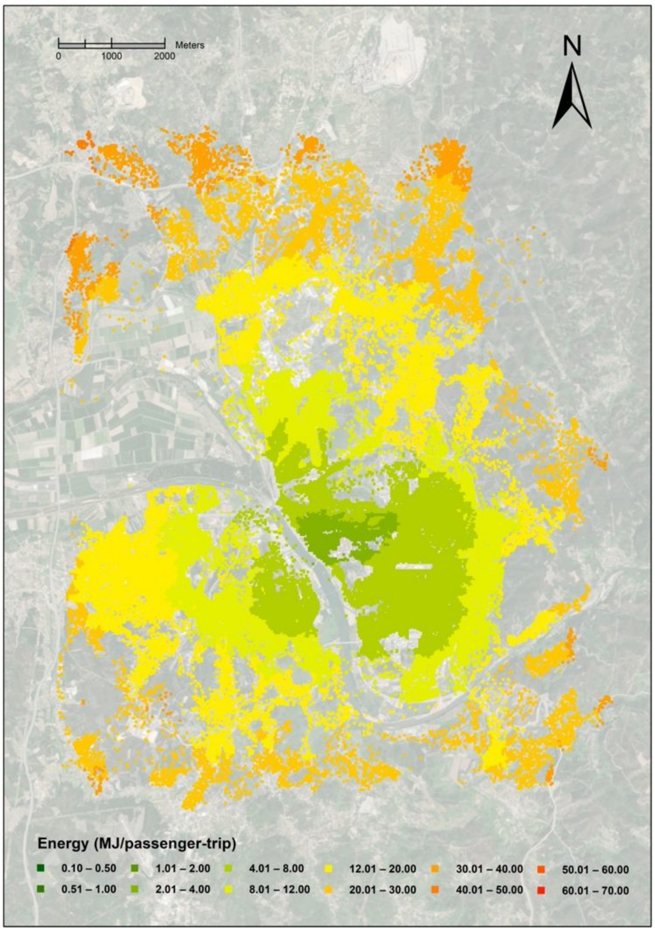
The active modal share has a direct but non-linear impact on energy consumption. It is non-linear because of the log–logistic relationship between active trip probability and OD distance. Figure 6.7 and Table 6.7. summarise that impact of compactifying Coimbra. The Infill Coimbra layout reduces average per-inhabitant transport energy consumption by 62% considering walking only and up to a staggering 76% for walking/cycling. Note that reductions for the furthest-away inhabitant ("Max" on Table 6.7.) are even greater (~80%), underlining how deeply urban sprawl impacts transport energy consumption.

Table 6.7. Transport energy consumption (MJ/passenger.trip) statistics.

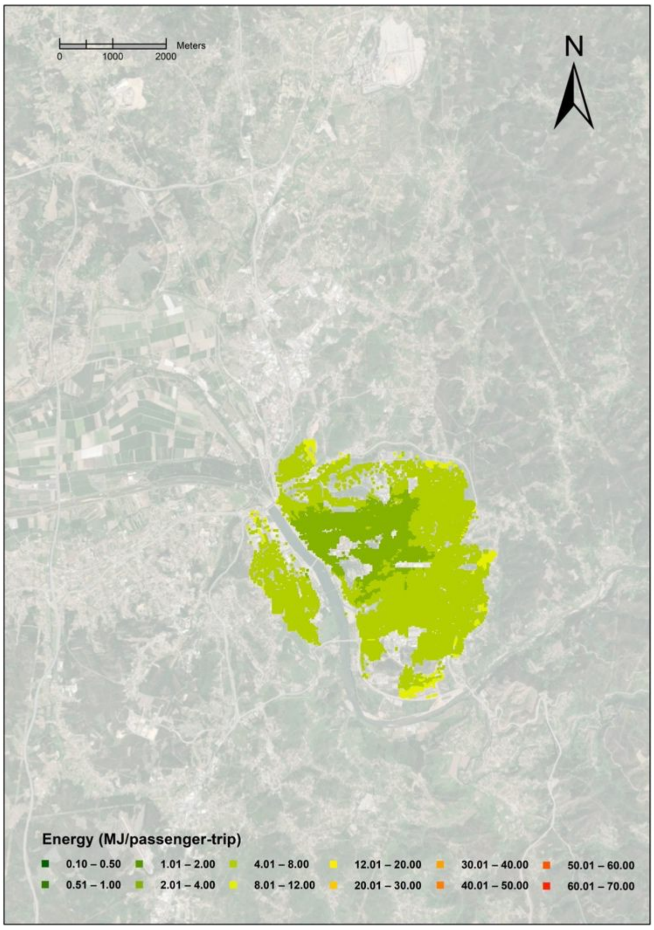
Transp. Energy (MJ/p.t.)	**Active: Walking**		**Active: Walking Plus Cycling**	
(Facilities Plus Jobs)	**Coimbra**	**Infill Coimbra**	**Coimbra**	**Infill Coimbra**
Min	0.690	0.605	0.190	0.132
Max	36.340	7.365	35.370	5.491
Average	8.180	2.056	6.700	0.954
Average per inhabit.	5.901	2.254	4.533	1.103
Standard deviation	6.210	0.830	6.170	0.578
Coeff. of variation	76%	40%	92%	61%

The map of Figure 6.7 shows that many residents living in the urban sprawled outskirts face high levels of transport energy consumption. Changing the city form by bringing everything and everyone closer together provides from the start a significant reduction in energy consumption. Along with the cycling infrastructure promotion, such policies could improve energy savings even further. Additionally, it provides a more equitable urban environment that is able to provide similar opportunities to everyone.

It would be interesting to estimate the effect of compactification on building energy consumption, which constitutes a share of total city energy consumption comparable to that of transport. If reductions can be found in the same order of magnitude of those of transport energy, compactification can arguably be presented as possibly one of the most impactful political decisions that can be taken to mitigate emissions.



(a)



(b)

Figure 6.7. Transport energy consumption (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.

6.4. Discussion

The case study results give an objective measure of how compactifying Coimbra impacts its accessibility, attainability of a 15-Minute-City status, active modal share, and transport energy consumption, revealing improvements on all indicators. Table 6.8. below summarises these improvements.

Table 6.8. Effects of compactification in Coimbra: indicator improvements.

Indicator	**Statistics**							
	Facilities				Facilities + jobs			
Accessibility (m)	Coimbra	Infill Coimbra	Reduction (m)	Reduction (%)	Coimbra	Infill Coimbra	Reduction (m)	Reduction (%)
Avg.	1936	594	1342	69%	3088	1491	1597	52%
Avg. per inhab.	1440	638	802	56%	2533	1570	963	38%
	Walking				Walking + Cycling			
15-min city (%) (Facilities + jobs)	Coimbra	Infill Coimbra	Increase	Increase (%)	Coimbra	Infill Coimbra	Increase	Increase (%)
Avg.	22.5	61.6	39.1	174%	66.3	88.5	22.2	33%
Avg. per inhab.	30.2	58	27.8	92%	71.1	85	13.9	20%
	Walking				Walking + Cycling			
Active modal share (%) (Fac. + jobs)	Coimbra	Infill Coimbra	Increase	Increase (%)	Coimbra	Infill Coimbra	Increase	Increase (%)
Avg.	12.7	28.1	15.4	121%	35.6	61.6	26	73%
Avg. per inhab.	16.8	25.6	8.8	52%	42.6	58	15.4	36%
	Walking				Walking + Cycling			
Transport energy (MJ/p.t.) (Fac. + jobs)	Coimbra	Infill Coimbra	Reduction (MJ/p.t.)	Reduction (%)	Coimbra	Infill Coimbra	Reduction (MJ/p.t.)	Reduction (%)
Avg.	8.18	2.056	6.124	75%	6.7	0.954	5.746	86%
Avg. per inhab.	5.901	2.254	3.647	62%	4.533	1.103	3.43	76%

The compact version of Coimbra shows improvements on all indicators, ranging from 20 to 174% (20 to 92% if only averages per inhabitant are considered). Accessibility values, being distances, are readily interpreted by decision makers for planning and make it clear that the compact version is mostly walkable. The 15-Minute City is a modern benchmark of urban sustainability not fully attainable for Coimbra with the present compactification procedure (but may be possible with other procedures). Active modal share is another such benchmark. A high modal share has health and environmental benefits and reduces congestion. Again, for Coimbra, compactification increases this indicator considerably.

Finally, transport energy is a measure of both efficiency and sustainability, which improves considerably as well with compactification.

Comparing the compact version with real Coimbra shows that urban sprawl posed a toll on all measures, in line with similar results found in the literature [474,688]. It is worth noting that the compactification procedure did not require any radical measures, such as, e.g., skyscrapers or vertical development, excessive densification, or excessive land-use mix. All the new construction was proposed in line with the municipal master plan that was already authorised for implementation, proving practical feasibility of the compactification procedure.

The high accessibility of Infill Coimbra is due to shorter OD distances, and this has an objectively positive effect at various levels, as described in the previous section and above. Along with these also come subjective effects such as, e.g., sense of place and liveability [689] or higher level of travel satisfaction, as active modes are arguably more pleasant than motorised ones [475]. Less energy spent on travel results in lower greenhouse gas emissions (GHG), but in the same way that active modal share is non-linearly related to energy consumption, GHG emissions are also non-linearly related to fuel consumption, as internal combustion engines typically have lower efficiency at warm-up than at cruise regimes [690,691]. Further research is necessary to quantify this effect, which becomes more important as distances are reduced.

Compactification also has non-tangible effects on public transport network and ridership, as recognised by refs. [489,617]. Urban sprawl makes it difficult to properly organise a public transport service: serving distant, low-density locations requires bus lines that are inefficient or unprofitable. Moreover, buses that connect frequently to the final destination are necessary, which discourages their use and pushes users to the private car. Compactifying reduces trip distances, leading to less time spent on public transport and fewer stopovers, a decrease on the number of bus lines, and consequently, an opportunity to increase the frequency of the remaining lines. Compactness also leads to more users within reasonable catchment areas of public transport stops, potentially leading to higher rates of ridership.

Equity and gentrification are growing concerns of the modern city and urban planning [490]. By observing the statistical dispersion measures of the results (standard deviation and coefficient of variation) for all indicators and both city layouts, it is seen that the city of Coimbra in its compact version has improved equity. In the real city of Coimbra, there a clear difference between those who live close to most of the facilities and those who live far away. In its compact counterpart, this difference is substantially smaller, with similar accessibility and transport opportunities for those who live in the centre and those who live at the furthest distances. Regardless of the social levers that led to inequity in the current city, its compact version presents itself as a possible instrument to fight this status-quo and ensure a more equitable and fair development.

Overall, results show that the idea of compactifying a city by filling in the available spaces is likely feasible for many cities and could be used as an urban regeneration and development tool. With the right set of urban policies and adequate promotion, new construction undertakings can bring back to the city centre residents that once left or even bring new people to the city. It is not about completely rebuilding a city area or destroying what is already there to build something completely different. It is about efficiently using urban areas that for different reasons are yet undeveloped or have been forgotten. There is no need to create new places to build but rather build on the free spaces that are already there, compactifying a city by filling in the spaces.

6.5. Conclusion

This chapter presented a quantitative methodology to estimate the impact of compactifying a city by urbanizing its vacant spaces and applied it on a comparison between the real city of Coimbra, Portugal, and its redraft as a compact version of itself. The methodology is based on indicators of accessibility, active modal share, transport energy consumption, and the degree to which it can be considered a 15-Minute City, all of which can be evaluated using a GIS environment and the necessary datasets.

The case study results showed the compact version has very considerable improvements in all indicators (from 20 to 92%), in line with previous research hat advocated compactification as a possible way to reduce the environmental and societal impact of urban sprawl. Furthermore, the compactification of Coimbra can be completed in strict adhesion to municipal master plan, thus attesting to its practical feasibility to implement the reurbanisation agenda and deliver on the desire for closer, more intense social interaction.

As far as the authors know, the proposed methodology is one of the first attempts to provide quantitative measurements of the impact of compactifying a city. The fact it considers the current municipal master plan was not previously tested, and it revealed that, despite the lack of changes in planned land use, a very small space is necessary to accommodate all the suburban citizens and concomitant facilities.

Insights from the case study provide urban planners with valuable information. By showing the plus values of compactifying a city in a quantitative manner, authorities are alerted to the advantages of developing urban planning policies that mitigate sprawl and incentivise the consolidation of city centres, e.g., urban regeneration projects. The implications of these findings go beyond the decrease of travelling and commuting times or the reduction of energy spent on transport. Better public transport operability and ridership and more walkable and cyclable opportunities can lead to a healthier, more sustainable, equitable, and efficient lifestyle. More tangible future objectives include use of the results to estimate city transport energy or emissions savings on a more global, e.g., monthly or annual, basis.

Nevertheless, the quantitative measures presented are not the only ones needed to analyse or compare different urban layouts. A more holistic view may require other measures to be implemented, such as urban environmental pleasantness (e.g., ref. [19]), land-use analysis, or to extend the energy considerations to the building sector. Such putative measures would need to be defined in a way that they can be calculated in a GIS environment, which is a fundamental prerequisite for applying the methodology proposed in this research given its quantitative nature. The growth and development of a city is unlikely to follow predefined theoretical patterns, but this research provides quantitative elements with intuitive map representations, allowing everyone to understand, judge, predict, and make decisions regardless of what the future may bring.

Acknowledgments: I would like to thanks Prof. Dr. Álvaro Seco for his suggestions on this topic of research.

7. The impact of geometric and land-use elements on the perceived pleasantness of urban layouts

"Neither city planners nor traffic planners put city space and city life high on their agenda. For years there was hardly any knowledge about how physical structures influence human behavior." - Jan Gehl

This chapter presents a model to estimate the impact of geometric and land use elements on citizens' perception of urban layout pleasantness. An ordinal regression cumulative link mixed model with those elements as regressors is proposed and calibrated using data from an online survey. Results show that landscape building height and density of green areas are the factors that most impact the perception of pleasantness. Based on the model, a methodology to derive pleasantness mean scores for a city is also proposed and applied to a case study. The methodology allows for benchmarking the pleasantness of different cities or comparing neighborhoods within a city. It can be used both as an urban evaluation tool and a decision-aid for city expansion programs.

7.1. Introduction

Over the course of history, social movements have led people to cities, making these the prime human habitat they are today. There are many reasons why these movements occur, such as economic factors (e.g. job opportunities), social factors (e.g. urban vibrancy), or accessibility (to have interaction opportunities nearby) [452,622,692–698]. Living in an urban environment provides citizens with all these benefits, but the urban landscape may not coincide with what people consider a pleasant physical environment. Therefore, the question arises of knowing which factors affect a person's perceived pleasantness of the urban layout, in particular, how landscape elements impact that perception. The aim of this research is to try and respond to the latter question in a quantitative manner, based on objective aspects of geometric and land use elements. Note that the term "urban layout" is understood as a synonym for what Lynch [437] defines as "settlement form" or "physical environment", that is, the spatial pattern of permanent physical objects in a city.

Research about human perception of the built environment has been the focus of studies in the areas of spatial planning, architecture, and environmental psychology [7,699,700]. More recently, research was done focusing on more specific, but subjective aspects, such as the aesthetic of tall buildings on the urban landscape [701], the aesthetical cognitive perception of urban street form [702], the beauty of urban settings considering four different domains: walkability, historical character, size and order, and greenness [703], perceptions of the rural–urban fringe [704], the relation between perceived environmental aesthetics and walking for exercise [705,706], the perception of parks and urban dereliction [707], and the effect of urban landscape on urban vitality [708]. Empirical studies on pleasantness perception in response to geometric and land use elements were presented by Lynch and Stamps [437,709], but only at a qualitative level. Recent quantitative work exists, but at the street level. Examples are Li et al. [710], who studied the quality of street space using logit models, street views, and expert validation, and Ye et al. [711], who used machine learning techniques to evaluate the visual quality of streets. Of the quantitative studies, only Calafiore and Li et al. [703,712] used field data to obtain a pleasantness indicator, respectively, a beauty index and a street quality index. Quantitative work exists on the impact of isolated geometric elements on pleasantness [713–716], but none of these works have evaluated the combined landscape at the neighborhood scale. Thus, the literature on quantitative evaluation of layout pleasantness is very much in its infancy.

This chapter contributes to the state-of-the-art on evaluation of citizen perception of urban layout pleasantness by proposing a quantitative methodology to estimate that perception, based on a statistical model with geometric and land use elements as explanatory variables. The model was calibrated from the results of a worldwide online survey, in which participants looked at images of city neighborhoods from around the globe and were asked to score, on a 1–5 Likert scale, how pleasant it would be for them to live in each neighborhood. To the best of the authors' knowledge, this is the first time a model is proposed to provide quantitative insights on the impact of landscape elements on the perceived pleasantness of the urban environment. It also fits the research framework of Mouratidis [717], who advocated for a better understanding of the links between the built environment and subjective well-being.

The model was applied to the mid-size city of Coimbra, Portugal, for which neighborhood pleasantness scores were obtained and used to estimate the global layout pleasantness of the city. This case study demonstrates the usability of the methodology on a large scale and shows that it can be used by local authorities to better plan their urban environment with an aim at citizen pleasantness and overall quality of life. This is especially useful for city expansion programs, as it can help predict the attractiveness of the various urban architectural layouts which may be under consideration.

7.2. Methodology

The methodology is based on the premise that different geometric and land use characteristics lead to different perceptions of pleasantness. People may, on average, enjoy, for example, open spaces with lots of green areas more than compact layouts with tall buildings. These perception differences have both objective and subjective aspects and are subject to random fluctuations, coming mostly from the latter aspects. Statistical modeling approaches are designed to deal with this randomness and capture the underlying trends that relate the explanatory and response variables. Such an approach is therefore necessary to relate the landscape elements (explanatory variables) to human perception (response variable), disentangling as much as possible the objective aspects of this relation from the subjective ones. A model of statistical quality can then form the basis for predictive analyses of new contexts.

7.2.1. Geometric and land use elements evaluated

To act as explanatory variables, landscape elements must be objective and measurable. This requires putting aside more subjective aspects, such as architectural beauty or building conservation status. The set of explanatory variables was thus restricted to geometric and land use elements and is presented in Table 7.1. These variables are to be evaluated on a neighborhood basis. The survey contained an open question whose answers were used to verify that the elements of Table 8.1. adequately reflected items looked at in rater judgment. See the survey section for details.

Table 7.1. Geometric and land use elements evaluated.

Variable	Definition	Measurement unit	Scale	Level
Green area	Publicly available green area in the study neighborhood	Percentage (%)	0 – 5 6 – 25 26 – 60 > 61	None Small Medium High
Street width	Average street width, including cycle lanes, parking space and sidewalks	Meters (m)	0 – 8 9 – 18 > 19	Narrow Wide Very wide
Nr. of floors	Average floor number of all buildings in the study neighborhood	Integer	1 – 2 3 – 5 6 – 11 12 – 37 > 38	House Short Medium Tall Skyscraper
Building distance	Average buildings side setbacks	Meters (m)	0 1 – 14 > 15	Compact Spaced Sprawled
Green private area	Average private green area	Square meters (m^2)	0 – 10 > 11	Not relevant Backyard

Evaluation of the elements in a neighborhood is made on the measurement unit indicated. When added to the dataset, measured values are transformed into a categorical value using the scale of Table 7.1. This transformation allows for identification of push-pull effects, such as people preferring, for example, wide streets to narrow or very wide ones, an effect that would not be detectable using the raw measured values. It is also more intuitive and improves the calculational convergence of the statistical models. In defining the scale levels, street width and building distance guidelines of municipal and national authorities were considered [718–721]. Similar standards for number of floors differ according to city and country [722]. The chosen scale was based on a combination of those standards. For green area and green private area, no standards were found, so the scale was based on the authors' judgment.

Other landscape elements were considered besides those in Table 7.1. However, a principal component analysis run on survey image data revealed those extra elements were highly correlated to existing ones and were therefore discarded to avoid perturbations in the statistical models.

7.2.2. Survey design

The survey was carried out on the Lime Survey online platform and consisted of 25 urban landscape images which the subjects rated, a demographic questionnaire and an open question. The survey's online character allowed for fast dissemination and wide reach over social media, and ease of access. The opportunity to show images from cities all around the world and the diversified participant pool, with people of different backgrounds and cultures, reduces biases and strengthens the universality of the study. The use of images for surveys related to urban planning is well documented in the literature [702,707,712,723–727]. The decision to show only 25 pictures was made to keep completion time to a maximum of 10 min, a time frame recommended by Galesic and Bosnjak and Revilla and Ochoa [728,729].

7.2.2.1. Demographics

The demographic questionnaire gathered subject age, gender, the type of area where the subject grew up in, and the type of area they currently live in. Possible area types were rural, urban, and rural-urban mix, that is, the fringe between rural and urban zones. Discrimination by area type allows for separate analyses based on subject past and present life experience.

7.2.2.2. Images

Images from 25 urban neighborhoods from around the world were taken from Google Earth. In the selection, variety was sought-after, from dense skyscraper landscapes to quiet-looking neighborhoods of one-story homes, to have enough representatives of all scale levels of Table 7.1. variables and a full spectrum of characteristics that would be possible, for most subjects, to find in their own cities and neighborhoods. Images were presented to the subject in a bird's-eye view, as street views cannot capture full pictures of a neighborhood and its surroundings. All images showed well-cared neighborhoods, so that subjective factors such as, for example, building or street degradation would not bias the subject towards lower scores. The study area of each settlement represented in the images is circa 80,000 m^2, a land plot size chosen having in mind the traditional neighborhood walkability range of a quarter mile (400 m) [576]. The set of images used and statistics on their geometric and land use elements can be found in volume II – chapter 7 supplementary material.

Subjects were asked whether they would like to live in the urban settlements presented on each image and gave their answers on a Likert scale of 1–5, with 1 as "definitely would not like to live here" and 5 "definitely would like to live here." They were also asked to try and abstain as much as possible from considering building aesthetics or proximity to shops and services (accessibility) from their evaluation. Before the start of the survey, subjects were given the opportunity to view all the pictures at the same time, to both create a sense of comparison and reduce sequence biases from showing similar images in blocks. The geometric and land use elements under scrutiny were not disclosed to the participants.

7.2.2.3. Open question

The open question was optional and asked each subject to disclose any particular aspects that they took into consideration in their evaluation of the images. This last question was meant to validate whether the geometric and land use elements of Table 7.1. were actually being looked at by the subjects. The answers were analyzed by a natural language processing machine learning algorithm, translating to English where needed, and in general confirmed the variables' adequacy (see also section CLMM for geometric and land use elements). Some participants mentioned elements other than those of Table 7.1., but they were not general enough (e.g. proximity to water fronts) or not suitable for the methodology (e.g. not quantifiable), so none were added.

7.2.3. Statistical model

The choice of a statistical model is dictated by the nature of the explanatory and response variables and the aim of the study. The perception of urban layout pleasantness (response) is assumed to be formed by a combination of the five geometric and land use elements (explanatory variables) modulo a statistical error. The statistical link between a response variable of discrete ordinal nature and explanatory variables of categorical nature can be expressed by a logistic regression model. In addition, the subject introduces a random factor that represents an overall more optimistic or pessimistic view by the person rating the images.

A cumulative link mixed model (CLMM) was selected for the approach, with logit link function and unstructured thresholds. This model is defined by Tutz and Hennevogl [730] with the notation adapted for clarity as:

$$\operatorname{logit}[P(Y_i \leq j)] = \theta_j - \sum_k \beta_k X_{ki} - u_i, \qquad \operatorname{logit} p = \ln\left(\frac{p}{1-p}\right), \qquad i = 1, \dots, N,$$
$$j = 1, \dots, J-1, \qquad k = 1, \dots, K \tag{7.1}$$

which represents the cumulative probability of the i-th rating falling in the j-th level of the response variable or below. The θ_j are threshold coefficients for the response variable, β_{ki} are regression coefficients for the k explanatory variables, X_{ki} is the value of k in observation i, and u_i the random effect of the person rating observation i, whose distribution is assumed $u \sim N(0, \sigma)$. CLMM allow for both quantitative and categorical explanatory variables and have been used in other research on urban analytics [710,731]. Calculations were carried out using the R software ordinal package [732].

7.3. Results and discussion

The survey was broadcast worldwide on social media for a period of four months, having obtained 1327 validated replies. Table 7.2. summarizes the sample demographics. Table 7.2. shows that older age groups and females may be under-represented in the sample. However, a CLMM with age and gender as explanatory variables reveals that only age is statistically relevant (p-value = 0.02%). Removing gender from the model yields a negative regression coefficient for age of -0.01258 (p-value ≈ 0%). Positive (negative) regression coefficients indicate a tendency towards higher (lower) scores of the response variable. So, per each year of age, the log-odds of eq. (8.1) decrease by 0.01258, hinting that people become more critical of their urban environment as they grow older. However, the explicative power of the age CLMM compared to a threshold only CLMM is low, having a Nagelkerke pseudo-R2 of just 0.13%.

Table 7.2. Demographics statistics.

Variable	Age (years)	Gender (%)
	0-19: 102 20-29: 676 30-39: 311 40-59: 198 60+: 40 Average: 30.8	Male: 64.3 Female: 32.1 N/A: 3.6
Living experience (%)	**Grew up**	**Currently living in**
Urban	45.9	68.8
Rural-urban mix	18.2	7.7
Rural	35.9	23.5

7.3.1. CLMM for geometric and land use elements

The CLMM with the five geometric and land use regressors yields Table 7.3. below, the main result of this chapter. Due to the low explicative power of age, that variable was left out of the analysis.

In logistic regression models with categorical explanatory variables, there exists a base, or reference scenario for regressor levels, in relation to which the other levels compare. The choice of base scenario levels is arbitrary and is usually done lexicographically by the software. For the CLMM of Table 7.3. this is of a neighborhood of high green area, narrow streets, house-like nr. of floors, compact distances, and with backyard. The high absolute value of the log-likelihood indicates good model fit and the Nagelkerke pseudo-R^2 suggests a moderate-to-good explicative power, as logistic regressions usually have low pseudo-R^2 values [733,734]. Random effects standard deviation of 0.8122 indicates ratings disperse almost one Likert scale point due to subject judgment. The slightly below-average mean scores of the images (2.665 for a scale mid-point of 3) evidence some displeasure with the urban environments under scrutiny.

The zero p-values for threshold coefficients indicate participants clearly distinguished between all the five Likert levels of scoring. The near-zero p-values for all category levels show that the levels are highly significant in changing the subjects' ratings with respect to the base scenario. Negative (positive) regression coefficients indicate changes towards lower (higher) neighborhood scores. A closer look at the coefficients' values reveals the direction and intensity of this change.

Table 7.3. R summary of the CLMM with geometric and land use elements as explanatory variables.

Element	Coefficient	Error	Z-value	P-value (%)
GreenArea medium	-0.3790	0.0421	-8.9984	0
GreenArea none	-0.9157	0.0537	-17.0580	0
GreenArea small	-0.9644	0.0321	-30.0439	0
StreetWidth wide	0.1737	0.0344	5.0474	0.000045
StreetWidth very_wide	0.8216	0.0382	21.4957	0
NrFloors medium	-0.8435	0.0453	-18.6243	0
NrFloors short	-0.7367	0.0479	-15.3636	0
NrFloors skyscraper	-1.3469	0.0527	-25.5505	0
NrFloors tall	-0.9499	0.0467	-20.3517	0
BuildingDist spaced	-0.2226	0.0340	-6.5505	0
BuildingDist sprawled	-0.2695	0.0542	-4.9758	0.000065
GreenPrivArea none	-0.6741	0.0458	-14.7135	0

Threshold coefficients	Estimate	Error	Z-values	P-value (%)
1|2	-3.0603	0.0479	-63.9435	0
2|3	-1.6770	0.0457	-36.6975	0
3|4	-0.3823	0.0447	-8.5470	0
4|5	1.1441	0.0463	24.7112	0

Random effects std. dev.	0.8122	(subject)
Mean score	2.6649	
Log-likelihood	-48005.94	
Nagelkerke pseudo-R^2	14.3%	

Green area: As compared to a neighborhood with a high percentage of green area, the negative regression coefficients show that lower percentages cause a decrease in the subjects' perception of pleasantness. The coefficient for "medium" percentage (0.3790) is less negative than that for "small" or "none" (<0.9000), meaning people penalize the latter more. The coefficient for "none" is slightly higher than that for "small," so a slight preference for no green area is perceived as better than a few scattered patches of green. However, the effect is small and could perhaps be due to the small image sample size.

Street width: The positive coefficients show that, as compared to narrow streets, the wider the streets are, the more pleasant neighborhoods are perceived to be.

Nr. of floors: The base scenario of a neighborhood made of short houses is highly preferred, as coefficients for other levels are highly negative. Also, coefficients decrease with building height, indicating pleasantness tends to decrease accordingly, with skyscraper neighborhoods being highly disfavored.

Building distance: This element shows slightly negative coefficients for spaced and sprawled neighborhoods, indicating people tend to favor closeness of dwellings. Albeit being the element with the smallest overall impact in the ratings, that impact is nonetheless significant. A possible explanation for this might reside in a feeling of uneasiness due to crime when buildings are far apart.

Green private area: With the base scenario of having a backyard, the negative coefficient for "none" shows that having a private open space is clearly preferred to not having one.

Answers from the survey open question add considerations that help to understand the results. Public and private green areas were the most mentioned element of the five, with participants reporting an overall positive impact of having public gardens and green areas near their homes, as well as having a private backyard. In the opposite direction, building height gathered strong opinions about how it would be unbearable for some to live in buildings with a lot of floors, especially skyscrapers. Even participants who disclosed living in cities where skyscrapers are part of the skyline felt that, given the option, they would choose not to live in such neighborhoods. With respect to street width, some participants (mostly women) found narrow streets to be unsafe, in association with lower traffic, less people, and back alleys. As to building setbacks, some expressed that a compact building is too claustrophobic, but admitted that if buildings were too far away, there would be less socialization and a sense of isolation. This last comment suggests a push-pull effect might occur, with medium-sized distances being preferred. However, that is not what the regression coefficients show.

Summarizing the results, participants declared a preference for urban environments with sizable green areas, wide streets, short but compact buildings, with private green spaces. Some of these tendencies are statistically strong enough to be expected to be general; others may become more precisely defined if more images were considered, such as, for example, the difference between the "small" and "none" green area levels or the possible push-pull effect of building setbacks. Some of the more pronounced tendencies have been identified in the literature, albeit at a qualitative level. The preference for larger urban parks has been identified in relation to various aspects [735–738]. Aversion to tall buildings has been recognized [739,740], while Mohsenin and Sevtsuk [741] found wider streets are better remembered. Day [742] concluded that the lack of a backyard was a factor of discontent. This research adds statistical power to these findings, enabling the possibility to evaluate and predict pleasantness levels beyond qualitative considerations.

7.3.2. Influence of present and past experiences

Present and past experiences shape the human mind, and the perception of urban layout pleasantness should be no exception. To better understand the effect of present and past experiences, the CLMM was rerun on two subsets of the data, namely, urbanite and ruralite subjects. Urbanites are defined as people who grew up or currently live in an urban environment and never lived in a rural environment. Similarly, ruralites are people who grew up or currently live in a rural environment and never lived in an urban one. People outside these definitions were deemed mixed subjects. Table 7.4. summarizes sample statistical data on those subsets.

Table 7.4. Data subsets statistics.

Urbanite		**Mixed**		**Ruralite**	
GrewUp/LivesIn	Sample %	GrewUp/LivesIn	Sample %	GrewUp/LivesIn	Sample %
Urban/Urban	41.3	Mixed/Mixed	15.2	Rural/Rural	4.9
Urban/Mixed	18.9	Rural/Urban	8.7	Rural/Mixed	1.7
Mixed/Urban	3.5	Urban/Rural	1.1	Mixed/Rural	4.7
Total:	63.7	Total:	25	Total:	11.3

It is worth pointing out that Table 7.4. gives insights as to the participants' social movements in-between the three landscape types (urban/rural/mixed), the largest one being the urban-to-mix movement, suggesting growing outskirts of the participants' cities, and the smallest the urban-to-rural movement, which might indicate very few job opportunities created in the rural areas.

7.3.2.1. Urbanites

Table 7.5. displays CLMM outputs for the urbanite subset. All coefficients remain statistically very significant (p-values ≈ 0). Unsurprisingly, urbanites have a slightly more positive perception of the urban environment, with a better mean score of the images and less-penalizing regression coefficients. The largest differences to the general case lay in the taller building types, which are not as heavily penalized, despite the clear tendency to still prefer shorter buildings. This tolerance of urbanites to taller buildings was also found by Ali and Al-Kodmany [739]. Similarly, for public green areas, the 'none' or 'small' percentages are now slightly better accepted.

Table 7.5. R summary of the CLMM for urbanites.

	Urbanites			
Element	**Coefficient**	**Error**	**Z-value**	**P-value (%)**
GreenArea medium	-0.3901	0.0527	-7.4072	0
GreenArea none	-0.7443	0.0668	-11.1383	0
GreenArea small	-0.9042	0.0400	-22.6241	0
StreetWidth wide	0.1501	0.0429	3.4971	0.047
StreetWidth very_wide	0.8346	0.0476	17.5267	0
NrFloors medium	-0.7104	0.0564	-12.5896	0
NrFloors short	-0.5664	0.0599	-9.591	0
NrFloors skyscraper	-1.2184	0.0656	-18.5736	0
NrFloors tall	-0.7448	0.0580	-12.8319	0
BuildingDist spaced	-0.2552	0.0424	-6.0227	0
BuildingDist sprawled	-0.2429	0.0675	-3.5969	0.032
GreenPrivArea none	-0.7052	0.0572	-12.3224	0

Threshold coefficients	**Estimate**	**Error**	**Z-value**	**P-value (%)**
1|2	-3.0048	0.0587	-51.1556	0
2|3	-1.6414	0.0561	-29.2847	0
3|4	-0.3651	0.0548	-6.6568	0
4|5	1.1450	0.0567	20.1897	0

Random effects std. dev.	0.7561	(subject)
Mean score	2.7201	
Log-likelihood	-31088.73	
Nagelkerke pseudo-R^2	12,0%	

7.3.2.2. Ruralites

The CLMM ruralite subset results are given in Table 7.6. Again, almost all the coefficients are statistically significant. While some p-values move away from zero, they are still close enough to be considered significant at 5%, except for the 'medium' level of green area percentage, which ruralites see (statistically) as equivalent to 'high', and for the 3|4 threshold. The Nagelkerke pseudo-R^2 also improved, indicating the CLMM fit is better for this subset. Ruralites rate the images with an overall lower mean score than the general case, but the interpretation of results is richer. The most striking difference lies in the regression coefficients for nr. of floors, which exhibit an increase in the aversion towards tall buildings, with considerably lower regression coefficients. The dislike for lack of public green areas also shows a steep increase. Interestingly, backyards do not seem as important to ruralites. Considering that most (if not all) rural inhabitants own lands near their houses, it is plausible that they do not feel such a strong need to have a backyard as their urbanite counterparts. Another interesting difference is on building distances, where the aforementioned push-pull effect is now evident: ruralites prefer spaced home setbacks to compact layouts, while still disliking living isolated and far away from their neighbors. The higher p-value for 3|4 threshold coefficient signifies ruralites find it slightly difficult to distinguish between these two levels of rating.

Table 7.6. R summary of the CLMM for ruralites.

	Ruralites			
Element	**Coefficient**	**Error**	**Z-value**	**P-value (%)**
GreenArea medium	-0.1543	0.1265	-1.2202	22.4
GreenArea none	-1.7641	0.1668	-10.5781	0
GreenArea small	-1.2712	0.0999	-12.7245	0
StreetWidth wide	0.3540	0.1054	3.3593	0.078
StreetWidth very_wide	0.8370	0.1176	7.1199	0
NrFloors medium	-1.3689	0.1401	-9.7699	0
NrFloors short	-1.4571	0.1458	-9.9949	0
NrFloors skyscraper	-2.0460	0.1648	-12.4159	0
NrFloors tall	-1.9365	0.1472	-13.1532	0
BuildingDist spaced	0.2181	0.1023	2.1315	3.31
BuildingDist sprawled	-0.5113	0.1669	-3.0627	0.22
GreenPrivArea none	-0.4481	0.1390	-3.2238	0.13
Threshold coefficients	**Estimate**	**Error**	**Z-value**	**P-value (%)**
1|2	-3.3184	0.1603	-20.6960	0
2|3	-1.7385	0.1536	-11.3190	0
3|4	-0.2622	0.1506	-1.7408	8.17
4|5	1.4591	0.1567	9.3128	0
Random effects std. dev.	1.1520	(subject)		
Mean score	2.4763			
Log-likelihood	-4884.36			
Nagelkerke pseudo-R^2	30.4%			

In short, people used to living in urban areas are more receptive to typical urban elements, such as higher buildings, compact real estate development or less green areas, while ruralite people apparently find it hard to accept those urban characteristics. While these analyses are in line with what might be expected given the subjects' experiences and sociological characteristics, it is nevertheless interesting to see how pronounced the effects are and their direction.

7.3.3. Case study: application to the city of Coimbra

The CLMM makes it possible to analyze pleasantness on a city scale, giving urban planners and municipal authorities a better understanding of how their citizens may be perceiving the city's layout pleasantness. The case study focuses on Coimbra, Portugal, a mid-size city with circa 104,000 inhabitants [583] located in the center region of Portugal. Founded in the Roman age, Coimbra has over a millennium of history of occupation by different cultures who left their mark on the city's layout. Currently, Coimbra is a typical European city, with an historical center of narrow cobblestone streets with low-rise commercial and residential buildings, modern compact neighborhoods with wide streets and tall residential and services buildings, and suburban neighborhoods consisting mainly of houses with gardens. It exhibits a variety of urban landscapes.

To apply the CLMM to Coimbra, the following methodology was used. On a digital map of Coimbra, a square mesh of 400 m diagonal (282 × 282 m sides) was created using a geographic information system (GIS), forming the neighborhoods. For each neighborhood, information concerning the five geometric and land use elements was collected from Google Earth imagery, and its number of inhabitants was obtained from census information. In a general case, if Google Earth imagery is not available municipal planning documents and/or on-site visits can be used alternatively. Based on the values obtained for the five geometric and land use elements of the neighborhoods of Coimbra, 1-5 rating predictions for the CLMM of Tables 7.3., 7.5. and 7.6. were derived in R for each neighborhood i following eq. (7.1.) with $u_i = 0$, and an average rating was calculated using $\bar{r}_i = \sum_{j=1}^{5}(p_{ij} \cdot j)$, with $\bar{r}_i$ the average rating of neighborhood i and p_{ij} the probability of neighborhood i having score j. Averaging $\bar{r}_i$ over i, with and without weighting to the respective population, led to the summarized results of Table 7.7. and the map of Figure 7.1. The map refers to the general model of Table 7.3.

Table 7.7. Average pleasantness for Coimbra.

Pleasantness scores (1-5)	General	Urbanites	Ruralites
Avg. per neighborhood	3.19	3.20	3.10
Weighted to inhabitants	2.69	2.74	2.64

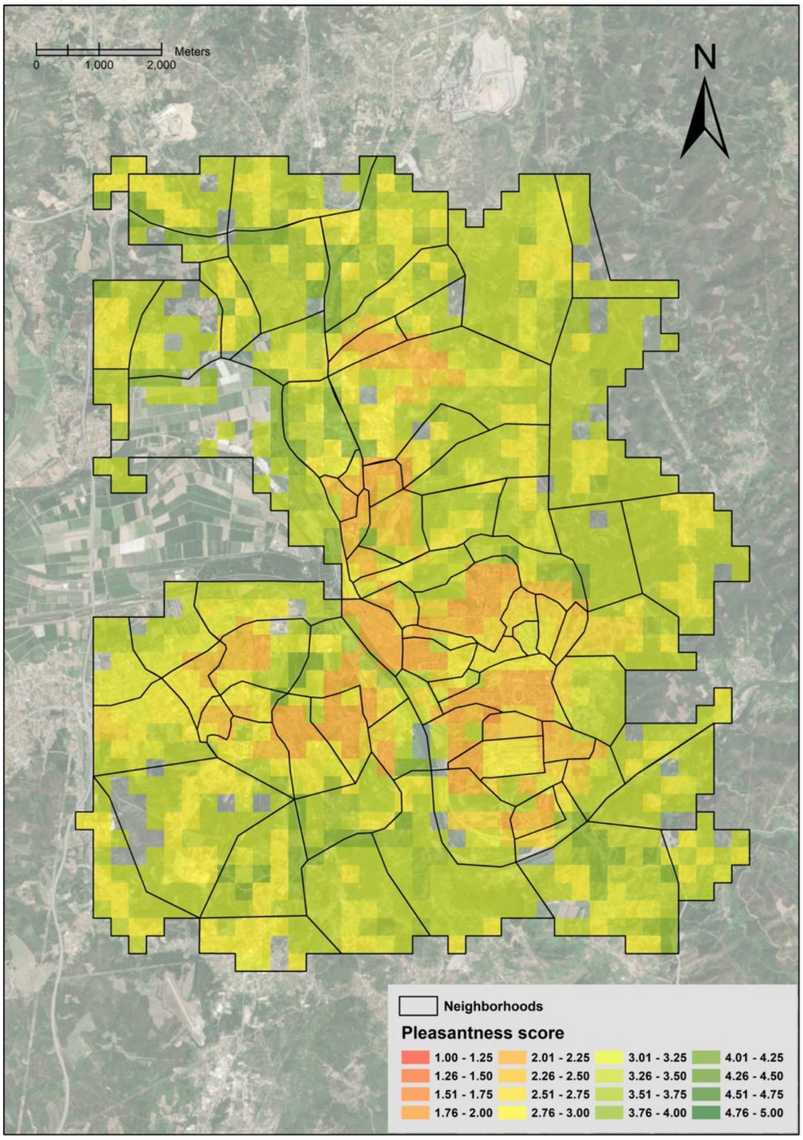


Figure 7.1. Coimbra pleasantness scores per neighborhood.

The non-weighted general average of 3.19 sits slightly above the Likert scale mid-point. However, the population-weighted average is more meaningful, and this is 2.69, below the mid-point. This is due to the less desirable neighborhoods (orange) having more people living in them, which is natural since zones of taller buildings and lower green area percentages are associated with denser urbanization and more inhabitants. Interestingly, there is close to no difference between the general, urbanite, and ruralite results, suggesting that Coimbra is viewed the same way despite the different backgrounds.

7.3.4. Application to planning

The CLMM methodology was constructed to estimate pleasantness in an abstract way, based on objective landscape elements that are quick to collect. It can be used to evaluate existing neighborhoods, but it can also be applied when new settlements are built, or existing ones regenerated. A city pleasantness score can be used as a standard for improvement. Municipal authorities can use it, for example, to evaluate new neighborhoods or urban regeneration projects, subsequently selecting the ones that have pleasantness scores higher than the city average or attain a certain threshold. This planning strategy provides a clear path to improving city pleasantness, with each new neighborhood or regeneration action raising the standard or guaranteeing a minimum one. A pleasantness score can also provide information to compare different cities. This can be done, for example, by applying the methodology used in Coimbra to other cities and deriving information such as that of Table 7.7. for the cities under scrutiny. For the private sector, real estate companies can use a pleasantness score to their advantage, by providing extra information about the surrounding areas of dwellings.

Neighborhood pleasantness is, however, far from the only criterion in urban planning. Other aspects are often taken into consideration as well, and in this respect, unpleasant elements such as, for example, tall buildings, have compensating plus-values such as better energy efficiency, accessibility, and housing availability. What this research adds is a tool to quantify the urban layout pleasantness aspects and put them on an equal footing with other aspects, such as those mentioned above, which are frequently treated by decision-makers in terms of numerical figures. The existence of quantitative scales for all evaluation criteria is the first step towards the application of multicriteria decision-making methods, which thus becomes feasible. Quality of life remains nonetheless an important benchmarking indicator to evaluate neighborhoods and cities, and in this respect, this research provides a means to quantify that benchmark.

7.4. Discussion and conclusions

This chapter presented a logistic regression model for estimating citizen perception of urban layout pleasantness, based on geometric and land use elements, and calibrated with data from a worldwide online survey. Results showed it was possible to find common ground among participants, who declared statistically significant preferences for smaller buildings, plentiful green areas, wider streets, and dwellings with private backyards and close to each other. The preference for these features was also shown to be stronger for people with experience of living in rural areas, whereas people with experience of living in urban areas were more tolerant towards the lack of those features.

Most of the statistical tendencies identified in this chapter are in line with other findings in the literature and strengthen these by providing quantitative support. Those findings, mentioned in section 7.3.1, were mostly qualitative. Recently, quantitative research surfaced which added further support for three of the tendencies found by this research. Tall buildings and skylines can be statistically traced back to oppressive sensations for the viewer [713] and smaller scenic beauty [716]. Those authors also found that higher proportions of vegetation and the presence of trees mitigate the aforementioned negative effects. Trees were also seen by Basu et al. [743] to contribute to a more pleasant walking experience, while Lee [715] argued, via a structural equation model, that large urban parks contribute to urban satisfaction. D'Acci [714] approached pleasantness from a financial perspective, having found that more green areas and wider open spaces lead to higher real estate values. The present research brings together all the above isolated evidence under a unifying statistical model and adds further explanatory variables. This model is, to the best of the authors' knowledge, one of the first contributions to the literature on perception of urban layout pleasantness based on quantitative methods. Furthermore, it provides municipal decision-makers with an evaluation tool which can be used for planning purposes alongside other aspects of urban planning. The case study of Coimbra proved its applicability at the city scale, helping municipal authorities to better understand the impact of urbanization projects on the quality of life.

Some of the tendencies found in this chapter are worth exploring deeper, such as the push-pull effect of building distance; i.e., people preferring homes that are not too close to each other nor too far apart, an effect which is only seen for the subset of people with life experience in rural areas. This could require rerunning the survey with more images.

Another interesting line of research would be to include subjective elements in the analysis, such as e.g., building aesthetics or landscape-architectural beauty, weigh the impact of these factors on overall scores when compared to the objective geometric and land use elements, and confront results with the recent findings on urban aesthetics mentioned in the introduction. We hope to address some of these issues in the near future.

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8. Do we live where it is pleasant? Correlates of perceived pleasantness with socioeconomic variables

"Cities have the capability of providing something for everyone, only because, and only when, they are created by everybody." Jane Jacobs [7]

Living in urban areas is the wish of many people. However, with population growth in those areas, quality of life has become a concerning element for achieving sustainable cities. Because quality of life is influenced by the built environment, the state of the latter is a fundamental issue for public policies. This chapter expands on previous chapter results, on the perceived pleasantness of built environments by presenting a large-scale case study of the urban layout pleasantness in the central area of Belo Horizonte, Brazil, a typical global south city, and correlating pleasantness scores with socioeconomic factors to understand whether people do in fact live where the urban layout is more pleasant and how pleasantness and socioeconomic factors relate and contribute to one's choice of living location. A comparison with the city of Coimbra, Portugal, representative of the global north, was also carried out. The findings showed that pleasantness tended to correlate negatively with urban density and positively with income. Possible explanations for these results and their generality are advanced.

8.1. Introduction

For the past decades, social movements have led people to cities. Cities provide more social interaction opportunities, better accessibility to day-to-day facilities such as schools, healthcare services, entertainment, cultural, and commercial sites, parks, and restaurants, among others, and also broader job opportunities [7,452,622,692,698]. However, with population growth in urban areas, quality of life has become a concerning and crucial element in achieving higher levels of sustainability in cities [696,697,744,745]. Therefore, the significance of the built environment is vital for public policies as it impacts the quality of life [746,747]. In general, the urban landscape does not always resemble what people think of as a pleasant physical environment [19]. Thus, to wage against the creation of unpleasant and unsustainable physical environments, the built environment and public policies have a crucial role in improving the quality of life and creating more sustainable and pleasant cities. However, changes to the built environment and public policies must be adapted to the realities of the cities and societies in question, i.e., to their local context [748]. The current knowledge about transport and spatial planning is primarily shaped by research conducted and based in the global north, whereas cities of the global south face deeper challenges [749]. In this respect, research that can help understand the differences between the northern and southern global hemispheres is essential, given the immense geographic regions these concepts encompass.

Broadly referring to Latin America, Asia, Africa, and Oceania regions, the global south refers to low-income, politically or culturally marginalized regions, where many live in overcrowded informal settlements [750,751], commonly contrasting with most regions on the global north. Cities in the global south encounter the same challenges as those in the global north, such as climate change, gentrification, and growing inequality [752–755], but also additional ones, such as large informal settlements, higher levels of pollution, food and water scarcity, human rights violations, violence and crime, migration and refugee flow, extremely high population density, and uncontrollable urban growth [752,756–760]. In the rush to build created by reterritorialization, i.e., restructuring a place or territory that has experienced deterritorialization [761], entangled discourses and intricate politics, and different actors and institutions, result in a patchwork city with various capacities and affordances [761]. Thus, the repercussions on the pleasantness of the physical environment end up being overlooked or not even considered in this conflicted process of urban growth.

The human perception of urban pleasantness is an important subject in spatial planning, environmental psychology, and architecture [19,437,701,703–706,708,712,713,715,716,762,763], and has been an active research topic in recent decades [699,700,764]. Generally, the built environment is important for improving well-being and achieving a higher quality of life and sustainable future development [717]. Moreover, factors such as green areas, pollution, and accessibility, directly impact property value [762,765–774]. Population density has a controversial impact on environmental quality, with studies identifying a negative effect [775,776], while others found no connection [777]. On the other hand, the quality of life in slums is lower than in other urban settlements [778,779]. Measuring the perceived pleasantness of the urban environment by resorting to physical elements alone (e.g., geometric and land use, as in Sousa et al. [19]) leaves aside socioeconomic factors that affect the quality of life, making it important to investigate whether and how the former elements correlate with the latter factors and how this interaction impacts one's choice of living location. This chapter presents a first step towards identifying those correlations. In other words, this chapter provides a tentative answer to the question: "People enjoy a certain type of physical urban environment, but is that the environment they actually live in, and how does it correlate to socioeconomic factors?"

8.1.1. Literature review

The research question, which can be rephrased as "Do we live where it is pleasant?", with pleasantness understood as an enjoyable physical environment, has not received much attention from quantitative studies, mainly because quantitative definitions of physical pleasantness are limited. Qualitative studies include [437,709], the first of which thoroughly discusses city image and form and has been a landmark reference in urban planning. The second studied the relation between perceptions of architectural complexity and geometric shapes. With respect to quantitative definitions, some progress was made since Zube et al. [780]. Several studies concentrate on one specific landscape element, e.g., walking path geometry [762] (having found that people tend to prefer curvy paths), oppressiveness due to building height [713], skyline impression [781], visual quality of urban water landscapes [782,783], and building exteriors [784]. Combined approaches include mostly landscape aesthetics indicators, e.g., Calafiore [703], who developed beauty indexes and also distinguished landscape type; the morphologic scenic beauty estimation model [785]; an aesthetic assessment approach [65]; and modelling of the aesthetics of urban–rural fringes

[786]. Models that use geometric and land-use elements include [19] who used field data to obtain a pleasantness indicator, the street quality indexes of [710,787,788], the path model of neighborhood satisfaction of [789], and the walkability analysis of Park et al. [790].

Because quantitative definitions of physical pleasantness are scarce, very few studies could be found in the literature that directly relate, quantitatively, physical pleasantness with socioeconomic variables. One example is Meng and Xing [696], which estimated urban vibrancy from landscape elements. Qualitative studies are also few and mostly refer to physical pleasantness as just one of the factors in choosing a living location. Overall, it is known that people tend to live in urban locations with good accessibility to facilities [715,791–793] and matching social environment [715,794]. However, those locations do not always coincide with a pleasant physical environment, a factor that was confirmed in [794] (p. 104) to also be important in household location preference. By being able to define quantitatively what a "pleasant physical environment" is, it becomes possible to understand, also quantitatively, whether or not people actually live in pleasant physical environments and how socioeconomic factors ultimately affect their choice of household location. This chapter aims to achieve that understanding, thus filling the corresponding literature gap. Below and throughout the chapter, the word "pleasantness" is understood as the physical pleasantness of the urban layout.

This chapter builds on the research presented in the last chapter, which estimated the impact of land use and geometric elements on the citizen's perception of the pleasantness of urban layouts using an Ordinal Regression Cumulative Link Mixed Model (CLMM). The methodology was created to benchmark and compare the pleasantness of different neighborhoods within a city or between different cities and as a decision tool for neighborhood regeneration or city expansion programs. This research applied the CLMM model to the center-south region of Belo Horizonte, Brazil, a typical global south city, and Coimbra, Portugal, a representative city of the global north. The results from the CLMM model were then correlated with different socioeconomic factors, namely the average income, population density, the existence of favelas (a Portuguese umbrella term for slum/ghetto), land value, and density of urban facilities, to respond to the research question. A comparison between the two cities was also made.

To the best of the authors' knowledge, this is the first time that socioeconomic factors were correlated with quantitative measures of the pleasantness of an urban physical environment. The case study provides important urban form and socioeconomic results that can help local authorities better plan their urban environments by improving pleasantness and, consequently, the overall quality of life.

8.2. Materials and methods

8.2.1. Study areas

8.2.1.1. The Global South case study: The center-south region of Belo Horizonte

Belo Horizonte was founded in 1897 as a symbol of modernity, mixing art nouveau and modern architecture. The project organized the area into urban, suburban, and rural zones. Aarão Reis and Francisco Bicalho sought inspiration in Washington, D.C., creating a city with modern lines, wide streets, and modern buildings in concrete. The city has nine regions, the center-south region being one. This region is shown in Figure 8.1 below and is administratively divided into 47 neighborhoods, of which 19 are favelas (blue in the figure). The initial 1897 project was limited by Contorno Avenue, the red line in the figure.

The project would meet the needs of 30,000 inhabitants and reach a maximum of 200,000 in the 21st century, a somewhat exaggerated view from the planning team [795]. However, in 2022, Belo Horizonte had over 2.5 million inhabitants distributed over 331 km^2, corresponding to a population density of 7167 inhabitants/km^2 [796].

Being such a large zone, it was impossible to survey the whole city. Therefore, the case study was limited to the original project and its surroundings, i.e., the center-south region. This region concentrates most of the historical, architectural, and cultural heritage in Belo Horizonte. Currently, the center-south region comprises 47 neighborhoods (10% of the total in Belo Horizonte), where 283,776 inhabitants (14% of the total) live in 107,565 households. Of these, 19 neighborhoods (40%) are considered favelas. The characteristics of this region are verticality, the concentration of economic activities, and a high standard of occupation. The center-south region has political, administrative, social, cultural, and economic functions with buildings and constructions of different architectural styles. Henceforth, this region is designated as ‘Belo Horizonte’ for brevity.

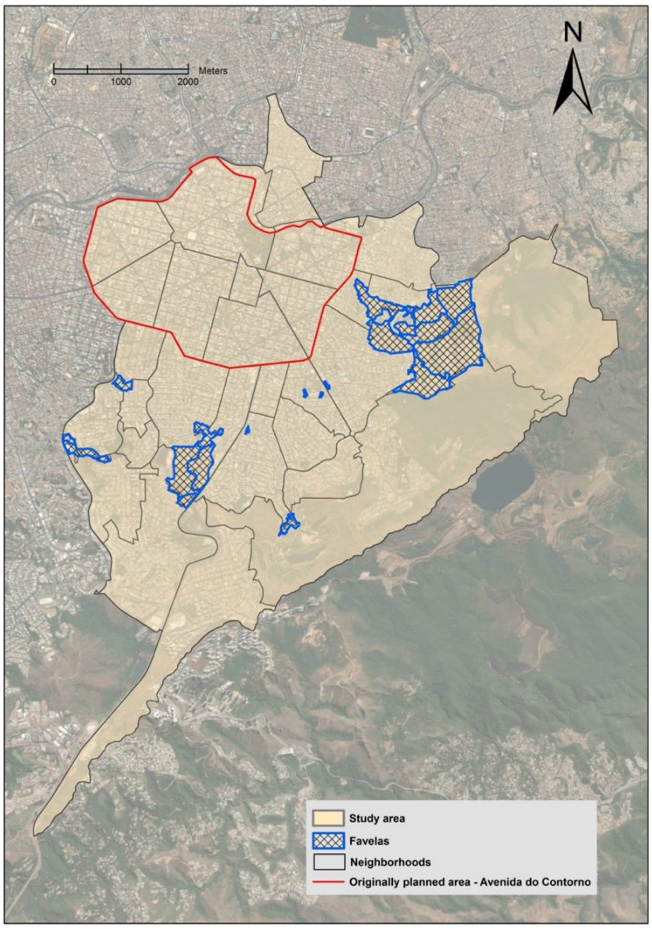
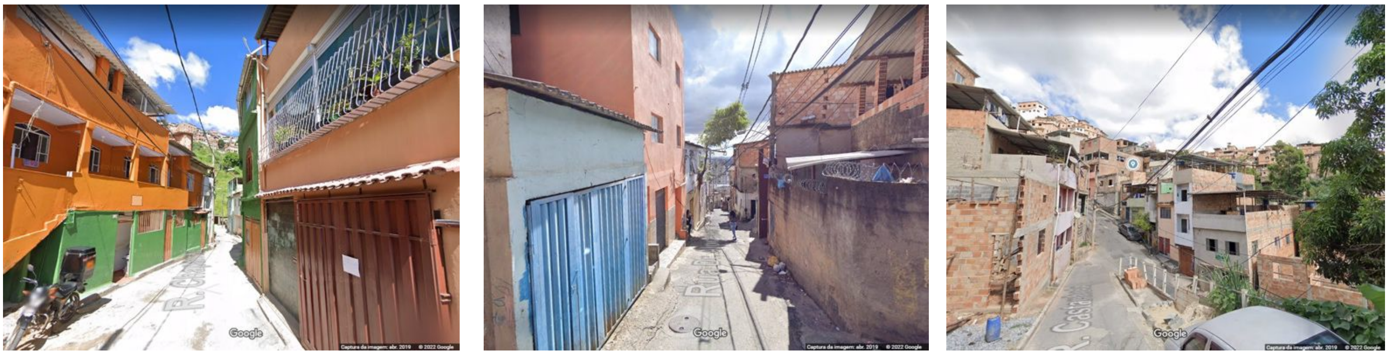


Figure 8.1. Belo Horizonte: study area, Contorno Avenue, and favela's location.

8.2.1.2. A note on favelas

As previously mentioned, cities in the global south face most of the challenges faced by cities in the global north and more. Additional challenges include the formation of large informal settlements, which in the Brazilian case take the form of favelas with uncontrollable urban growth, resulting in narrow streets, no building standards or government control on construction, dense occupation, low income, and a lack of basic sanitation and social services. The center-south of Belo Horizonte has 19 favelas, which occupy 8% of its area. Favelas are related to low average pleasantness due to their urbanistic characteristics, mostly narrow streets. The research team surveyed 193 residents from Belo Horizonte, asking which urbanistic elements would be, in their opinion, in the most need of an improvement in the favela-type urban environments of Figure 8.2 (this figure was shown to the participants, please see Figures II.8.1-3. for better resolution).

The results revealed that street width came out on top, with 34% responding this element, followed by building distance (22%), public green areas (18%), number of floors (14%), and private green area (12%). The original, worldwide CLMM calibration of Sousa et al. [19] puts a stronger dislike on the number of floors (see Section 8.2.4). However, as Belo Horizonte inhabitants are more exposed to favelas-type urban development, with narrower street widths and no building distance, these two elements presented themselves as main concerns, hinting at a local effect on the CLMM regression coefficients.



(**a**) Situation 1 (**b**) Situation 2 (**c**) Situation 3

Figure 8.2. (a-c) Situations considered in the survey with residents of Belo Horizonte.

The rush to build leads to lower pleasantness scores and consequently shifts the perception of the pleasantness of their inhabitants, as hinted at by the survey on the population. In fact, pleasantness is not a concern in urban developments like favelas. As indicated by the CLMM, a lower number of floors leads to a more pleasant environment (physically speaking). Still, while the number of floors is typically low in favelas, this is not due to municipal plans or clear orientations but rather to extreme poverty and a lack of living conditions and construction techniques that enable vertical construction. Given the densification and compactification of favelas, one can argue that, if given the ability and tools, favelas would quickly grow vertically to accommodate a growing impoverished population, making that environment even more unpleasant than it is now.

8.2.1.3. The Global North case study: Coimbra

Located in the center region of Portugal, Coimbra is a mid-sized city, currently home to 104,643 inhabitants [583]. The city grew mostly unrestrictedly due to a long history of occupation by different cultures, ideals, and needs, ultimately culminating in a situation of urban sprawl, with single-use areas and low-density buildings surrounding the center, in an assortment of urban landscapes typical of European city layouts. Figure 8.3 shows the study area of Coimbra, whose center (red in the figure) has the highest density of buildings and population.

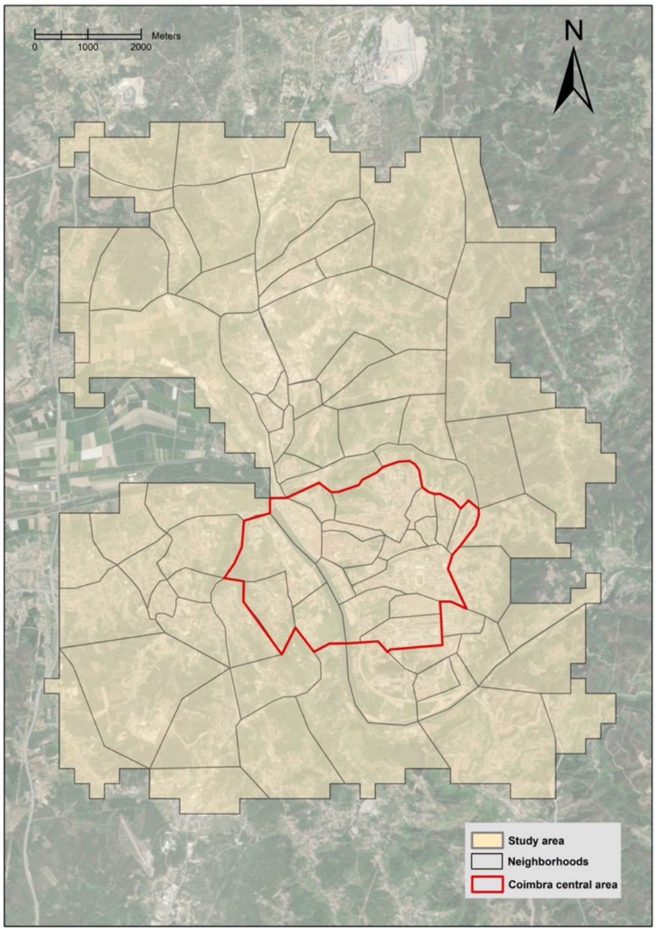


Figure 8.3. Coimbra: study area.

8.2.2. Parametrization

The CLMM model of Sousa et al. [19] can be used to obtain pleasantness perception scores on a 1–5 Likert scale. Applying the model requires obtaining field data concerning five geometric and land use elements for each study unit (usually mesh squares), namely green area percentage, street width, average number of floors, distance between buildings, and existence of green private areas. The field data measurements were obtained and converted to ordinal categorical values following Table 8.1., from which the statistical model could be run.

Table 8.1. Geometric and land use elements evaluated.

Variable	Definition	Measurement unit	Scale	Level
Green area	Publicly available green area in the study neighborhood	Percentage (%)	0 – 5 6 – 25 26 – 60 > 61	None Small Medium High
Street width	Average street width, including cycle lanes, parking space and sidewalks	Meters (m)	0 – 8 9 – 18 > 19	Narrow Wide Very wide
Nr. of floors	Average floor number of all buildings in the study neighborhood	Integer	1 – 2 3 – 5 6 – 11 12 – 37 > 38	House Short Medium Tall Skyscraper
Building distance	Average buildings side setbacks	Meters (m)	0 1 – 14 > 15	Compact Spaced Sprawled
Green private area	Average private green area	Square meters (m^2)	0 – 10 > 11	Not relevant Backyard

Concerning socioeconomic variables, Table 8.2. shows the five considered: average income, population density, favela (slum) presence, land value, and urban facility density. The absence of income data for Coimbra is related to privacy issues of census data, which came into effect following legislation in 2018 [797]. Likewise, there is no neighborhood in Coimbra with the same characteristics of a favela. Finally, land value data for favelas is not available due to nonexistence of official transactions; thus, the values are not computed by municipalities and are not available in public databases. Land value refers to the price per m^2 of parcel area.

Table 8.2. Socioeconomic variables analyzed.

Socioeconomic Variables	Units	Observations	Source
Average monthly income	BRL (R$)	Belo Horizonte only	Census [796]
Population density	Residents per km²		Census [583,796]
Favela (slum) presence	Binary: 1/0-yes/no	Belo Horizonte only	Census [796]
Land value	Belo Horizonte: BRL * per m² Coimbra: EUR ** per m²	No data for favelas	Belo Horizonte [798] Coimbra: previous projects
Urban facilities density	Facilities per km²		Previous projects [584]

* BRL 1 = USD 0.19; ** EUR 1 = USD 1.06 (27/Feb/2023).

8.2.3. Study design

Belo Horizonte and Coimbra were selected as representatives of the global south and global north, respectively. Their study areas were divided into study units, for which pleasantness scores were obtained. This was executed by dividing the study area onto a square mesh of 400 m diagonals (282 × 282 m sides), the study unit (index: i), collecting the geometric and land use information for each square via Google Earth imagery, transforming it according to Table 8.1, and calculating scores using the CLMM model. Averaging of mesh scores per neighborhood (see Figures 8.1 and 8.3) was then carried out, as prescribed by the methodology. Concerning the socioeconomic variables, these were obtained from the sources indicated in Table 8.2.

8.2.4. Statistical analysis

The CLMM model has logit link function, unstructured thresholds, and includes a mixed effect related to rater bias. It is formally described by:

$$\operatorname{logit}[P(Y_i \leq j)] = \theta_j - \sum_k \beta_k X_{ki} - u_i, \qquad \operatorname{logit} p = \ln\left(\frac{p}{1-p}\right), \qquad i = 1, \dots, N, \qquad j = 1, \dots, J-1, \qquad k = 1, \dots, K \tag{8.1}$$

where:
i, j, k: indices for, respectively, the study unit, ordinal pleasantness ranks ($J = 5$), and explanatory variables ($K = 5$).
$P(Y_i \leq j)$: cumulative probability of the i-th rating falling in the j-th rank of Y.
θ_j: threshold coefficients for Y.
β_k: regression coefficients.
X_{ki}: value of k in study unit i.
u_i: random effect of the judge rating study unit i, $u \sim N(0, \sigma)$.

Table 8.3. shows the regression coefficients obtained from the worldwide survey for a base scenario of high green area, narrow streets, a house-like number of floors, compact building setbacks, and the existence of a backyard. The regression coefficients show that people tend to prefer urban environments with abundant green areas, wide streets, house-like buildings, short building distance, and dwellings with private green areas. For more details on the model and how it was designed and calibrated, see the previous chapter.

Table 8.3. CLMM regression coefficients and threshold coefficients.

Element	**Level**	**Coefficient**
Green area	medium	−0.3790
Green area	small	−0.9644
Green area	none	−0.9157
Street width	wide	0.1737
Street width	very wide	0.8216
Number of floors	short	−0.7367
Number of floors	medium	−0.8435
Number of floors	tall	−0.9499
Number of floors	skyscraper	−1.3469
Building distance	spaced	−0.2226
Building distance	sprawled	−0.2695
Green private area	none	−0.6741
Threshold coefficient	1|2	−3.0603
Threshold coefficient	2|3	−1.6770
Threshold coefficient	3|4	−0.3823
Threshold coefficient	4|5	1.1441

The pleasantness score of a new study unit i is estimated by $\bar{r}_i = \sum_{j=1}^{5}(p_{ij} \cdot j)$, with p_{ij} the probability of i being perceived as belonging to category j, considering a judgement bias of zero (the p_{ij} can be obtained from Equation (1) after β_k and θ_j are known). Note that $\bar{r}_i$ can be interpreted as the expectation value of the rank of i, a quantity that has a higher resolution than other pleasantness estimates such as the most likely score (i.e., the j for which p_{ij} is the highest). The transformation of ordinal ratings to numeric ranks assumes equally spaced intervals between those ratings, an acceptable practice unless the real spacing is very non-linear [799–802].

After obtaining pleasantness scores for the study units, average values for each neighborhood were derived, as socioeconomic variables were unavailable at the study unit scale. Finally, Spearman correlations were derived to find the connection between neighborhood pleasantness scores and socioeconomic variables. Correlations enable one to ascertain the degree of association between the variables, thus providing quantitative evidence on how the two relate. Spearman correlations were chosen over Pearson ones because the data are not normally distributed. A principal component analysis of the socioeconomic variables was also carried out, and correlations of pleasantness scores with the two main components were derived. Note that a regression analysis does not make sense here because (physical) pleasantness is built off geometric and land use elements, not socioeconomic variables. Hence, despite the attractiveness of such an analysis, applying it here would be inconsistent. Correlations, on the other hand, are acceptable because they do not imply causation. Model and statistical calculations were carried out using the R software and its packages ordinal for the CLMM and FactoMineR for the PCA. Figure 8.4 below shows a workflow of the methodology, including the data used in each step and the output achieved.

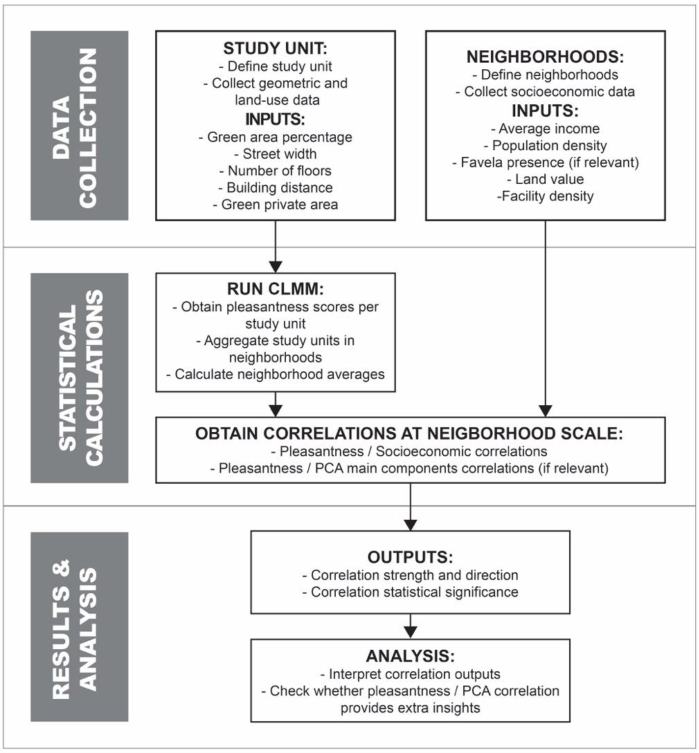


Figure 8.4. Methodology workflow.

8.3. Results

8.3.1. Pleasantness scores and socioeconomic variables for Belo Horizonte

Figure 8.5 maps the pleasantness scores in the center-south region of Belo Horizonte, and Table 8.4. provides descriptive statistics per neighborhood.

Table 8.4. Descriptive statistics of the pleasantness scores of Belo Horizonte.

Pleasantness Score (1–5)	Belo Horizonte Center-South
Count	47 neighborhoods (364 mesh squares)
Minimum	2.46
Average	2.71
Average per inhabitant	2.70 *
Maximum	3.31
Standard deviation	0.18

* Weighted by neighborhood population.

The average pleasantness was just below the mean value of 3 out of 5, both per neighborhood and weighted by population, indicating moderate dissatisfaction with the current urban layout. The 47 neighborhood pleasantness values were used to calculate the correlations with socioeconomic variables.

Since the original project of Belo Horizonte was an urban structure like a Garden City, many green areas are a natural feature of the region, which contribute positively to the pleasantness of the studied area. Another characteristic that contributes positively to the pleasantness is related to the subdivisions that were destined for middle and upper middle classes during the planning phase. Since most of the new residents came from the rural interior of Minas Gerais State, they valued private and open spaces. Accordingly, the center-south region was built with many large houses, with enough distance from the neighbors and the public road for gardens and balconies. Additionally, since the city was planned to be modern, the design of the street prioritized the symbol of development at that time: the automobile, leading to wide streets in the original part, inside Contorno Avenue. However, beyond the boundaries of Contorno Avenue, the streets are narrow and oppose the primary design of the city. In addition to the width of the streets, another aspect that negatively contributes to pleasantness is the height of the buildings, many of these with more than 10 floors in the center-south region.

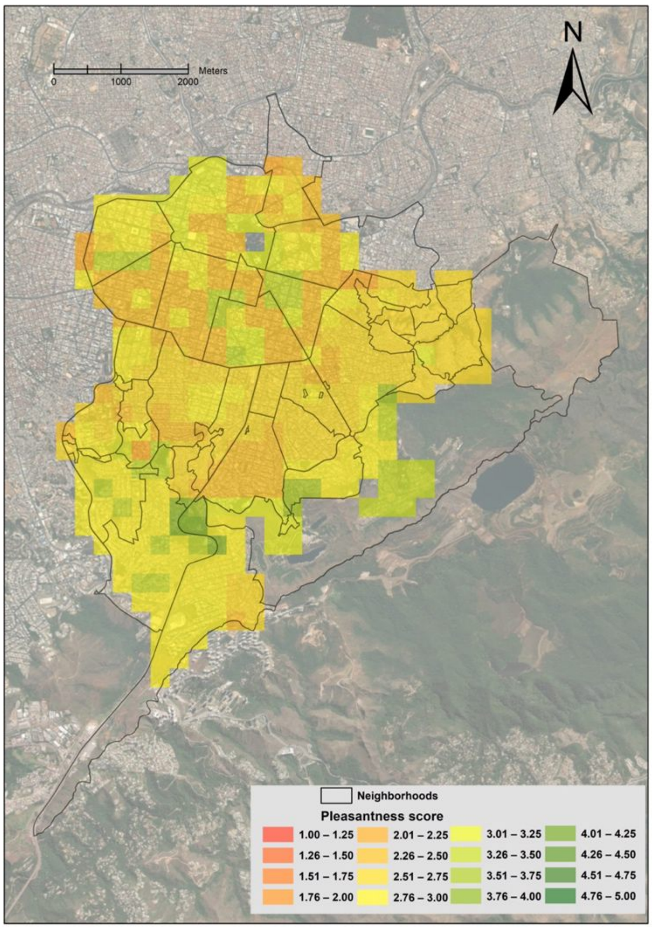


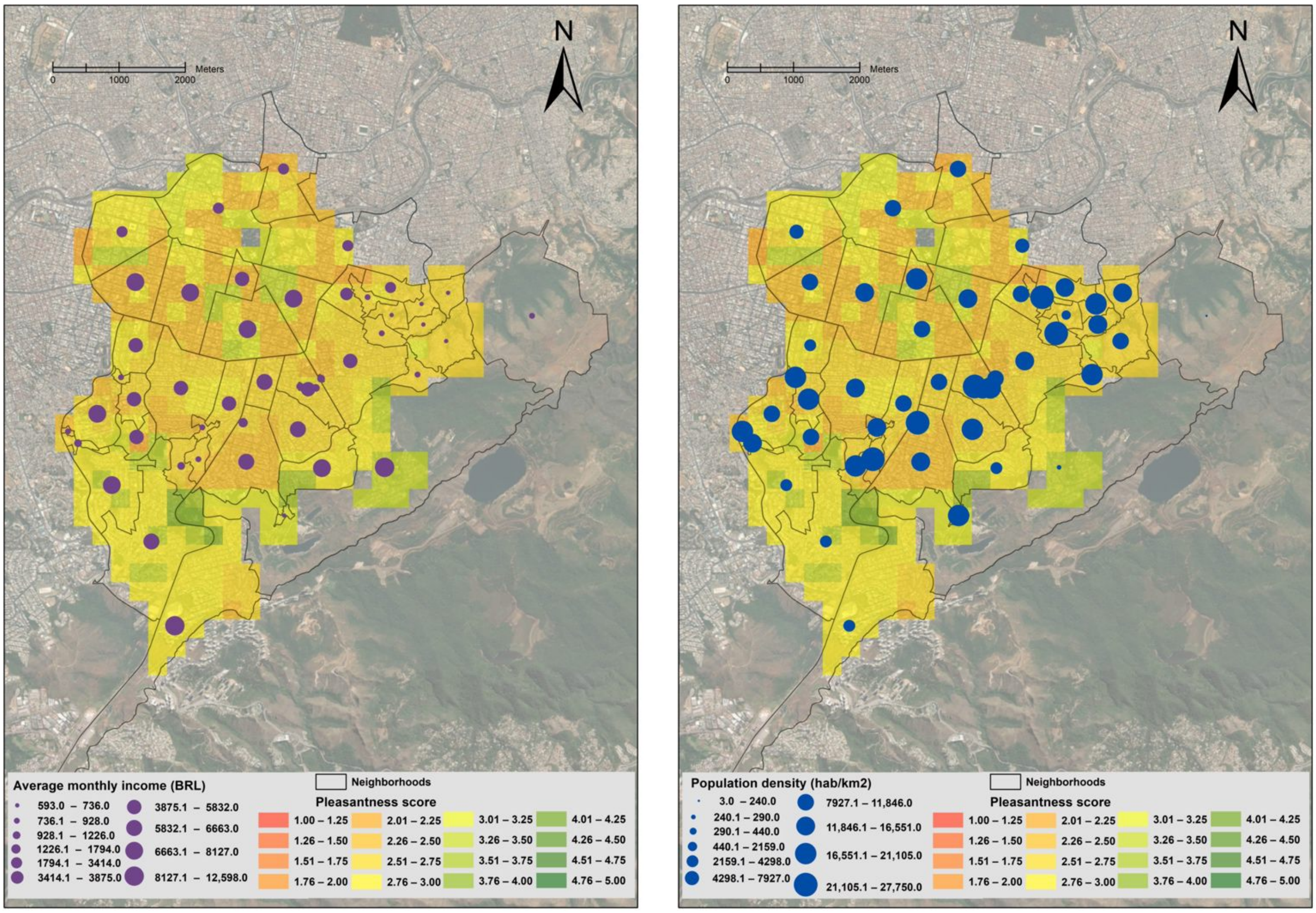
Figure 8.5. Pleasantness scores of Belo Horizonte.

Table 8.5. shows descriptive statistics for socioeconomic variables in Belo Horizonte, per neighborhood, and Figures 8.6 and 8.7 the geographic distribution of these variables, except for the favelas, which appear in Figure 8.1.

Table 8.5. Descriptive statistics for socioeconomic variables of Belo Horizonte.

Socioeconomic Variable	Average Monthly Income	Population Density	Favela	Land Value *	Facility Density
Minimum	593.5	3.4	0	2421	0.3
Average	3940.2	12,798.1	0.404 (19/47)	4206	266.3
Maximum	12,598.3	27,750.0	1	8818	2433.7
Std. deviation	3096.8	7089.1	N/A	1312.5	364.4

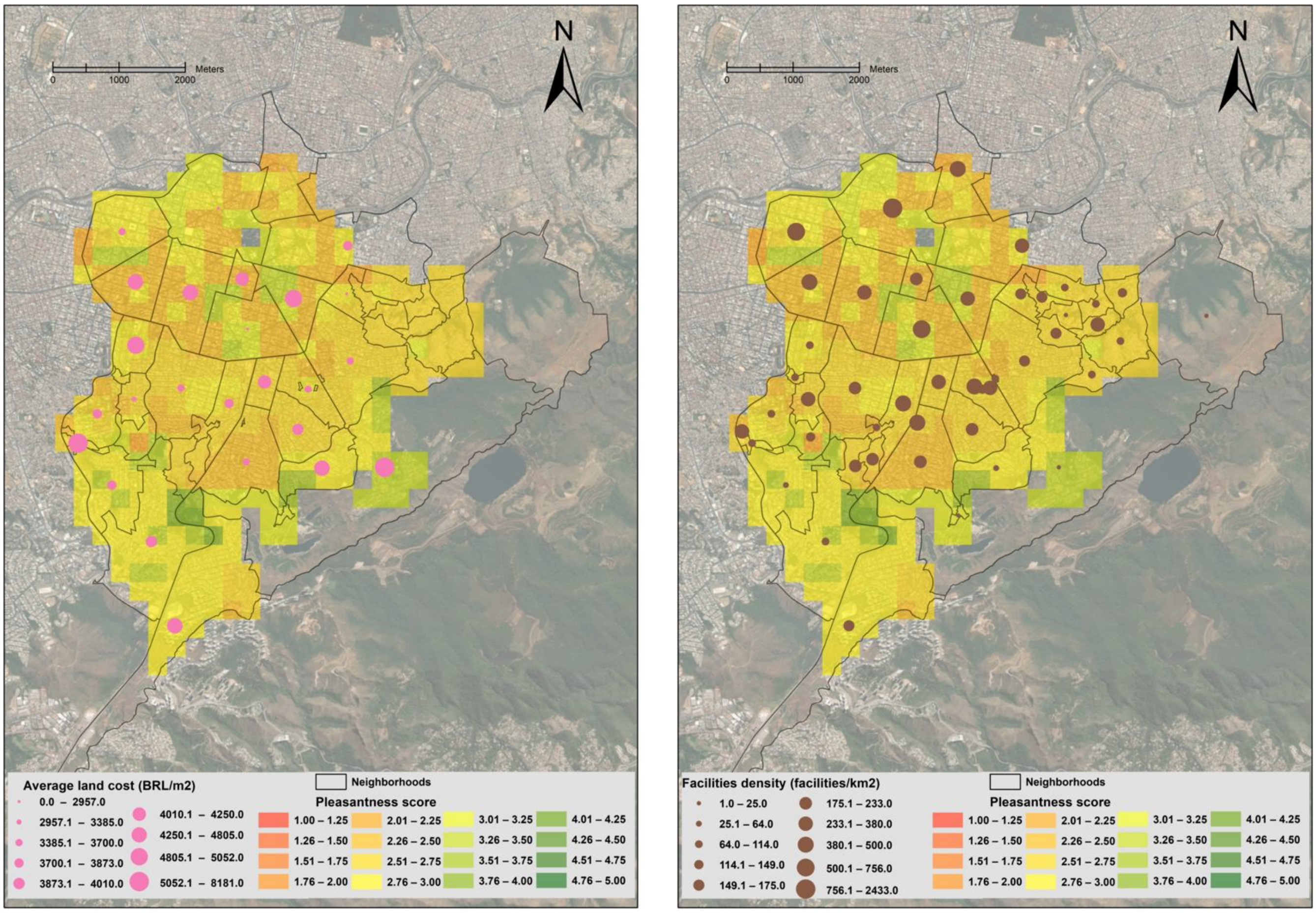
* BRL/m², restricted to existing data (26 out of 47 neighborhoods).



(a) (b)

Figure 8.6. Socioeconomic variables: (a) average monthly income; (b) population density.

Of the 20 neighborhoods with an income lower than the average, 19 are favelas. Favelas also tend to concentrate people: all neighborhoods (seven in total) with more than 20,000 inhabitants/km^2 were favelas. The average density for favelas was 16,852 inhabitants/km^2, while for other neighborhoods it was 9304 inhabitants/km^2. Baleia, the southeasternmost neighborhood, was a big farm in the past with a botanic garden. Currently, 30% of this neighborhood is a green park, thus providing higher values of pleasantness for this zone. Concerning urban facilities, the center-south region includes the city's downtown area, which has a high concentration of facilities (2433.7/km^2), as shown in Figure 8.7. On the other hand, favelas had some of the lowest concentrations of commercial establishments.



(a) (b)

Figure 8.7. Socioeconomic variables: (a) land value; (b) facility density.

8.3.2. Correlations between variables: Belo Horizonte

Table 8.6. shows the Spearman correlation values between pleasantness scores and socioeconomic factors per neighborhood.

Table 8.6. Spearman correlations between pleasantness and socioeconomic variables: Belo Horizonte.

Pleasantness VS.	**Average Income**	**Population Density**	**Favela Presence**	**Land Value**	**Facility Density**
Correlation	25.6%	−33.4%	−25.4%	18.6%	−15.1%
p-value	0.083 *	0.022 **	0.085 *	0.361	0.312

* Significant at 10%; ** Significant at 5%.

Only three of the five socioeconomic variables were significantly correlated to pleasantness. Albeit significant correlations were only mild, they could be understood. First, higher-income citizens have more financial power to live where they desire, resulting in a higher likelihood of living in more pleasant environments. Second, higher population density is often achieved by taller buildings and narrower streets, leading to a negative correlation. Third, due to the above-mentioned urbanistic characteristics, favelas also have low pleasantness, leading to a negative correlation. Concerning land value, the positive correlation between pleasantness and land value may be justified by a higher demand for the most pleasant environments, but this effect was not strong enough to be statistically significant. Additionally, indeed, as will be seen, the trend was the opposite for Coimbra. The negative correlation of facility density is justified because the higher population density of compact and taller environments leads to increased demand for facilities, which the market ultimately provides. However, given the statistical non-significance of this correlation, this inference was not clear-cut.

By applying a principal component analysis to unit-scaled socioeconomic variables, it was possible to find combinations of these variables that correlate even better with pleasantness. In doing so, the variable 'favela presence' was excluded due to missing data. The correlations of the two principal components with pleasantness were, respectively, 41.7% (*p*-value = 0.035) and −58.8% (*p*-value = 0.022), which indeed represents an improvement. However, looking at the variable composition of the two principal components, they turned out to be 29/18/22/31% and 16/39/24/21% (by order of Table 8.6.), combinations that are not straightforward to interpret, making it unclear why the correlation improved. This is also why the principal components are not presented in Table 8.6.

8.3.3. Pleasantness scores and socioeconomic variables for Coimbra

To obtain the socioeconomic variables, the city was divided into neighborhoods of similar size to those of Belo Horizonte. Pleasantness scores for mesh squares were available from the chapter 7. Figure 8.8 shows the neighborhoods and pleasantness scores, and statistics per neighborhood are summarized in Table 8.7. The pleasantness scores were lower in central neighborhoods, primarily due to the presence of tall residential buildings, narrow streets, and the lack of green spaces. As one moves away from the center, urban density decreases, and scores improved. However, the outskirts have poor accessibility, few facilities, and a limited supply of public transportation [16]. Despite not being a big metropole and due to its history and urban development, Coimbra comprises several urban forms and designs that scored differently in terms of the perceived pleasantness and is a typical global north city.

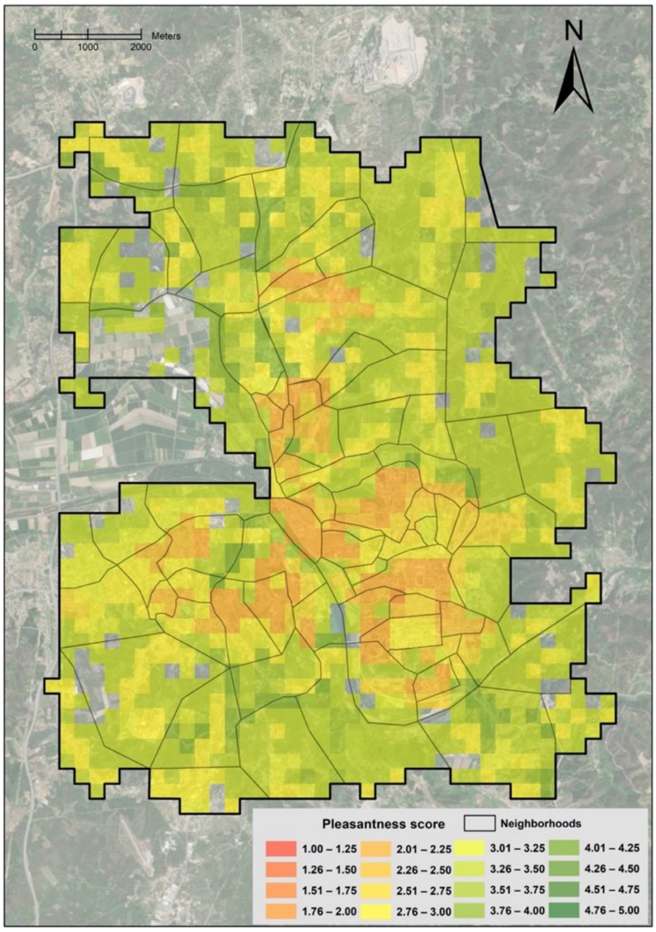


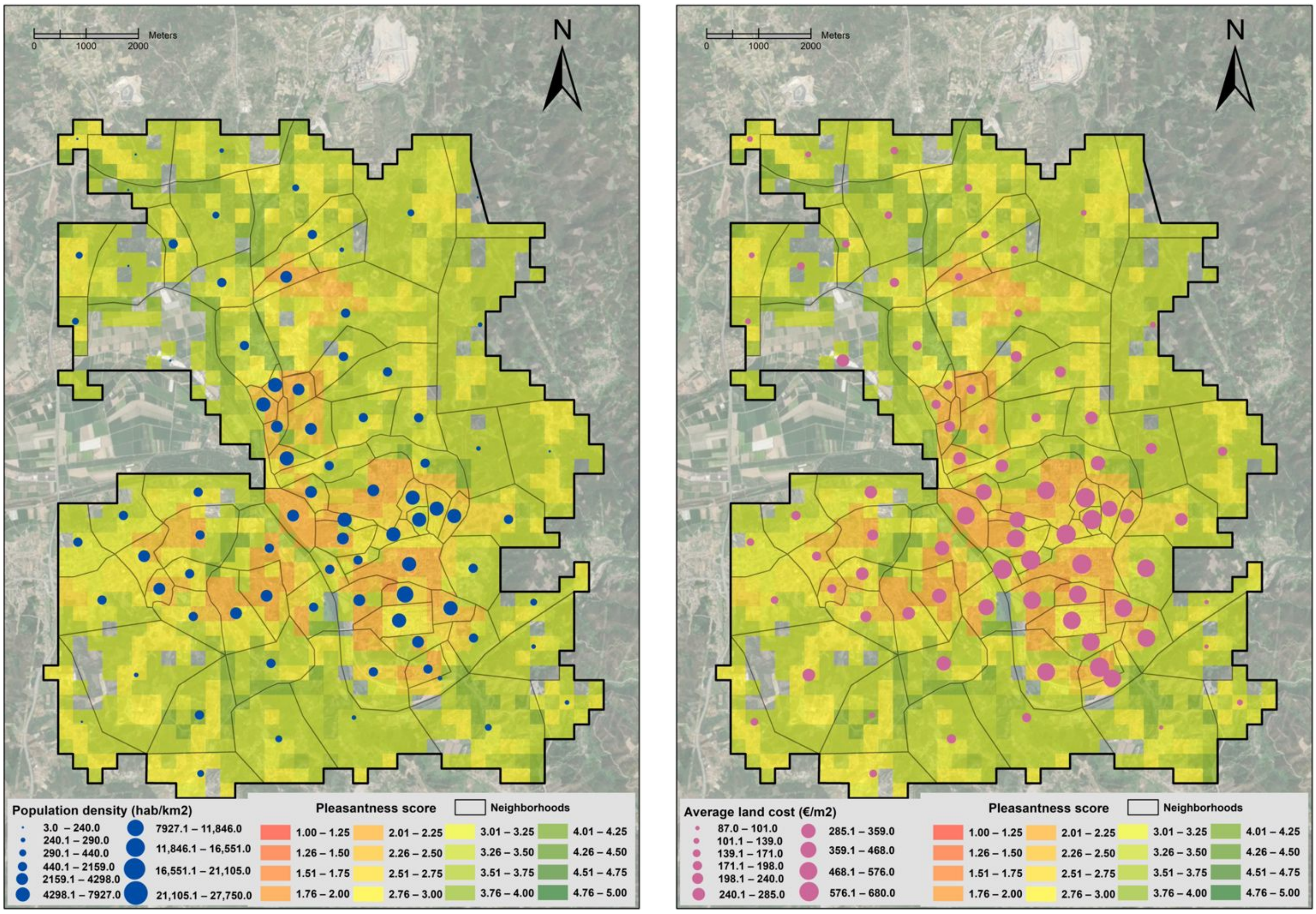
Figure 8.8. Pleasantness scores of Coimbra.

Table 8.7. Descriptive statistics of the pleasantness scores of Coimbra.

Pleasantness Score (1–5)	**Coimbra**
Count	82 neighborhoods (1224 mesh squares)
Minimum	2.32
Average	3.06
Average per inhabitant	3.07 *
Maximum	3.73
Standard deviation	0.33

* Weighted by neighborhood population.

Comparing with Table 8.4., it is seen that, in general, Coimbra had higher average scores than Belo Horizonte. Whether or not this conclusion can be generalized is discussed in the next section. Figures 8.9. and 8.10. display the pleasantness and socioeconomic variables for Coimbra and Table 8.8. shows the descriptive statistics for these variables. As mentioned, Coimbra does not have favelas, and average income data is not publicly available. Additionally, land value data were not available for 2 of the 82 neighborhoods of Coimbra.



(a) (b)

Figure 8.9. Socioeconomic variables: (a) population density; (b) land value.

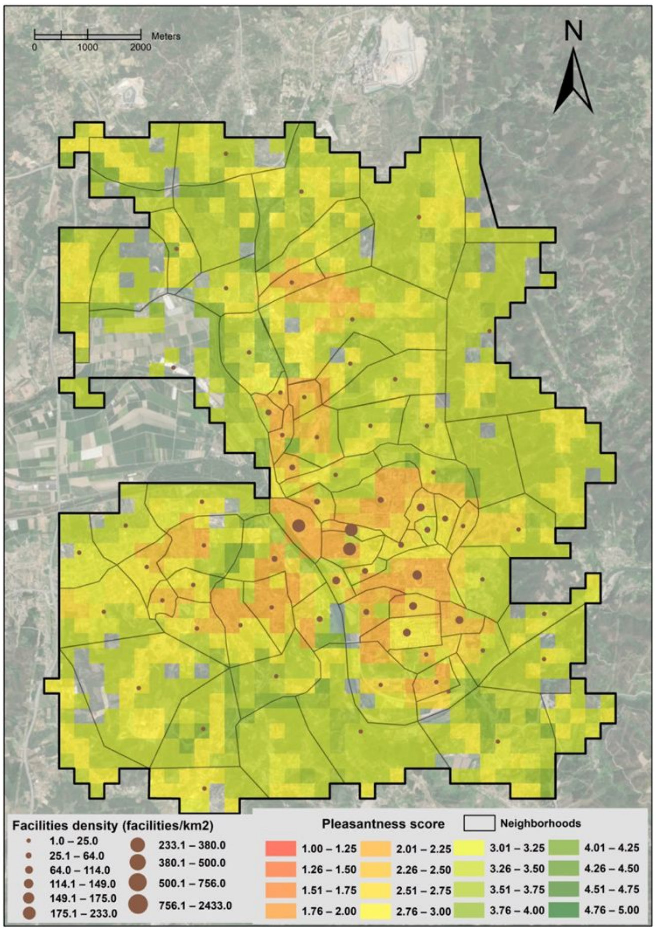


Figure 8.10. Socioeconomic variables: facility density.

Figure 8.9 shows a graphical pattern of high population density in lower pleasantness areas that is clearer than for Belo Horizonte, and Figure 9.10 shows that a pattern of "high density in low pleasantness areas" also emerged for facility density.

Table 8.8. Descriptive statistics for socioeconomic variables of Coimbra.

Socioeconomic Variable	Population Density	Land Value *	Facility Density
Minimum	21.9	87.63	0.0
Average	1893.9	298.25	23.5
Maximum	10,162.6	680.87	225.9
Std. deviation	2058.0	173.13	45.1

* EUR/m², restricted to existing data (80/82 neighborhoods).

Coimbra has a lower population density than Belo Horizonte, but more relative dispersion due to urban sprawl (coefficients of variation [cv] 55% for Belo Horizonte; 109% for Coimbra). A similar phenomenon was observed for facility density (cv: 137% vs. 192%, respectively), confirming the effect of sprawl.

8.3.4. Correlation between variables: Coimbra

Variable correlations are given in Table 8.9. For this city, the correlations were not as mild as they were for Belo Horizonte; rather, they were quite conclusive and showed a clear pattern: the denser the environment, the less pleasant it is, confirming the suspicion in Belo Horizonte of a negative correlation between facility density and pleasantness. These findings are explored further in the next section.

Table 8.9. Spearman correlations between pleasantness and socioeconomic variables: Coimbra.

Pleasantness VS.	Population Density	Land Value	Facility Density
Correlation	−86.9%	−60,9%	−83.6%
p-value	0.00 *	0.00 *	0.00 *

* Significant at 1%.

A principal component analysis was not carried out for Coimbra, as the correlations were clear and only three variables existed.

8.4. Discussion: Comparison between the global south and the global north

Tables 8.10. and 8.11. summarize the results of the previous section and add statistical testing. As noted above, in general, the pleasantness scores of Coimbra were higher than those of Belo Horizonte.

Table 8.10. Statistical comparison of the pleasantness scores of Belo Horizonte and Coimbra.

Pleasantness Score (1–5)	Per Neighborhood	
	Average	Average per inhabitant
Belo Horizonte (BH)	2.71	2.70
Coimbra (Cbr)	3.06	3.07
Mann–Whitney test *p*-value (two-way)	0.00 *	N/A

* Significant at 1%.

The two-way Mann–Whitney test in Table 8.10. confirmed that Coimbra was the more pleasant city. Based on this, it would be tempting to claim that global north cities have better pleasantness scores than global south ones. However, that would be too bold of a claim since only two cities were compared, and only its center-south region was considered in one of them. No matter how representative those two cities may be, more comparisons between the global north and global south cities would be needed before any conclusive claims could be made. Such caution is not just common sense; the research in *Residential Location Preferences: New Perspective* [803] also warns against undue generalizations. Table 8.11. summarizes the correlations found between pleasantness scores and socioeconomic variables, which shed light on the characteristics of the inhabitants and their distribution pattern throughout the city.

Table 8.11. Recap of Spearman correlations between pleasantness and socioeconomic variables of Belo Horizonte and Coimbra.

Pleasantness VS.	Average Income	Population Density	Favela Presence	Land Value	Facility Density
Belo Horizonte	25.6% *	−33.4% **	−25.4% *	18.6%	−15.1%
Coimbra	N/A	−86.9% ***	N/A	−60.9% ***	−83.6% ***

* Significant at 10%; ** significant at 5%; *** significant at 1%.

The mild correlation between income and pleasantness, which was only possible to validate in Belo Horizonte, revealed that, given the choice, people tended to live in more pleasant urban environments. The anti-correlation between population density and pleasantness, disclosed in Belo Horizonte and confirmed in Coimbra, showed that densification ultimately leads to compact environments that favor tall constructions, narrow roads, and few green spaces and are thus, less pleasant. However, given that such environments still contain many people living in them, it is inevitable to conclude that the amenities brought by density (e.g., accessibility, increased social interaction) compensate for the lack of pleasantness. Alternatively, one may also reason that poorer people are pushed towards dense environments, which is corroborated by the correlation between income and population density in Belo Horizonte, which was −45.5% (p-value = 0.001). Facility density is a by-product of population density, as correlations between these two variables confirm: +30/82% for Belo Horizonte/Coimbra (p-values = 0.04/0.00); thus, its negative correlation with pleasantness was predicted, albeit for Belo Horizonte this conclusion was not as firm.

Finally, land value correlation with pleasantness had mixed tendencies. In Belo Horizonte, the two did not seem to correlate significantly, while in Coimbra a considerable and significant anti-correlation was found. A possible explanation for this might be as follows: pleasant environments attract wealthier people, potentially increasing the land value of those locations (positive correlation). Indeed, the presence of green spaces, a positive pleasantness proxy, increases property value [804,805]. However, denser, less pleasant neighborhoods also attract people due to better accessibility and social opportunities, increasing the land value of those locations as well (negative correlation). When both effects are added, they may either cancel out, and the correlation ends up losing any meaningful trend, as seems to be the case in Belo Horizonte, or they may be stronger in one direction, as in Coimbra, where accessibility and socialization seemingly carried more weight than the physical environment. More research is needed to determine whether this is a regional north/south issue, an overall tendency, or just an artifact of the data. As with pleasantness scores, the north/south comparison of pleasantness/socioeconomic correlations is to be taken with a grain of salt, and in this case, mostly because this chapter only explored a single case of each kind, which is a limitation. More cities of the two kinds need to be examined before assertive conclusions can be drawn.

8.5. Conclusions

This chapter presented a correlational study between the perceived physical pleasantness of the built environment and socioeconomic variables in two cities, which served as representatives of the global north (Coimbra, Portugal) and global south (Belo Horizonte, Brazil). The study aimed to unravel whether people actually live where the urban environment is pleasant, in the physical sense, and how pleasantness and socioeconomic variables relate and contribute to one's choice of living location. To the best of the authors' knowledge, this research is one of the first attempts to try and achieve that objective with quantitative models. In addition, the differences between the global north and global south representatives were also investigated.

The results showed a mild positive correlation between pleasantness and income, although this was only possible to ascertain for Belo Horizonte (data protection issues prevented the same calculation for Coimbra). A negative correlation between pleasantness and density (of population and urban facilities) was also revealed, which was due to the more compact, and thus less pleasant, environments that inevitably entail higher concentrations of people and buildings. This result shows that factors other than physical pleasantness, e.g., accessibility or social interaction, come to play when selecting a place to live, confirming similar findings in the literature [715,791–794]. The correlations of land value with pleasantness were found to be non-significant in Belo Horizonte and negative in Coimbra, suggesting contrary effects of high income (positive) and urban density (negative) that are likely of local nature. Together with the result that pleasantness was statistically higher in Coimbra, this was the only difference between the global north and global south representatives.

However, if one wishes to volunteer a tentative answer to the research question "Do we live where it is pleasant?", with pleasantness understood as an enjoyable physical environment, that answer seems to be "Not really, unless you're wealthy". While this is not unexpected, the present research reinforces the prejudice that wealthier people have more options. Those people can afford more expensive houses and have private transport, thus fewer accessibility problems. Therefore, they can live where they wish, in line with the findings by refs. [806,807]. Other people may end up living in places other than their desired locations, which Hasanzadeh et al. [808] also concluded. With respect to urban planning, the CLMM model can help design more pleasant neighborhoods should a city expand beyond its current limits. However, the correlation of pleasantness with socioeconomic variables shows that the former, despite being a goal per se, may not necessarily attract flurries of residents, as they may prefer the advantages of living in denser urban environments. It may, however, attract wealthier people.

The main limitation of this study is that only two cities were examined. Generalization of the results would require more examples. Other limitations include scalability difficulties, e.g., obtaining geometric and land use elements for large urban areas or land value data for regions in the outskirts, and the fact that more accurate measurements of physical pleasantness may require extra elements (e.g., the conservation status of buildings). The rank transform and averaging of pleasantness scores may also have introduced some imprecisions, but the authors believe this is a minor trade-off for the added resolution of the results.

8.5.1. Future work

For future work, it would be interesting to identify other factors that may be related, directly or indirectly, to pleasantness, such as the state of conservation of buildings and public roads, public cleanliness, and safety concerns, among other subjective factors. Likewise, the introduction of more socioeconomic variables can be useful. The relationship between land value and pleasantness is also worth exploring in more detail and with larger datasets, so that a trend can be identified, or lack thereof verified. Finally, the role of neighborhood size is also important to consider, as neighborhood aggregations could mask the effects of population density. Urban pleasantness is an important element of city form and planning that can directly impact the urban quality of life and sustainability, making it indispensable to consider in today’s urban environment development.

9. BENCHMARKING REAL AND IDEAL CITIES – A MULTICRITERIA ANALYSIS OF CITY PERFORMANCE BASED ON URBAN FORM

"In the 21st century, it is too late for innocence, raw nature is gone. If we can manipulate genetics, then it must be possible to artificially create special strains of urbanism that work better." – Andrés Duany [809]

The debate on the ideal urban layout, or form has long been an active topic of research. This chapter adds to this debate by presenting a multicriteria analysis of city performance, based on quantitative indicators obtainable from geographic information systems calculations, which focus on sustainability and physical pleasantness issues. Indicator values were derived for a real city, its Infill version, and five redrafts as ideal city concepts existing in the literature. The city layouts were then compared with a multicriteria method, results showing a preference for the more compact urban layouts due to the multiple advantages of having shorter distances between supply and demand points. The methodology provides quantitative insights on city performance and efficiency and can be used to compare options for city expansions or major urban regeneration projects.

9.1. Introduction

Cities play an immensurable role in society. For centuries, urban conglomerations have been the prime places for evolution and the development of mankind [428]. The way cities are planned and built directly impacts the quality of life of billions of people. Sustainable and resilient planning towards higher quality of life standards has never been more important, for example, as the COVID-19 pandemic stressed [15]. However, planning cities is not an easy task, as it involves several areas of knowledge, a holistic understanding of the different city dimensions, cooperation among different decision-makers and city dwellers, and comprehensive understanding of local context and its shortcomings. The job of spatial planning researchers is to provide the necessary knowledge and tools so that, in practice and on the field, decisions are made based on sound methodologies and with the best possible outcomes in view.

Understanding urban development and how it should be planned is a research avenue which has been constantly evolving, thanks to new knowledge, socioeconomic and technological advances, and considering new challenges and goals. Urban development and spatial planning are related, among other, by urban morphology, i.e., 'the study of urban forms, and of the agents and processes responsible for their transformation' [810], which emphasizes the spatial layout, or form of the city. A city urban form encompasses its size, shape, land uses, distribution of facilities, and transport networks, and can have a close relationship with the city function, i.e., the actual use of urban space for human activities [811–814]. Studying the form and function of cities is thus pivotal towards understanding urban problems, evaluating planning strategies and supporting urban policies [813]. The advances in Geographic Information Systems (GIS) improved our capability to map large-scale urban areas and made it possible to add quantitative arguments to urban planning, based on the city form and function [812].

This chapter intends to contribute to the debate by presenting a multicriteria analysis of city performance, based on urban form and making use of GIS capabilities. It aims to study the impact of urban form on the efficiency, sustainability, and pleasantness of the physical environment using quantitative benchmarking indicators, and compare different layouts for the same city. Accessibility, active transport modal share, transport energy consumption, road network directness, mix land use, and neighborhood perceived pleasantness make up the six indicators that are evaluated in GIS, derived solely from geographic characteristics of the spatial layout of urban areas.

Urban conglomerations are constantly facing new challenges, aiming to improve the inhabitants' quality of life and create a more resilient and sustainable urban future. This has led to the development of different city concepts that, based on urban form, planning strategies and policies, aimed to deal with the challenges that our cities have faced, still face, and will continue to face over the next decades. The proposed multicriteria methodology (MCM) allows benchmarking those concepts, i.e., to make a comparative study between real and ideal cities. The methodology was put to test by analyzing and comparing seven urban layouts for a case study, the city of Coimbra, Portugal, namely the real city of Coimbra; its redraft as five city concepts, the Garden City, *Ville Radieuse*, Compact City, Transit-Oriented Development, and Transect Planning; and one urban development approach, the Infill [815]. This research ultimately aims to present an understanding of the pros and cons of planned urbanism and provide a clear path to transpose some solutions to practical contexts.

The presented MCM is also directed at policymakers, as its use only requires data that is usually readily available and provides quantitative results that can be used to analyze and compare the different urban planning solutions. Its results are easily interpreted and can be presented to city dwellers to increase collaborative planning and all stakeholders participation towards a better quality of life for everyone.

9.1.1. Literature review

Urban studies have long been an important research topic that aims to provide the necessary tools and knowledge to improve the inhabitants' quality of life [427,428,816]. Modelling cities and studying their spatial layout has been a long-term item of that topic, and its relevance has risen due to the increase of migration flows towards cities [22,425,817]. Nevertheless, most research so far focused on a single urban layout or benchmarking indicator, aiming to find a direct resolution or model to the problem at hand [235,431,432]. When quantitative, these approaches usually lead to specific solutions, where the impact of a particular idea or city concept is limited, not implying major changes in the city structure [229,433,434]. The research involved in creating and developing those concepts usually carries on with a deep analysis of the concept itself, by analyzing specific problems, policies, future sustainability and value, applicability to worldwide cities [438,475,818–821]. Because of this focus, it is not yet clear how the different city concepts and indicators can combine to provide the knowledge and possible guidelines needed to improve the sustainability and resiliency of real cities [429]. It is important to ascertain the different concepts, their relevancy and role on the quest for sustainability in urban planning and evaluates the degree of sustainability incorporation in the different concepts [429].

Far-reaching and multidisciplinary comparative analyses between different city concepts are uncommon and were mostly done in a qualitative way. Past debates on the ideal spatial layout of cities include Lynch (1960), Fishman (1982) and Frey (1999), the latter standing out as one of the most important pieces of research made on the study of urban and spatial planning, whose conclusions are still valid to this day. Similarly, to the present research, Frey analyzed and compared six different city concepts based on several (qualitative) indicators. However, this qualitative nature and the need for various assumptions lead to many inaccuracies on the results, as Frey himself recognizes. The present research aims to overcome this problem and contribute to the literature by proposing quantitative indicators and a MCM to compare city concepts. As far as the authors are aware, other quantitative comparisons between different city concepts based on their urban form and resorting to objective indicators do not exist in the literature. This research fills that gap by proposing both a methodology and by carrying out an extensive benchmarking study on the best-known city concepts.

9.2. Methodology

The methodology to benchmark city concepts based on their urban form revolves around redistributing a city's geographic elements according to the alternative layouts under study [16]. The criteria by which each city concept is evaluated consists of indicator values that depend on the layouts and are calculated in a GIS environment. The set of alternatives and criteria values form the so-called decision matrix in multicriteria analysis. The outcome of this analysis may come in several guises, depending on which multicriteria method is applied. This chapter uses the TOPSIS method, a ranking method whose output is a quantitative figure that may be termed the "Combined Spatial City Index" (CSCI) for each layout.

The geographic elements of a city consist of three datasets: #1 origins (O), residential centroids representing trip demand; #2 destinations (D), urban facilities and jobs, representing the supply of interaction opportunities; and #3 the road network, which connects origins to destinations.

This approach is now detailed and further demonstrated with a case study for the city of Coimbra, Portugal, in which its actual layout was compared to six city concepts, according to the benchmarking methodology. When redrafting Coimbra, the number of inhabitants and jobs was kept equal to that of the real city. For urban facilities, similar, but smaller numbers than those real Coimbra were considered, as preserving the original numbers in the alternative layouts would just create supply redundancy. Nevertheless, the lowest distortion possible was sought-after.

The quantitative indicators, i.e., the criteria whose scores form the decision matrix, were selected due to their importance for city planning and their intrinsic correlation with the urban layout. Motivation and calculational details are presented below.

9.2.1. Accessibility

Accessibility is a wide-ranging concept that is being increasingly incorporated into city form [447,487,624]. Accessibility directly relates to the urban layout, transport planning, land use, socioeconomic factors, and environmental goals [449,460,486,625]. As a sustainable development strategy, accessibility by active modes emphasizes proximity and local daily living, as opposed to long distance and energy-intensive transportation [450,621,622]. The classic definition of accessibility, as the ease, or more widely, the cost of reaching destinations [451] was considered for this research. Cost-based views of accessibility have been used on spatial and transport planning [16,17,452–457,459,460,656]. The accessibility indicator selected for this research is akin to that used by [16–18,464,466]. It is given by:

$$A_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} d_{ij}^k}{\sum_k L_{kj}}, \tag{9.1}$$

where

i: 1, … , I number of origins;
j: 1, … , J number of facility types (includes jobs);
k: 1, … , K number of closest facilities (when it applies), and in this thesis, $K = 3$;
A_i: accessibility score of origin i;
d_{ij}^k: network distance from origin i to the k-th closest facility of type j (or job zone centroid).
w_j: weight of facility type j (destination attractiveness);
L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

This accessibility indicator can be interpreted as the average distance from origins to destinations, weighted by destination attractiveness and by choice factor. It can be further weighted by the number of inhabitants of the origin, h_i (representing demand) to yield the (doubly weighted) average distance per inhabitant to all destinations.

Some considerations with respect to destinations are due at this point. A total of 20 destination types were considered: 19 urban facilities, plus jobs. Destination weights were assigned as according to their trip frequency. A 1-2-3 scale was used for urban facilities [16] and $w_j = 22, j$: jobs, in accordance to the commuting trip share for Coimbra of 37% [542].

The choice factor is used to model supply diversity, i.e., the fact that for some facility types, inhabitants might wish to be able to choose between two or more. Since by convenience the closest ones will be preferred, the inequality $L_{kj} > L_{k+1,j}$ follows naturally. In this research the set $L_{kj} = \{70,20,10\}$ was used. Note that choice factor does not apply to all facilities. For some, e.g., post-offices or primary healthcare, people usually choose the closest one.

Another issue, which concerns active travel modes, is as follows. The propensity to use an active mode depends on the distance to destination. For some destination types, e.g., bakeries or grocery stores, the permanence time at destination is short, and the person feels as if she effectively must travel twice the distance. Other facility types, e.g., cultural or entertainment sites, have long permanence time, allowing the person to rest at destination. This makes it more plausible that the traveller is only deterred to use an active by distance itself, not twice its value. Thus, for some facility types, the distance used to calculate active trip probability was twice the OD distance. These will be called "extended trips".

Finally, the jobs destination type requires a special treatment. Jobs require employees to go where their job is located, so the notion of "closest job" does not apply. Instead, a zone analysis was considered, as previously used in literature [469,676]. For each city layout, the study zone was divided according to neighbourhood similarities. Then, job locations and employee count in each zone were used to obtain the geometric average job location for that zone. Accessibility to jobs was then calculated using eq. (9.2) with

$$d_{ij}^{k} = \sum_{z} f_z d_{iz}\,, \qquad j\text{: jobs} \tag{9.2}$$

where

z: $1, \dots, Z$ number of job zones;
f_z: fraction of total jobs in zone z;
d_{iz}: distance from origin i to the average job location of zone z.

Table 9.1. summarizes the above considerations on destinations.

Table 9.1. Characterization of destination types.

Destination type	Weight	Choice type	Extended trip?
Post offices	1	Closest	Yes
Sports facilities	1	*k*-closest	Yes
Cultural organizations	1	*k*-closest	No
Higher education institutions	1	*k*-closest	No
Elderly care centers	1	*k*-closest	No
Churches	1	*k*-closest	No
High schools	2	*k*-closest	No
Shopping centers	2	*k*-closest	Yes
Entertainment sites	2	*k*-closest	No
Primary healthcare services	2	Closest	No
Pharmacies	2	Closest	Yes
Restaurants	2	*k*-closest	No
Parks and green areas	2	Closest	No
Kindergartens	3	Closest	Yes
Primary schools	3	Closest	Yes
Middle schools	3	Closest	No
Grocery stores	3	*k*-closest	Yes
Supermarkets	3	*k*-closest	Yes
Bakeries and pastry shops	3	*k*-closest	Yes
Jobs	22	Job zone analysis	No

9.2.2. Active transport modal share

Active transport, such as walking or cycling, has been widely promoted worldwide [630–632] as an affordable, equitable and inclusive means of transport that promotes energy efficiency and overall sustainable and resilient urban environments [456,635–640]. Strategies towards achieving higher active transport modal share are gaining traction worldwide and directly relate to planning policies and the urban form itself [40,456,643,645,646,648,649,822].

Estimation of active transport modal share followed the methodology of Monteiro et al. [17,18] and was determined by transforming trip distances onto active trip probabilities using log-logistic distributions. Albeit trip probability is inversely monotonous to distance, the relation is non-linear, which justifies studying the two variables separately.

Walking and cycling were considered as the active modes. However, rather than making separate analyses for both modes, the option was made to combine both modes onto one active trip probability indicator following the method of Monteiro et al. [17]. Its outcome is to provide a number, $p_{\mathrm{A}ij}^{k}$, which represents the probability of active travel, i.e., walking or cycling, from origin i to the k-th closest destination of type j. With this number, the modal split can be calculated, as follows:

$$M_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} p_{\mathrm{A}ij}^{k}}{\sum_k L_{kj}}, \tag{9.3}$$

where
M_i: active modal share of origin i;
$p_{\mathrm{A}ij}^{k}$: active trip probability from origin i to the k-th closest destination of type j, with
$p_{\mathrm{A}ij}^{k} = \sum_z f_z p_{\mathrm{A}iz}$ for j: jobs ($p_{\mathrm{A}iz}$: active trip probability from i to average job location of zone z).

9.2.3. Transport energy consumption

Trips not made by active modes require motorized transport, which in turn consumes energy and typically produces greenhouse gas (GHG) emissions. Since the fraction of non-active trips is represented by $1 - p_{\mathrm{A}ij}^{k}$, it suffices to estimate the energy consumption associated to this fraction. In Coimbra motorized trips resort almost totally to fossil fuels, with a modal split of 70% for private cars and 30% public transport [584]. Thus, the following expression was used to obtain transport energy consumption [17,18]:

$$E_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} \left(1 - p_{\mathrm{A}ij}^{k}\right)\left(f_{\mathrm{car}} F_{\mathrm{car}} + f_{\mathrm{pub}} F_{\mathrm{pub}}\right)\left(d_{ijk}^{\rightarrow} + d_{ijk}^{\leftarrow}\right)}{\sum_k L_{kj}}, \tag{9.4}$$

where
E_i: average fuel consumption of accessibility-related trips originating in i;
f_{car}: fraction of motorised trips made using the private car;
f_{pub}: fraction of motorised trips made using public transport;
F_{car}: private car average fuel economy (MJ/passenger.km);
F_{pub}: public transportation average fuel economy (MJ/passenger.km);
$d_{ijk}^{\rightarrow}, d_{ijk}^{\leftarrow}$: one-way distances from origin i, respectively, towards/away the k-th closest destination of type j.

The E_i is measured in MJ/passenger-trip (at the tank) and trips are always considered as two-way regardless of facility type. Motorized fuel consumption is assumed to be 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport [823].

Note that although transport energy consumption depends on the non-active fraction, this dependence is not linear, since it also depends on distance. Like active modal share, transport energy consumption is monotonous to accessibility in a non-linear way, which again justifies treating it separately.

9.2.4. Route directness

Although for most transport related analysis network distances are preferred to the straight-line, or Euclidean distances [824,825], the latter may be of use as a reference for network performance. Route directness [509], also termed detour index or circuity [598], is the ratio of the shortest distance between two points on a network to the Euclidean distance between these points. Directness is a permeability, or connectivity, indicator, i.e., a measure of the extent to which urban form facilitates (or restricts) the movement of travelers, and a proxy for mobility [509,826–828]. It has also been used to study active transport in the context of filtered permeability, i.e., different permeability for different modes [829–831].

To decouple accessibility from mobility, instead of the OD routes used in (1-2), the following procedure was used to evaluate route directness. A square mesh of neighborhood size (282 m ´ 282 m; diagonal of 400 m, a walkable distance) was created in GIS over the study area, together with its associated centroids. To remove squares outside the study area, those with a centroid more than 150 m away from the network were deleted (for Coimbra this threshold was lowered to 50 m to reduce computational complexity). Then network and Euclidean trip distances from each centroid to all other centroids were obtained and directness was calculated using:

$$D_{ij} = \frac{d_{ij}}{E_{ij}}, \qquad \forall_{ij} \in \text{set of mesh centroids} \tag{9.5}$$

where
d_{ij}: network distance between mesh centroids i and j.
E_{ij}: Euclidean distance between mesh centroids i and j.

Route directness improves as the ratios D_{ij} get closer to 1, since network distances get closer to the shortest possible distance. The average of D_{ij} can then be calculated and used as global directness indicator for each city layout.

As a proxy for mobility, directness is limited, in that it does not consider aspects such as traffic congestion or intersection turn times. However, obtaining a more representative global mobility indicator would require running traffic simulations, which are out of the scope of this research.

9.2.5. Pleasantness

Urban pleasantness is a concept with social, proximity, and physical aspects [794]. Proximity aspects were included in the accessibility indicator and social ones tend not to depend on the urban layout. Thus, this indicator concentrates on physical pleasantness. Human perception of the pleasantness of the physical urban environment is related to well-being, better quality of life and sustainable development [717] and has been an active topic of research [19,699–702,708,710,715,716].

As a quantitative indicator was needed, this research evaluated the perceived physical pleasantness following Sousa et al. [19], an ordinal regression model based on geometric and land use qualities of the urban environment, evaluated at the neighborhood level. The model has five explanatory variables, namely green area percentage, street width, number of floors, building distance, and existence of green private area, which estimate perception of pleasantness in a 1-5 Likert scale. The results of Sousa et al. [19] show that people tend to prefer higher percentages of green areas, wider streets, a lower number of floors, small building distances, and having green private areas.

Similarly to the calculation of route directness a neighborhood-size square mesh was used to evaluate the explanatory variables for each layout. Neighborhood-scale values were extracted for each explanatory variable, from which neighborhood pleasantness expectation values were derived. Squares with no inhabitants were removed from the calculations.

9.2.6. Mix land use

Mix land use is an important attribute of the urban built environment [40] and a common topic in urban planning for sustainability [604,607,609,611], since higher degrees of this indicator lead to better proximity life, vibrancy, environmental quality, and comfort [19,40,104,114,115,165,456,643,649,696,774,832].

A square mesh of neighborhood size was again used as unit to evaluate mix land use. For each city layout, neighborhoods were evaluated for the existence of eight different types of possible land use: residential, educational, entertainment and cultural, commercial, parks and green areas, industrial and offices, healthcare, and governmental and institutional [833]. A neighborhood unit can have up to eight different land use types (highest score) or only one (lowest score). Neighborhoods without dwellings or facilities, i.e., whose land use does not correspond to any of the type above, were deleted, as these correspond to rural or otherwise non-urbanized land parcels.

9.2.7. Multicriteria methodology

The six urban layout benchmarking indicators are criteria representing different dimensions of reality. When comparing alternatives against multiple, often conflicting, dimensions, a multicriteria method is the appropriate assessment tool. It is important to note that multicriteria analysis does not necessarily yield a “optimum solution”; it merely offers the decision-maker a viewing window for the trade-offs that occur when choosing between the different alternatives, in this case the city layouts. Multicriteria methods also imply setting parameters. Some may relate to technical aspects of the method, while others, such as e.g., criteria weights, reflect different perspectives of the decision-maker. Multicriteria analysis has been widely used in urban and spatial planning and is an important day-to-day tool for municipal authorities [834–841].

The rank multicriteria method selected was TOPSIS, one of the most wide-used methods of this kind in the literature [842]. TOPSIS has been used in urban and spatial planning and previous research [843–850], including its integration with the GIS environment [834,851–853]. TOPSIS works by measuring criteria weighted distances of the alternatives to the hypotheticals' reference points: ideal and anti-ideal. The result is a rank for each alternative, in a [0,1] interval scale, with 0 (worst) to 1 (best). Details on the method can be found in [854].

9.3. Case study: a real city vs. its redraft as six different city concepts

The methodology proposed to benchmark the different layouts was applied in a comparative analysis between the real city of Coimbra, Portugal, with its redrafts as six different city concepts. For this purpose, the geographic elements of real Coimbra were redisposed following the above mentioned city concepts for a total of seven layouts to be compared. Of the six concepts, five represent ideal city concepts and were chosen based on their impact on urban planning and policies. These concepts span circa a century of trends in the planning field and have, directly or indirectly, been considered on the urban development of cities worldwide.

Each of the six hypothetical layouts was obtained by moving residential areas, urban facilities, job locations, and redesigning the road network, all according to the principles guiding each city concept. As noted before, in these redrafts of Coimbra, the number of actors in play, i.e., inhabitants, urban facilities, and jobs, was preserved as much as possible, to keep a baseline for comparison. To redraft the real city as ideal concepts, a comprehensive analysis was carried out for each concept's blueprints, general urban form, land-use features, inhabitants' distribution and general population density, mobility considerations, policies, and underlying ideas. This in-depth analysis also involved some trial and error and, moreover, as some of the concepts, e.g., the Garden City, are over a century old, the redraft had to consider adaptations to the 21st century. When redrafting, provisions for walking and cycling were considered, namely street space would be wide enough to ensure adequate separation for cycleways and sidewalks. The following subsections motivate and give procedural details for each layout.

9.3.1. Coimbra, Portugal

Coimbra is a mid-sized city in the center of Portugal with 106,768 inhabitants, founded in the Roman age [855], with higher education and healthcare as its main economic activities. Due to its occupation by different cultures, Coimbra grew mostly in an unrestricted way. Coimbra had a compact layout in its origin and the medieval times, mostly concentrated on a hill for defensive reasons. In the modern era, and similarly to many cities at the time, Coimbra grew and evolved in the wake of the cheap fuel boom of the 1950s onwards, developing onto a low-density, low-mix pattern of land use and sprawled urban environment, with wide streets to accommodate the motorized traffic. Figure 9.1 shows the city evolution towards sprawl. Between 1930 and 2021 the population increased 190%, but the urban area of the city increased 5018%, demonstrating the sprawling.

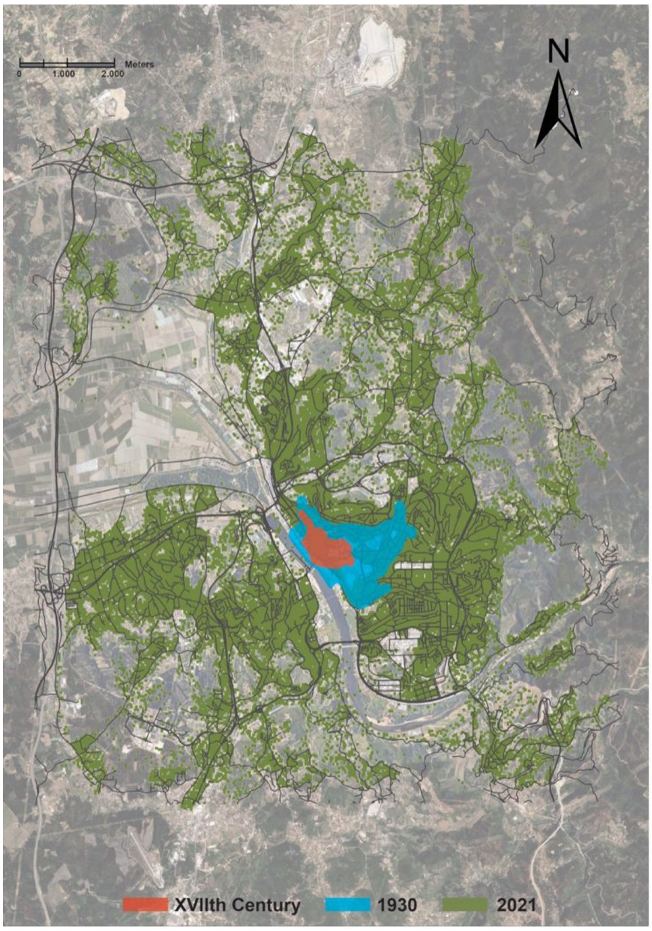
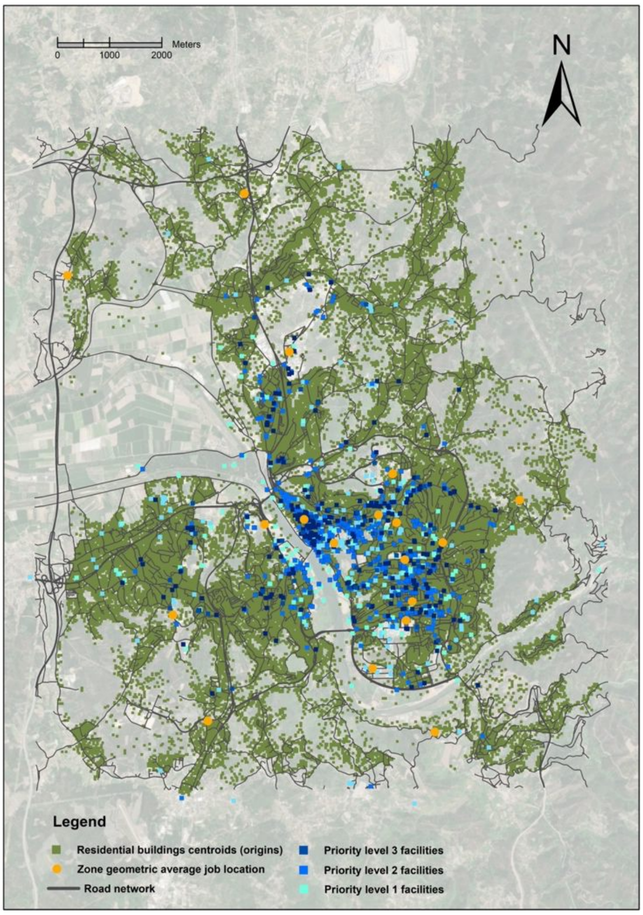


Figure 9.1. Evolution of Coimbra's urban perimeter and population [18].

The origins, destinations, and road network GIS datasets for Coimbra were available from previous team projects. Survey data relating to daily trips shows circa 19% active mode share, of which only 0.2% is cycling. Motorized transport complements the remaining percentages, from which a 30/70% split between public transport and private car, respectively was observed [584]. Commuting trips in Coimbra represent 37% of total trips [542].

9.3.2. Infill Coimbra

The sprawling of Coimbra resulted in many spaces left unurbanized, as well as spaces that became derelict over the years. The infill redraft, presented in Monteiro et al. [18], made use of those available spaces by filling them with new residential buildings, urban facilities or jobs located on the outskirts of the city, in full compliance with the current municipal regulations and Municipality's development master plan. Additionally, for residential buildings, areas and construction modelling were made according to national regulations. New land plots were infilled with residential, commercial and mix use buildings that would house inhabitants moved in from the city peripheries. Results showed that 40% of Coimbra's current population could migrate inside the city's new perimeter. Urban facilities located on the outskirts were also moved inside while retaining their original business volume. The total urbanized area of the city was reduced from circa 142,000 m^2 to 16,700 m^2, a reduction of 88%, as Figures 9.2a and 9.2b show. This reduction also impacted accessibility, active modal share, and transport energy consumption. Exact figures for these indicators are given in the results section. The reader is referred to Monteiro et al. [18] for more information on the infill procedure.



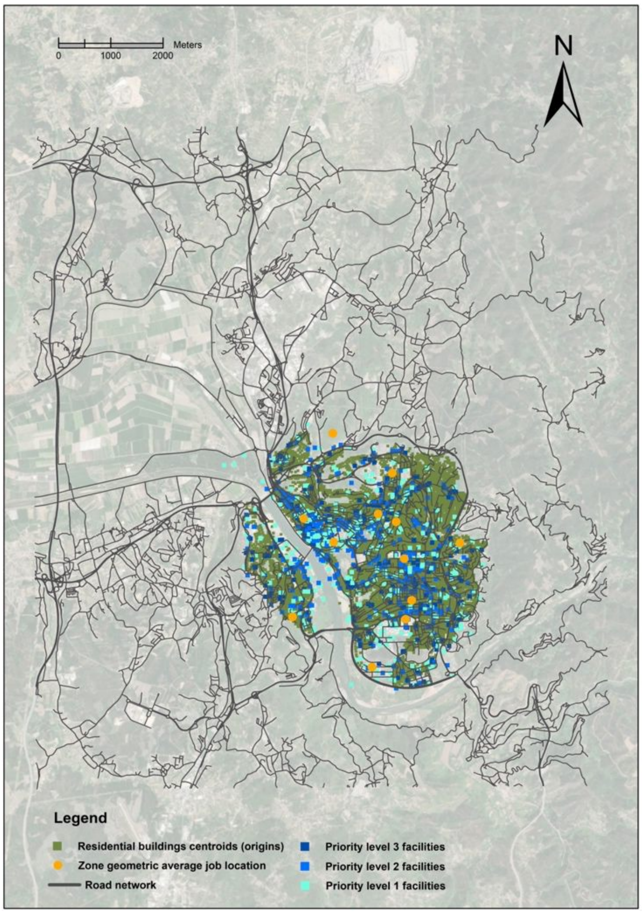


Figure 9.2. Origins, destinations, and road network. (a) Layout of Coimbra; (b) Layout of Infill Coimbra [18].

9.3.3. The Garden City

The Garden City concept was created by Ebenezer Howard amid the New Town movement in the turn of the XIXth to the XXth century as an alternative to the overcrowded, and industrialized cities like London [445,856]. According to Howard's plans [4], the city would house around 30,000 inhabitants, in its hallmark circular shape of ring-like concentric zones, with clear land-use specifications encompassing residential areas, green parks, and a full range of industrial, cultural, and commercial facilities. City expansions would be achieved via the creation of hexagon-like clusters of Garden Cities that together would form the Social City [4]. More than a century later, the Garden City is still present in academic research [16,429,438,445] and is considered as a valid solution for the expansion or the development of new cities [503–505].

Coimbra’s redraft as a Garden City followed Howard’s descriptions and blueprints which, considering the population of Coimbra, led to a cluster of three Garden Cities (Figure 9.3). The distribution of facilities was made in two stages: in the first stage the smaller facilities were placed in an equal number throughout the three Garden Cities; in the second stage the larger facilities (e.g., regional hospitals) were distributed according to their actual location in Coimbra. The original Garden City and Coimbra’s redraft as this concept are presented in Figures 9.3 and 9.4. For more details on the redraft, see Monteiro et al. [16].

Figure 9.3. The Garden City concept: layout of a ward of the Garden City [4].

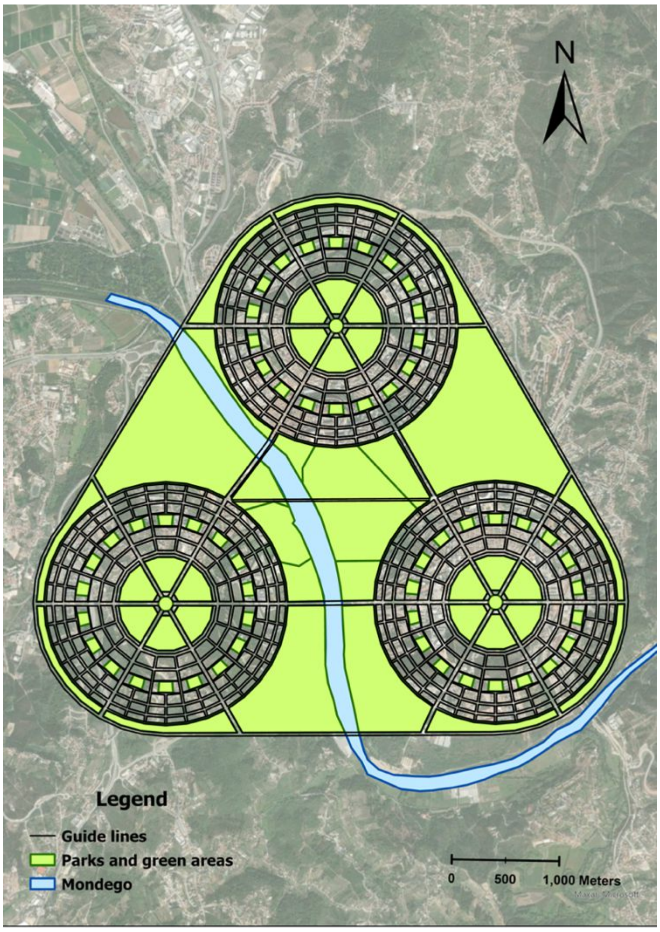


Figure 9.4. Coimbra redrafted as the Social City [16].

9.3.4. Ville Radieuse

Ville Radieuse was a project of Le Corbusier developed between 1920 and 1940 [857,858], to be implemented in cities such as Moscow and Paris. The *Ville Radieuse* concept main characteristic is its landmark skyscrapers. In its larger version, the skyscraper could hold around 100,000 inhabitants and expansion plans would be implemented by adding new skyscrapers [211,857,859].

The *Ville Radieuse* city center would encompass an intermodal station, streets with wide sidewalks, parking spaces, and roads of four lanes on each direction. Above the streets, perpendicular concrete bridges formed two axes of arterial roads for fast one-way traffic. *Ville Radieuse* was idealized for mobility and a central role for the car. The city center skyscrapers would house offices, services, and commerce. From the center, three sides would be filled with residential buildings, with space for local business, surrounded by green areas. Residential skyscrapers could be adapted to fit from a few hundred to thousands of people. The remaining side of the city would be reserved for public buildings, such as universities, city hall, and library. Before reaching a perpetual green belt, two to three stories high residential buildings with private gardens were planned for the higher classes of the society. The city would be complete with an industrial, commercial, and service area on the outskirts. Figure 9.5 illustrates the city layout concept. *Ville Radieuse* was grounded on four principles: de-congested city center; high density of residential and services; ample means for moving around the city; and generous areas of parks and open spaces [5,211].

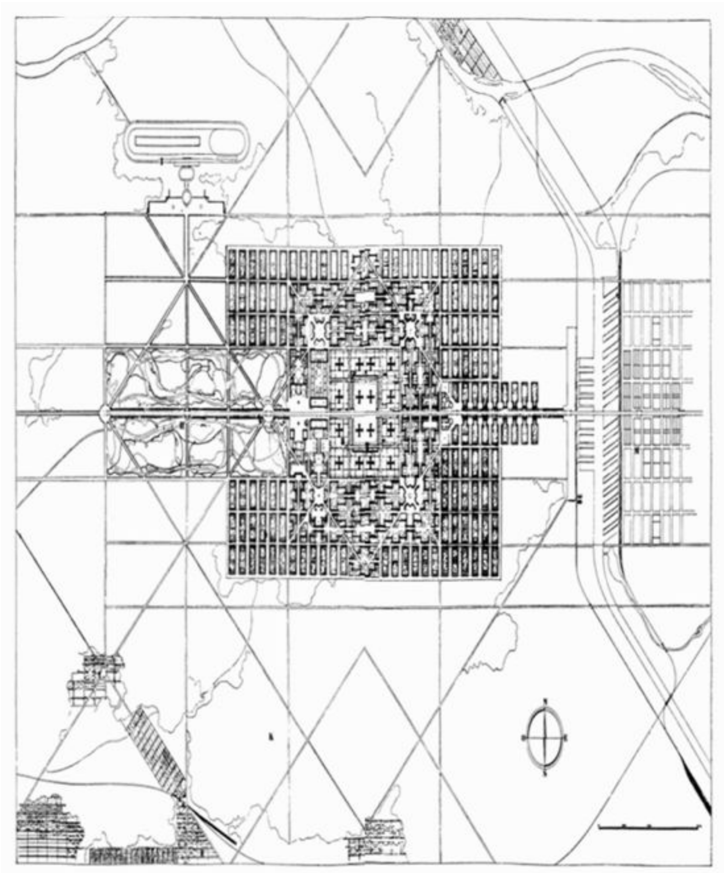


Figure 9.5. The *Ville Radieuse* concept layout [5].

The redraft of Coimbra as a *Ville Radieuse* was carried out following blueprints and the author's notes. The concept was adapted to suit Coimbra's population numbers, with population density, facilities location and green areas matched to the original work, resulting in a symmetric urban layout, as Figure 9.6 shows.

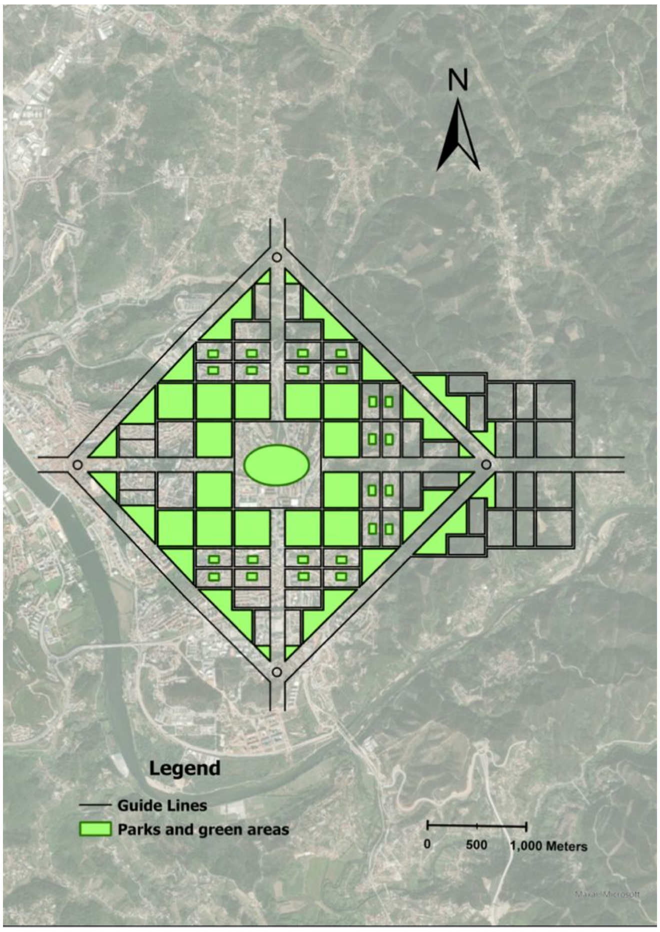


Figure 9.6. Coimbra redrafted as the *Ville Radieuse* concept.

9.3.5. Compact City Theory

The Compact City Theory was put forward as a planning solution towards urban sustainability [604,860,861]. One of the first approaches to the Compact City Theory was made by Burnham in 1909 [862] with the Plan of Chicago, presented in Figure 9.7. The concept was based on a set of policies that aim for more a compact environment [863], such as: mix and fine grain of land use, low open-space ratio, high degree of accessibility and street connectivity, contiguous development, multimodal transportation, and its hallmark high residential and jobs density [235,864,865]. It stands on the opposite part of the spectrum of urban sprawl with higher proximity, accessibility, decreased car dependency and commuting time, reduced transport energy consumption, and conservation of surrounding natural areas [604,863,866]. Downsides of Compact City Theory urbanism come mainly from conflicts between its proclaimed efficiency and citizen well-being due to excessive density [235,860,861,863,867–869].

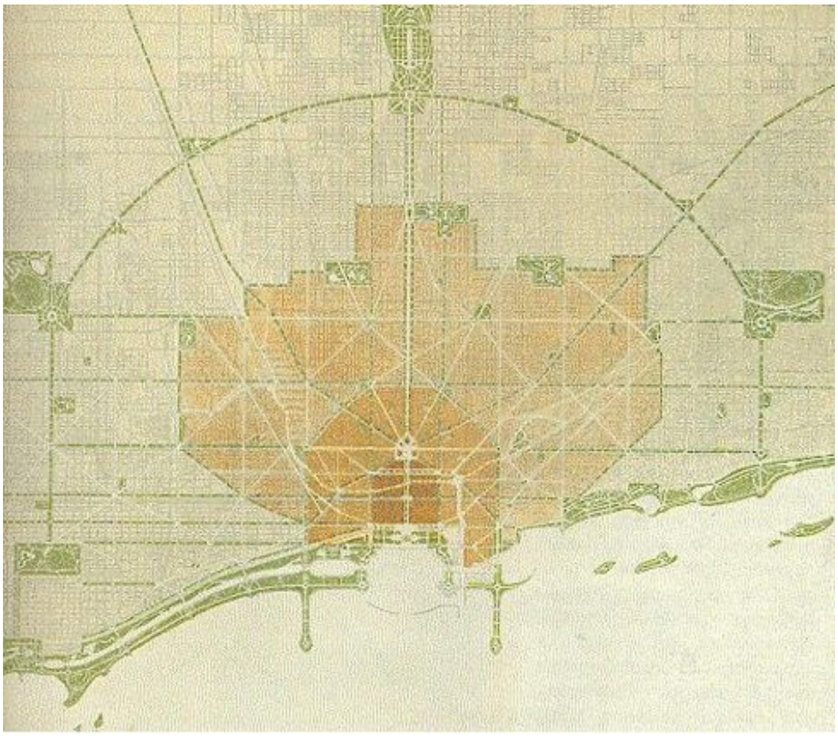


Figure 9.7. The Compact City Theory concept: the plan of Chicago [862].

As Compact City Theory is not based on any blueprints or detailed design rules, but rather on a set of planning policies, the redraft of Coimbra as a Compact City Theory layout merely followed those policies. This led to an extremely compact urban environment on both river banks of the Mondego river that crosses Coimbra, a decision made based on the historic evolution of cities, which tend to side river banks [428]. The layout, shown in Figure 9.8 was drawn as a grid-like system, similar to the Plan of Chicago.

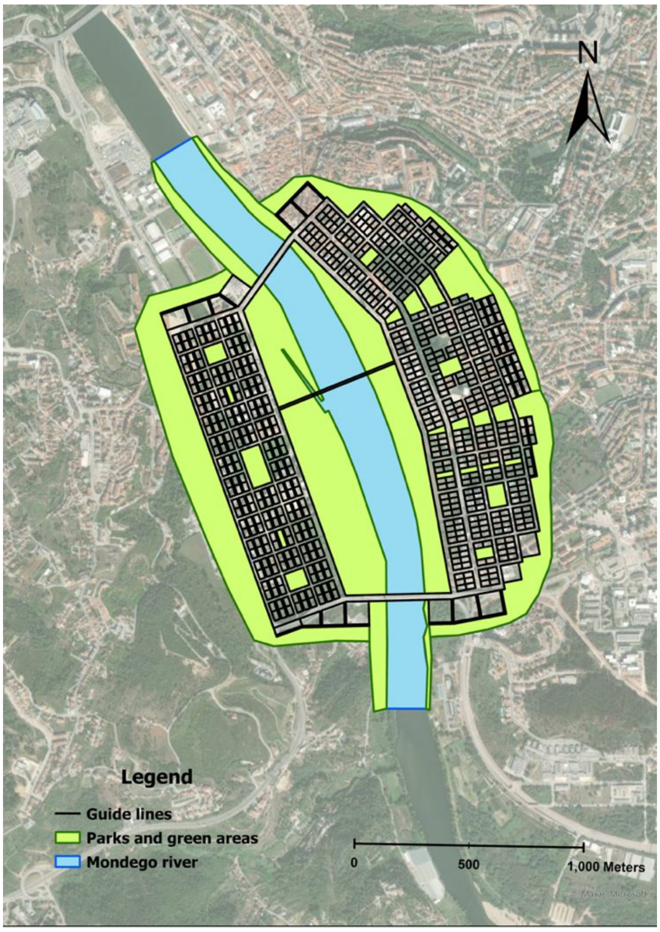


Figure 9.8. Coimbra redrafted as the Compact City Theory concept.

9.3.6. Transit-Oriented Development

Despite the relationship between land use and transport planning, many cities have treated these as separate processes [870–873], usually with transport planning as a subsidiary (Holz-Rau and Scheiner, 2019; Mattioli, 2014). The lack of assessment tools that combine these two planning aspects left cities without a way to estimate the impact that decisions on one aspect have on the other and on overall sustainability and resiliency [874–876]. Transit-Oriented Development (TOD) integrates both transport and spatial planning in a concept that aims at improved sustainability and smart growth [231,877–879]. The TOD concept was developed by Peter Calthorpe (Figure 9.9), who described it as the integration of the transit system with a compact land use pattern of moderate to high-density housing [231,232]. Its policies and strategies target mix land use development, reduction of private motorized transport, provision for high-quality pedestrian and cycling infrastructure, and allocation of civic spaces near public transport stations [231,880,881]. Albeit TOD sometimes gives rise to fuzzy interpretations and practical applications [881–883], overall it is viewed as a city concept that deploys both transport and land use interventions combinedly. TOD ideas are present in several urban form concepts of the past century, namely the work of Howard, Soria y Mata (linear city) or Le Corbusier. TOD has been one an active research avenue in spatial and transport planning, with worldwide cities implementations [103,450,818,883–887].

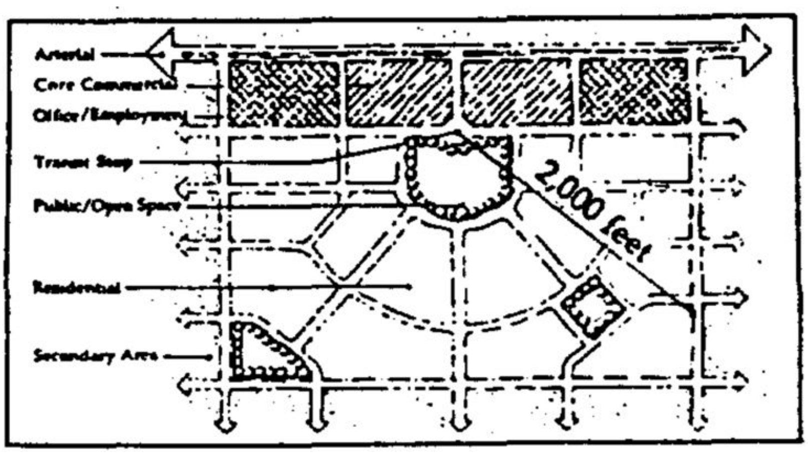


Figure 9.9. TOD original blueprints from San Diego guidelines [230].

Coimbra's redraft as a TOD (Figure 9.10) followed Calthorpe's manual for the city of San Diego. The manual contains TOD strategies and policies, blueprints, and detailed analysis on how develop a TOD city [231,232]. Coimbra is soon due to upgrade to a Bus Rapid Transit system (BRT), which is expected to become the main mobility option for most inhabitants. The two BRT main lines were considered as basis for the redraft of Coimbra as a TOD city. These lines took into consideration the location of inhabitants, urban facilities, and jobs. As in TOD transit lines take precedence, the city was disposed around them, keeping the main residential zones and urban facilities in situ as much as possible. The redraft itself followed a grid-like network, ensuring that all inhabitants and facilities were kept within a 600 meters buffer from a BRT station.

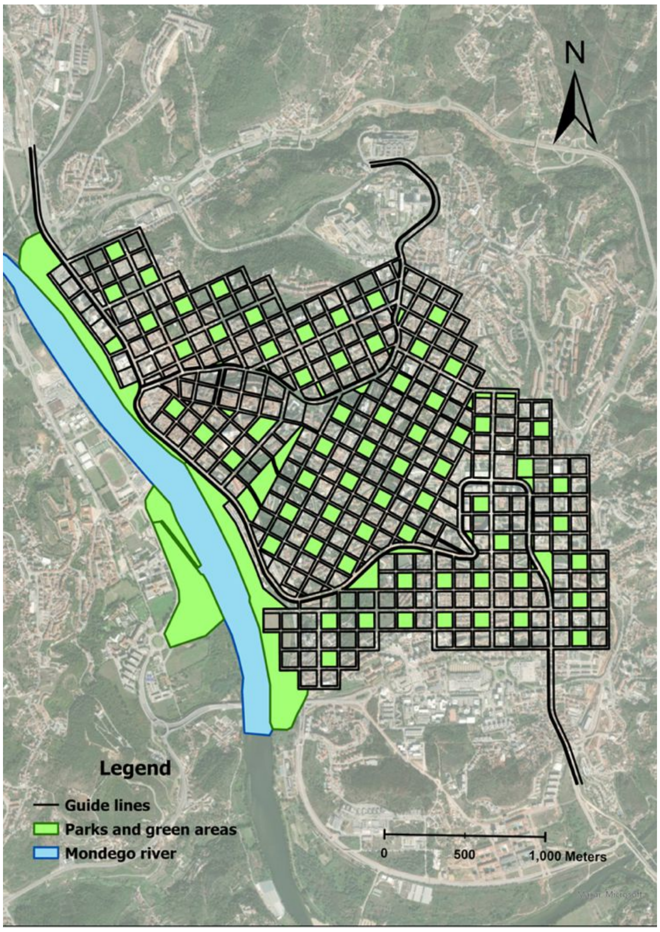


Figure 9.10. Coimbra redrafted as the TOD concept.

9.3.7. Transect Planning

A transect is a cut or path through a landscape [12]. This concept originated in the biological sciences and was demonstrated by Patrick Geddes in 1909 with a representation of the Valley Section [12,888,889]. In the context of urban planning, Andrés Duany proposed Transect Planning as a gradual change from the natural environment towards an urban center, with a wide-range of habitats of increasing degree of urbanization [12]. Many cities worldwide already exhibit transect characteristics.

However, the implementation is incoherent, with sprawl along highways, single land use, and a lack of infrastructures for active mobility [13,868,888]. Transect planning aims at improving this status-quo, giving it a systematic and consistent organization that naturally interpolates between nature and urban center. CATS [12] developed the SmartCode in 2003, a municipal master plan for Transect Planning which presents the necessary policies, strategies, and layouts for a successful urban form based on a compact, walkable, and mixed-use urban environment (Figure 9.11). The SmartCode is adaptable to local context and up to 2007 over one-hundred urban areas have adopted it [890].

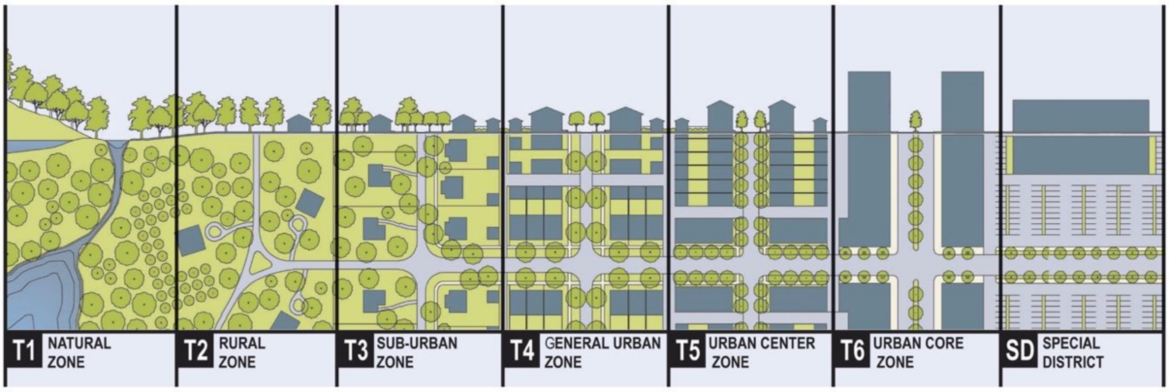


Figure 9.11. Transect concept applied to urban planning [889].

The SmartCode provided all the necessary guidelines and blueprints necessary to redraft Coimbra as Transect Planning. Urban facilities and job locations were adapted to the code regulations and the redraft, Figure 9.12, turned out similar to that of Compact City Theory, with a city is built on both riverbanks in a grid-like system.

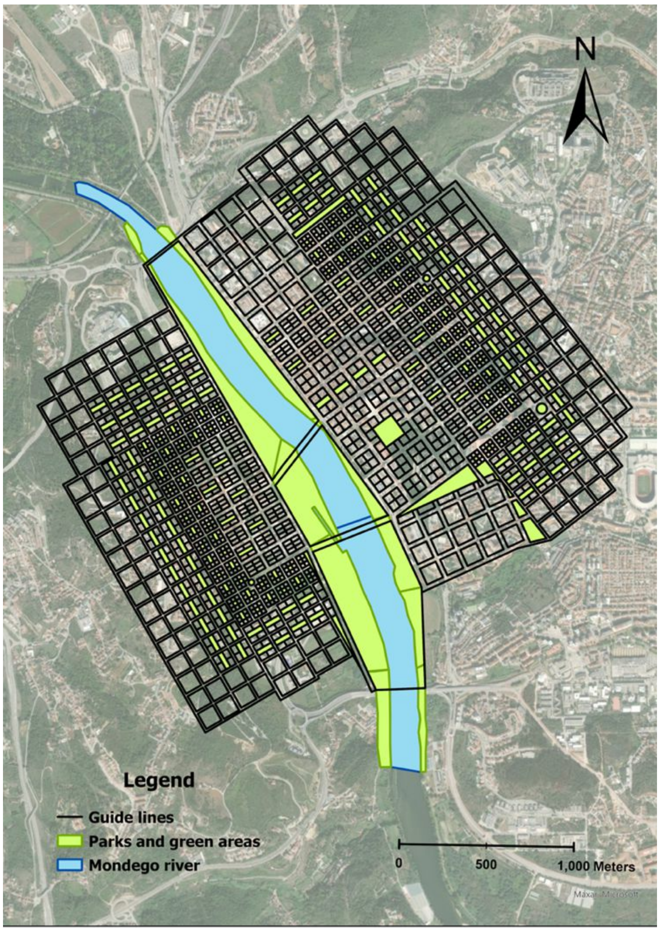


Figure 9.12. Coimbra redrafted as Transect Planning.

9.3.8. Summarizing characteristics

Table 9.2. summarizes the global geographical characteristics of Coimbra after each redraft.

Table 9.2. Redrafts summarizing characteristics.

Summarizing characteristics	Urban area (km^2)	Urban perimeter (km)	Road length (km)	Road density (m/m^2)	Green areas (km^2)	Green areas (%)
Compact Theory	3.7	7.4	36.2	10.5	0.7	18.4
Transect Planning	9.2	11.8	110.0	11.9	1.1	12.0
TOD	9.5	12.7	94.7	10.0	1.2	12.1
Ville Radieuse	17.7	16.4	80.8	4.6	3.8	21.3
Infill Coimbra	20.3	16.7	320.1	15.8	1.2	6.0
Garden City	24.6	21.4	135.6	5.5	8.6	35.0
Coimbra	129.4	47.2	873.0	6.8	1.5	1.2

Due to sprawl, the real city of Coimbra has the largest urban area and perimeter, and consequently also requires the longest road network length. Infill Coimbra is smaller, reducing the urban area in 84% and the perimeter in 65%. Its road network is similar to real Coimbra, just cut short and with small additions in the new infill sites. On the opposite of the spectrum, lies the Compact Theory, whose redraft has a very small urban area in comparison to the other layouts. The TOD and Transect Planning redrafts are very similar in most characteristics, just as the Garden City and *Ville Radieuse* are similar in size and perimeter and have the highest areas dedicated to parks and green areas. In general, all redrafts are smaller and more compact than the real city, while managing to keep a better ratio of green area to constructed area.

9.4. Results

Results are firstly presented and discussed for each indicator, after which the TOPSIS multicriteria analysis is carried out to compare all the layouts. TOPSIS requires normalization of the decision matrix, and a ratio normalization was used, as this preserves the proportions between criteria values.

9.4.1. Accessibility

Accessibility statistics are presented Table 9.3. Statistics were run over the set of origins i, except for the average per inhabitant column, which is given by $\frac{\sum_i h_i A_i}{\sum_i h_i}$.

Table 9.3. Accessibility statistics.

Layout\measure (m)	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	459	572	**572**	745	61	0.107
Transect Planning	448	748	**649**	1484	168	0.224
TOD	481	664	**623**	1008	123	0.185
Ville Radieuse	1010	1337	**1230**	1819	207	0.154
Infill Coimbra	948	1491	**1602**	3092	280	0.188
Garden City	1194	1486	**1487**	1914	171	0.115
Coimbra	1063	3088	**2578**	9239	1483	0.480

All redrafts improve accessibility considerably. To test statistical significance of the layout differences a one-way non-parametric factorial analysis at 5% significance was carried out over the set of origins, namely a Kruskal-Wallis test, followed by post-hoc Dunn tests with Benjamini-Hochberg correction. This yielded an accessibility ranking that can be loosely written as:

$$\text{Compact} = \text{TOD} = \text{Transect} < \text{Ville} < \text{Garden} = \text{Infill} < \text{Coimbra}$$

with "=" standing for statistically equivalent and "<" for statistically different, shorter distances (better accessibility). When considering population weighting, the Infill, Garden City and *Ville Radieuse* layouts reduce average per inhabitant distances by around 40% and the more compact layouts, Compact, TOD and Transect, by around 75%, showing the high impact sprawl has on the real city.

The dispersion measures, which can be seen as a benchmark of equity, improve very considerably for all redrafts of Coimbra, evidencing a striking difference between the inhabitants of the real city that live close to the center and those far away from most urban facilities and job locations.

9.4.2. Active modal share

Table 9.4. presents the statistics for active modal share. All redrafts double or triple their active transport modal share with respect to Coimbra, with the more compact layouts achieving very high active modal shares, over 85% per inhabitant averages.

Table 9.4. Active transport modal share statistics.

Layout\measure	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	0.821	0.878	**0.878**	0.918	0.020	0.022
Transect Planning	0.564	0.817	**0.851**	0.918	0.059	0.072
TOD	0.702	0.844	**0.858**	0.910	0.044	0.052
Ville Radieuse	0.440	0.612	**0.666**	0.730	0.077	0.126
Infill Coimbra	0.289	0.616	**0.591**	0.763	0.072	0.118
Garden City	0.533	0.624	**0.623**	0.683	0.029	0.047
Coimbra	0.035	0.356	**0.433**	0.737	0.187	0.526

The one-way factorial analysis post-hoc tests reveals an active share statistical rank similar to that of accessibility, namely:

$$\text{Compact} = \text{TOD} = \text{Transect} > \text{Garden} = \text{Ville} = \text{Infill} > \text{Coimbra}, \qquad (\text{Garden} > \text{Infill})$$

where the "Garden > Infill" means the differences between those layouts are significant, but not when compared in sequence with *Ville Radieuse*. This happens because statistical equivalence is not transitive (i.e., A = B = C does not imply A = C). Considering population weighting the active share tends to improve slightly, as people concentrate on the central locations.

It must be mentioned that the cycling mode requires adequate provisions for its feasibility, i.e., properly designed and maintained cycleways. That is not the case for real Coimbra: the existing cycleways are scattered, fail to link origins to destinations and serve mostly recreational purposes. Consequently, the actual cycling share of Coimbra is far from the 30-40% it could theoretically aspire to, representing currently only the aforementioned 0.2%. This might suggest suppressing the cycling mode from the calculations. However, the redraft layouts were all designed with cycleway provisions and sized according to engineering guidelines and best practices [539]. If ideal layouts are to be implemented, it would not make sense to disregard this very important active mode. Because this research is about layout geometry, to put all layouts on the same footing, the option was made to assume that cycling provisions will exist for all, regardless of the investment necessary to implement those provisions. Results for the walk mode only can, nevertheless, be derived. These are presented in the supplemental materials and reveal that removing the bicycle reduces the active modal share by about one-half to two-thirds for all layouts, a difference that should not be overlooked.

9.4.3. Transport energy consumption

Qualitatively, transport energy consumption results are similar to those for accessibility and active modal share, as Table 9.5. shows.

Table 9.5. Transport energy consumption statistics.

Layout\measure (MJ/pass.-trip)	Min	Average	Avg. Per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	0.459	0.845	**0.845**	1.346	0.226	0.267
Transect Planning	0.372	1.480	**1.059**	4.778	0.740	0.494
TOD	0.388	1.034	**0.866**	2.575	0.522	0.505
Ville Radieuse	2.487	4.012	**3.681**	6.269	1.006	0.250
Infill Coimbra	2.563	5.163	**5.745**	14.250	1.461	0.283
Garden City	3.667	5.336	**5.341**	7.922	1.066	0.200
Coimbra	3.296	13.542	**10.876**	46.165	7.870	0.581

The one-way factorial analysis again yields statistical equivalence between the more compact layouts and a clear hierarchy over the remaining layouts:

$$\text{Compact} = \text{TOD} = \text{Transect} < \text{Ville} < \text{Infill} < \text{Garden} < \text{Coimbra}$$

Slight differences emerge on weighting to inhabitants, but an interesting feature is that if the *Ville Radieuse*, Infill and Garden City layouts are considered as a group, the ratios between the compact layouts, this group and Coimbra are approximately 10/5/1, which are far larger than the same ratios for accessibility, at approximately 4/2/1. This difference is due to the relation between accessibility and energy, the latter raising quickly and with distance because of the non-linear decrease of active modal shares. In a sense the impact of distance on transport energy is greater than distance itself, once again emphasizing the importance of minimizing urban sprawl.

9.4.4. Road network directness

Road network directness results are shown in Table 9.6. As mentioned, directness statistics did not consider population weighting.

Table 9.6. Road network directness statistics.

Layout\measure	Min	Median	Average	Max	Std. Dev.	Coef. of Var.
Compact Theory	1.00	**1.263**	1.360	3.545	0.369	0.271
Transect Planning	1.00	**1.294**	1.313	4.824	0.220	0.167
TOD	1.00	**1.219**	1.239	3.121	0.136	0.110
Ville Radieuse	1.00	**1.282**	1.352	8.209	0.393	0.291
Infill Coimbra	1.00	**1.581**	1.767	19.453	0.779	0.441
Garden City	1.00	**1.264**	1.332	18.086	0.361	0.271
Coimbra	1.00	**1.337**	1.412	24.738	0.350	0.248

The high maximum values of directness correspond to locations that are close to each other, typically within pedestrian range, but road network configuration force the traveler to take a large detour. These routes cause the directness distribution to be right skewed. For this reason, median values were used in the multicriteria analysis, as they are less prone to skewness distortions. Note that for origins and destinations that are close-by, people are likely to take Euclidean-like pathways shortcuts rather than using the network, which further justifies using the median.

The one-way factorial analysis over all routes per layout yields the ranking:

$$\text{TOD} < \text{Garden} \leq \text{Compact} = \text{Ville} = \text{Transect} < \text{Coimbra} < \text{Infill}$$

where the ≤ sign indicates that the Garden City is equivalent to the Compact Theory, albeit marginally so (p-value = 6.9%), but better than the *Ville Radieuse* and Transect layouts. Indeed, it would seem that sprawl and otherwise unrestricted growth create mobility inefficiencies rather than solutions.

9.4.5. Mix land use

Table 9.7. presents the mix land use scores.

Table 9.7. Mix land use statistics.

Layout\measure (uses/neighb.)	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of var.
Compact Theory	1	4.673	**7.310**	8	2.968	0.635
Transect Planning	1	4.213	**6.416**	8	2.569	0.610
TOD	1	5.406	**6.008**	8	1.764	0.326
Ville Radieuse	1	3.110	**4.306**	6	1.536	0.494
Infill Coimbra	1	3.294	**3.674**	7	1.713	0.520
Garden City	1	3.453	**3.907**	6	1.606	0.465
Coimbra	1	1.506	**2.606**	7	1.126	0.748

Again, the best scores are achieved by the planned layouts, but this time the infill version of Coimbra is competitive. Coimbra's low score is due to sprawl, single land use and derelict land plots. Its infill version corrects these inefficiencies, resulting in average scores comparable to the planned layouts.

A one-way factorial analysis over the unweighted set of neighborhoods confirms that TOD is statistically superior to all other layouts, while real Coimbra is inferior to all. The other layouts are in-between those two and on par with each other, for a ranking $\text{TOD} < \text{other} < \text{Coimbra}$. When weighting to inhabitants, the more compact layouts, Compact Theory, TOD and Transect, further improve their status, as they concentrate more people in the denser neighborhoods.

While it could be argued that the better scores of the planned layouts is due to their more compact nature, the higher mix land use appears by design, not because of compactness itself, as most planned layouts provide for proximity activities.

9.4.6. Pleasantness

The pleasantness scores are presented in table 9.8.

Table 9.8. Pleasantness statistics.

Layout\measure	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of var.
Compact Theory	2.123	2.470	**2.331**	2.715	0.266	0.108
Transect Planning	2.248	3.169	**2.867**	4.093	0.407	0.128
TOD	2.057	2.680	**2.514**	4.093	0.470	0.176
Ville Radieuse	2.442	2.792	**2.900**	2.989	0.193	0.069
Infill Coimbra	1.962	2.635	**2.439**	3.951	0.496	0.188
Garden City	3.083	3.637	**3.620**	3.976	0.264	0.072
Coimbra	1.988	3.187	**2.698**	3.951	0.460	0.144

Physical pleasantness is one criterion where the real city is competitive with the other layouts, albeit only moderately so when population weighting is considered. This is a benefit of urban sprawl, which allows for constructing many detached homes with few floors and large bodies of green areas in the surrounding space. In the infill version, those sprawled areas reduce considerably, leading to worst scores. The one-way factorial analysis over the unweighted scores yields the ranking Garden < Coimbra = Transect < other, confirming the status of Coimbra as a front-runner, second only to the Garden City.

Since high pleasantness scores tend to require wide spaces, short buildings and abundant green areas, it is difficult to achieve such scores with the more compact layouts, as the table shows, and the factorial analysis concurs. Note that these contrasts between independent dimensions of reality are what justifies a multicriteria approach, because it can yield an aggregated preference. The overall reduction of scores in the population weighted average is due to the denser zones having taller buildings and narrower streets, which degrade the pleasantness scores.

The Garden City was originally created to be a wide, enjoyable urban environment, while being compact enough that active transport is still possible; it looks to be a compromise between accessibility and pleasantness. Its has the largest portion of parks and green areas, wide streets, and the tallest buildings have only four floors, so it has the best pleasantness scores. More than a century old, this city concept remains a paradigm in that respect. It is in fact surprising that no more proposals focusing on pleasantness appeared in so much time.

9.4.7. Multicriteria analysis

The *a priori* decision matrix for the multicriteria analysis consists of seven alternatives (layouts) and six criteria (indicators). Before proceeding with the application of TOPSIS, it is important to realize that three of the criteria are very highly correlated, namely accessibility, active modal share, and transport energy, as the latter two are built off the first (Pearson correlations exceeding 97%). In multicriteria analysis the criteria should be as independent as possible, so, if these three criteria were to be considered in the decision matrix, a sizeable bias towards accessibility would emerge in the results. Two possibilities exist to solve this issue: in the decision matrix, consider only one criterion or a combination of the three. If a combination is the choice, it must be determined which one, and the natural candidate would be the principal component of the three criteria. However, this would introduce negative values in the decision matrix, requiring a change of the preferred ratio normalization scheme.

Since most normalization schemes that deal with negative numbers tend to magnify the spacing between alternatives, a feature that is undesirable (most criteria are on a ratio scale, so the ratio normalization is the most natural choice), the option was made to consider only one of the three criteria. Accessibility, the most basic of the three, was thus chosen, leaving the decision matrix with seven alternatives and four criteria. For completeness, an analysis replacing accessibility with active modal share and transport energy was carried out. As expected, results were very similar to those of accessibility and did not provide additional insights, so they are not reported in this chapter.

Running TOPSIS requires setting one parameter, namely criteria weights. Weights reflect different judgements by the decision maker of the relative importance of the criterion. Rather than selecting a particular set of weights for the analysis, it is more elucidative to explore the weight space, and this was the preferred approach. Several ways exist to explore weight space [891–894]; for this research a combination search was carried out: each criterion weight took the value 1 or 2 and all possible combinations were evaluated. After weight normalization, i.e., division by $\sum_i w_i$, one duplicate combination was removed, leading to the weight sets summarized in Table 9.9. below.

Table 9.9. Weight sets for sensitive analysis.

Weight sets	w_{access}	w_{direct}	$w_{pleasnt}$	w_{mix}
Set 1	1/4	1/4	1/4	1/4
Set 2	2/5	1/5	1/5	1/5
Set 3	1/5	2/5	1/5	1/5
Set 4	1/5	1/5	2/5	1/5
Set 5	1/5	1/5	1/5	2/5
Set 6	1/3	1/3	1/6	1/6
Set 7	1/3	1/6	1/3	1/6
Set 8	1/3	1/6	1/6	1/3
Set 9	1/6	1/3	1/3	1/6
Set 10	1/6	1/3	1/6	1/3
Set 11	1/6	1/6	1/3	1/3
Set 12	2/7	2/7	2/7	1/7
Set 13	2/7	2/7	1/7	2/7
Set 14	2/7	1/7	2/7	2/7
Set 15	1/7	2/7	2/7	2/7

Set 1 has equal weights, i.e., same importance for all criteria. Sets 2-5 put emphasis on one criterion, sets 6-11 put emphasis on two criteria, and sets 12-15 de-emphasize one criterion.

Running TOPSIS for all 15 sets of weights yields the scores and final rank presented below in Tables 9.10. and 9.11 (Table 9.10., the closer to one the better).

Table 9.10. TOPSIS preference rank ([0 – 1] scale).

Weight sets	Compact Theory	Transect Planning	TOD	*Ville Radieuse*	Infill Coimbra	Garden City	Coimbra
Set 1	0.7418	**0.7607**	0.7056	0.3694	0.1819	0.3791	0.1422
Set 2	**0.8257**	0.8086	0.7925	0.3364	0.1770	0.2945	0.0922
Set 3	0.7489	**0.7590**	0.7248	0.4215	0.1692	0.4274	0.2204
Set 4	0.5905	**0.6674**	0.5767	0.3866	0.1629	0.5013	0.1786
Set 5	**0.8091**	0.7836	0.7135	0.3654	0.2055	0.3353	0.1018
Set 6	**0.8265**	0.8053	0.7981	0.3638	0.1718	0.3281	0.1485
Set 7	0.7039	**0.7467**	0.6939	0.3487	0.1687	0.3857	0.1228
Set 8	**0.8501**	0.8090	0.7730	0.3437	0.1925	0.2899	0.0784
Set 9	0.6019	**0.6732**	0.5993	0.4255	0.1543	0.5218	0.2324
Set 10	**0.8107**	0.7813	0.7242	0.3947	0.1978	0.3695	0.1628
Set 11	0.6801	**0.7193**	0.6255	0.3758	0.1927	0.4280	0.1343
Set 12	0.7072	**0.7467**	0.7011	0.3720	0.1643	0.4035	0.1638
Set 13	**0.8501**	0.8066	0.7777	0.3631	0.1883	0.3159	0.1275
Set 14	0.7399	**0.7612**	0.7000	0.3520	0.1855	0.3636	0.1058
Set 15	0.6846	**0.7205**	0.6377	0.4005	0.1865	0.4459	0.1782

Table 9.11. TOPSIS ranking positions.

Weight sets	Compact Theory	Transect Planning	TOD	*Ville Radieuse*	Infill Coimbra	Garden City	Coimbra
Set 1	2	1	3	5	6	4	7
Set 2	1	2	3	4	6	5	7
Set 3	2	1	3	5	7	4	6
Set 4	2	1	3	5	7	4	6
Set 5	1	2	3	4	6	5	7
Set 6	1	2	3	4	6	5	7
Set 7	2	1	3	5	6	4	7
Set 8	1	2	3	4	6	5	7
Set 9	2	1	3	5	7	4	6
Set 10	1	2	3	4	6	5	7
Set 11	2	1	3	5	6	4	7
Set 12	2	1	3	5	6	4	7
Set 13	1	2	3	4	6	5	7
Set 14	2	1	3	5	6	4	7
Set 15	2	1	3	5	6	4	7
Average rank	1,60	1,40	3,00	4,60	6,20	4,40	6,80
Final rank	2	1	3	5	6	4	7

Table 9.10. is the main result of this chapter, and its meaning is clear: regardless of the set of weights, the more compact layouts, Transect, Compact Theory and TOD, come out on top of the quantitative analysis, followed by the two less committal planned layouts, the Garden City and *Ville Radieuse*. The Infill proves to be overall an improved version of the real layout, but still considerably far from planned layouts. The real layout comes last, except against its infill version when the focus is on pleasantness, proving it has clear problems of inefficiency.

The fact is that results favor the compact layouts can be traced back to them outscoring the other one in three out of four criteria. Compact urbanism has been criticized on several fronts [92,209,213,214,235,895], but the actual quantitative calculations do not support those views. Considering efficiency and physical pleasantness as dimensions of reality, the compact layouts offer tangible advantages over both the real layout and other layouts that try and compromise between those two dimensions.

9.5. Discussion

The analysis ultimately lead to a well-defined conclusion: the more compact layouts have a sizeable advantage, mainly due to better transport and land-use efficiency. In terms of the indicator values, the alternative layouts tend to form three clusters: Infill, pleasantness-oriented (Garden City, *Ville Radieuse*), and the more compact layouts (Compact City Theory, Transect, TOD).

The Infill layout mitigates much of Coimbra's sprawl, but that was not enough to make that layout competitive with the other ones. Nevertheless, Infill Coimbra proves that improvement is possible within municipal master plans, i.e., without structural changes to the urban fabric.

The pleasant-oriented group, Garden City and *Ville Radieuse*, also the two oldest concepts in the analysis, emerged in a time where cities were far away from environmentally friendly, or even people oriented. By the beginning of the XXth century most urban dwellers had no access to public green spaces and adequate sanitation, living in polluted neighborhoods that later became brownfields. More than urban planning concepts, both were socioeconomic stands towards equity and more humane living conditions [4,5,211,856,858]. Their large number of parks, green areas, and wide streets led to higher pleasantness scores. However, mix land use did not play such an important role as it does in the top three concepts, leading to lower scores for this criterion and accessibility, limiting layout performance from that side. That said, these two concepts should not be discarded, as both are important sources of planning motifs towards pleasantness and equity.

The more compact layouts, Compact City Theory, Transect Planning and TOD, have in common high compactification and densification. These layouts, especially Compact City Theory, have been widely debated in the past decades and the present research provides quantitative evidence that vindicates claims on efficiency, which arguably leads to a better chance at achieving much-needed urban sustainability. The Transect and TOD layouts are slightly different, in that they consider different housing types and city areas while taking advantage of all the available space, making them slightly more balanced and with a more diversified built environment. Within the three compact layouts, Transect Planning comes out marginally above the others so, if a “winner” is to be called, this would be the most natural candidate. In a sense, the Transect layout can be seen as a compromise solution within the more compact layouts.

Given that at least some planned layouts are arguably older than the massive inflow of people towards cities, it is fair to ask why only very few cities follow those layouts. Cities worldwide have put into practice the best knowledge, strategies and policies that were available at the time, aiming at not only to solve the problems at hand but also preparing the built environment for the future. While fine in theory, this intention usually fell short in practice. The solutions are neither universal nor always applicable on the field, and strategies may not yield the same outcomes. As such, politics influenced the solutions in the local context, playing a crucial role in adapting them to a specific urban area, often improvising to overcome the initial problem while responding to peoples’ interests, aspirations, and needs. This reality, to which the rise of the private car contributed greatly, has led to urban features recognizable in most cities: sprawled residential neighborhoods with single-house families, industrialized city outskirts, historic city centers reminiscent of older times, large highways and viaducts connecting different city areas, and newer central areas with high-rise construction and a high concentration of city dwellers. Coimbra’s inefficiency testifies that urban planning should follow well-grounded long-term strategies that can define a clear path for city development, improving their sustainability and resiliency while preventing the creation of a city patchwork that is outperformed by all the alternative layouts evaluated.

What the present research shows is that, long term, planned urbanism can provide better urban solutions in comparison to unrestricted urbanism, which does not encompasses long term strategies and policies with definite goals and tends to disregard efficiency.

9.5.1. Impact in city planning

The quantitative evidence this research provides favors planned urbanism. However, as argued, realizing it in practice will be difficult, especially given that cities are already built, and it is not conceivable to reconstruct them for the sake of efficiency. Nevertheless, practical applications of the results found in this research may come in two ways: cities expansion programs, and development of new cities. Many cities around the world are growing and this trend is expected to continue in the next decades [22], requiring the creation of new neighborhoods and urban areas.

The urban layouts studied in this research were proposed for mid-size and large cities, but their ideas are general and can be applied at smaller scales. Also, city expansions could go potentially reach large dimensions, in which case the concepts can be applied in their full extent [503–505]. New cities are also being built developing countries [507,508] and these are the prime candidates to apply one of the planned concepts.

9.5.2. Research limitations

On the technical side, studying more city concepts and real cities could strengthen the conclusions. More quantitative benchmarking indicators could also be added (e.g., an explicit equity indicator), as well as improvements on the current ones. Mobility in particular was represented only by one proxy indicator that does not consider traffic congestion. Also, chain trips, i.e., round trips which include stopovers at multiple facilities, were not considered in the transport indicators.

Finally, concerning practical implementation of the results, these are mostly limited to new construction, as real cities are very static, evolve slowly, and are subject driving forces that may be stronger than planned urbanism. Furthermore, factors such as orography, floodplains, and other geographic issues are non-trivial determinants of city growth and may constrain constructive solutions. Full cycling may also prove difficult achieve. Factors such as lack of road safety, hilliness, harsh climate, or absence of parking facilities are known deterrents to cycling [17,538,543–545,593] and could take a toll on the active modal share and transport energy indicator values.

9.6. Summary

In this chapter a quantitative multicriteria methodology for the analysis and benchmarking real and ideal city layouts was presented. The debate around urban form and its impact on quality of urban life has been ongoing for centuries and the results presented add to that debate, providing a common ground of comparison between city layouts, based on multiple quantitative indicators that evaluate different dimensions of reality, thus providing tools for municipal authorities to evaluate past, present, and future urban forms.

The methodology was applied to a case study of a real city and its redraft as five ideal city concepts and an infill version of itself. Results showed that densification, compactification, and mix land use are important to urban sustainability and resiliency, as they can shorten distances and lead to better accessibility, higher active modal share, shorter public transit lines and travel time, reduction in transport energy consumption and associated greenhouse gas emissions. Sprawl has developed for over half a century in many cities, making it commonly present in urban environments. As there is now a clear understanding of its negatives, municipal authorities are well-advised to acknowledge this and revert trends, although it seems likely it will take another half a century of planning strategies and policies to correct it.

Ideal city concepts can have an important role on cities future development by providing guidelines and concepts that can create more sustainable and resilient urban environments. These denser, more compact urbanism paradigms also have higher mix land use and retain acceptable levels of physical pleasantness, thus scoring better in comparison to the patchwork urbanism present in most of nowadays cities.

The quantitative benchmarking of cities, made possible by advances in computer science, enables putting to the test real cities and classic and contemporary city concepts. We hope the ideas proposed in this chapter can open new research avenues and stir the debate on the ideal form of cities, as well as shaping the view of urbanists on how to plan upcoming city expansions.

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10. CONCLUSION

"The best way to predict the future is to invent it." – Immanuel Kant

The final chapter of the thesis is divided into two sections: main conclusions and future work.

10.1. Main conclusions

In the first two chapters of the thesis two literature reviews are presented. Two comprehensive literature reviews which allowed for an in-depth understanding of the current challenges ahead of cities towards higher sustainability and resiliency. The first one, reviews the critical issues surrounding the development of sustainable urban environments, focusing on the impact of urban form and the transport system on energy consumption and GHG emissions. The second, presents a review of the state-of-the-art research produced on the impacts of COVID-19 in spatial and transport planning. It systematises the knowledge in the field, contributing to the creating of a coherent overview of the research landscape.

Following the two reviews, the next chapters identify and build the set of indicators to be used in the performance benchmarking relative to each one individually, and their aggregation in the CSCI indicator. The individual indicators and the multi-criteria methodology (CSCI) were successfully applied to benchmark the case study - the City of Coimbra - and its redrafts based on the concepts´ original guidelines and plans, which made it possible to obtain an accurate basis of comparison. As far as the author is aware, it was the first time that classic and contemporary city models were quantitively compared and benchmark with each other.

The use of the selected indicators to quantitively analyze and compare different city layouts proved to be feasible and may be a contribution to municipal and central administration departments/agencies. Results are conveniently depicted in maps in order to convey the useful information to decision makers and all stakeholders. Additionally, most of the geometric and land-use characteristics taken into consideration for the indicators can be targeted for interventions and improvements. Results can help the decision making on new policies, urban regeneration actions, infrastructure interventions, and planning strategies for city expansions.

At this stage it is important to underline, once more, that the big takeaway is not to fully rebuild existing cities in a more efficient manner, as local context, costs, and resources spending, etc., make it unrealistic. Rather, results provide important guidelines, urban planning strategies and policies that can, at least to some extent, be applied in current urban areas. These can be used for urban regeneration projects, expansion programs and generally, for changing and adapting current policies and urban planning strategies towards more sustainable, resilient, equitable and inclusive urban areas. More rarely, results can also be applied to the design new cities from scratch.

The result of applying the CSCI to seven layouts of the same urban database show that the most compact layouts have an advantage due to their transport and land use efficiency. They may not be the most physically pleasant urban spaces, but they exhibit excellent potential to reduce motorized transport while providing a socially vibrant city. The benchmark encompassed six indicators and seven city concepts. The six indicators can be categorized in accessibility (accessibility, active modal share and transport energy consumption), mobility related (route directness), land-use (mix land-use) and pleasantness (perceived neighborhood pleasantness). Although comprehensive, there is room for improvement and future work, the latter presented in more detail in the next subsection (10.2 Future work).

Nevertheless, some future improvements and add-ons can be considered. First, the indicators developed are not the only ones that can be considered to evaluate the form and function of urban layouts. For example, a road hierarchy and a more subjective pleasantness indicator, based on the buildings and neighborhoods aesthetics and also urban infrastructure and public space condition. Along the same line, more city concepts could be included in the benchmark. For the past century, other city concepts were developed and presented, such as the Linear City or the Broadacre City that have notably impacted urban planning both in theoretical and practical debates. Finally, other real cities representative of different scales and cultures could be considered as a based scenario for the comparison. The context of some cities in the north of Europe and many cities from both South and North America, Africa, or Asia may provide results and conclusions in accordance with the respective contexts.

10.2. Future work

Further research avenues can be envisaged. As previously mentioned, additional city concepts can be analyzed, and new indicators introduced. To best of the author's knowledge, this is the first large scale benchmark and comparison of city concepts based on quantitative indicators. As such, is natural that new research avenues emerge. Possible developments are listed below in Table 10.1.

Table 10.1. Future research

Tentative title /Status	Short description
#1 **Tentative title:** Perceived urban pleasantness in a Brazilian metropole: Belo Horizonte case study **Status:** paper in final version for international journal submission	This article builds upon the research presented in chapters 7 and 8 and aims to provide an initial answer to the question: Do people adapt to where they live? i.e., do locals perceive their cities as more pleasant than outsiders do? Do we grow fond of the place we live in?
#2 **Tentative title:** Urban real estate prices correlation with accessibility and perceived neighborhood pleasantness: a mid-size European city case-study **Status:** dissemination	Evaluation of the correlation of real estate prices with accessibility and perceived neighborhood pleasantness based on the presented indicators. The main objective is to try understanding what influences housing prices: accessibility, pleasantness or neither in specific.
#3 **Tentative title:** Evaluation of road hierarchy vulnerabilities: A transport planning benchmark tool **Status:** data analysis	A new indicator to be added to the methodology presented. Based on road hierarchy classification, it takes into consideration the design of road networks but also the development of a municipal tool capable of identifying existing vulnerabilities in transport networks.
#4 **Tentative title:** Route directness towards sustainable transport: An active modal share and transport energy consumption analysis **Status:** under research.	Based on the difference between Euclidean distances and urban network distances this research aims to take a closer look on the relationship between the route directness indicator with both active modal share and transport energy consumption indicators.

Tentative title /Status	Short description
#5 **Tentative title:** Determinants of children's physical activity: An accessibility and neighborhood pleasantness-based analysis. **Status:** under implementation	Physical activity is beneficial to children's physical and psychological health. Physically active children are likely to become active adults. This research aims to explore the relationship between the built environment and children's physical activity by statistically relating activity with accessibility to urban parks and green areas, neighborhood perceived pleasantness, and demographic control factors. Physical activity was objectively measured using accelerometers, while accessibility, pleasantness, and control factors were evaluated in a geographic information system. Based on the results, guidelines and planning strategies are put forward to increase children's physical activity towards the creation of more sustainable and resilient cities.
#6 **Tentative title:** Do people adapt to where they live? A ten cities perceived neighborhood pleasantness survey **Status:** conceptualization	Results from this thesis suggest that inhabitants find their own city more pleasant than people from other cities. This research intends to extend the analysis to over ten cities around the world, retrieving survey answers and neighborhood geometric and land-use elements.

As a final note, for current and future research, one should not forget that urban planning does not seek to attain the optimum solution *'irgendwie, irgendwo, irgendwann'* (somehow, somewhere, sometime). Urban planning problems are complex, ill-defined, and important but non-immediate. Complex as the obstacles inhibiting efforts to achieve solutions are diverse, problem-solving occurs under uncertainty in changing environments; ill-defined as preferences structure, relevant criteria for effectiveness, solution paths, existing reality and goals may be unclear in usually multidisciplinary problems; and, important but non-immediate as unnecessary to find an instant solution being preferable to follow a systematic approach in the analysis. Urban planning aims at identifying feasible solutions, considering all drawbacks and obstacles, acknowledging that compromises must be made, and that decision-makers often need to follow a learning process being prompt to revise early conclusions. The current and future research builds on that idea, aiming to create and provide the necessary quantitative knowledge components and tools towards making better choices and achieve a more sustainable future for our cities.

"By far the greatest and most admirable form of wisdom is that needed to plan and beautify cities and human communities." - Σωκράτης (Socrates)

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João Pedro Medina Monteiro

FORM AND FUNCTION

BENCHMARKING REAL AND IDEAL CITIES

VOLUME 2

PhD Thesis in Doctoral Program in Spatial Planning, supervised by Professor João Manuel Coutinho Rodrigues, Professor Nuno Miguel Marques de Sousa, and Professor Eduardo Manuel Ferreira Almeida da Natividade de Jesus, submitted to the Department of Civil Engineering of the Faculty of Science and Technology of the University of Coimbra.

December 2023

Faculty of Sciences and Technology, University of Coimbra
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"Maps are a way to organize wonder." - Peter Steinhart

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1. OUTLINE

This is thesis is divided into two volumes. Volume I, organized as a collection of scientific papers, is the main body of the thesis and volume II is reserved for the supplementary materials. Volume II was created to reduce the size of Volume I and functions only as the collection of all the supplementary materials from the chapters in Volume I.

As mentioned in volume I, maps are extremely important to convey the data used and results obtained in the different instances that form this thesis. Different journals, editors, and reviewers input result in heterogenous maps layouts. For this thesis, maps were all remade to have the same layout and graphic appearance. Nevertheless, a map representing the same results might have different scales, as each scale has been adapted to the context of each paper. As previously mentioned, there will be maps repetitions throughout the thesis that could not be avoided. Due to size and orientation of some maps and tables, to improve readability paper orientation may vary, resulting in a not so straight-forward readability when printed.

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2. CHALLENGES AHEAD ON SUSTAINABLE CITIES: AN URBAN FORM AND TRANSPORT SYSTEM REVIEW

2.1. Table II.2.1. Built environment related research articles in Spatial and Transport Planning

Table II.2.1. Built environment related articles.

Authors	Publication date	Location of Research	Article topic
Acker, V.V.; Derudder, B.; Witlox, F.	2013	Flanders, Belgium	Active mobility
Adams, S.; Boateng, E.; Acheampong, A.O.	2020	Sub-Saharan Africa	Developing countries urban energy challenges
Aguiléra, A.; Voisin, M.	2014	Paris, France	Transport and the built environment
Ahern, J.	2013	Unspecified	Eco-districts and built environment towards clean energy
Ahmed, K.S.	2003	Dhaka, Bangladesh	Active mobility
Akbari, H.; Kolokotsa, D.	2016	Worldwide	Urban public spaces
Akbari, H.; Matthews, H.D.	2012	Worldwide	Urban public spaces
Al-Obaidi, K.M.; Hossain, M.; Alduais, N.A.M.; Al-Duais, H.S.; Omrany, H.; Ghaffarianhoseini, A.	2022	Unspecified	Urban geometry, IOT and buildings energy consumption
Alahmad, M.; Hasna, H.; Sordiashie, E.	2011	Unspecified	Transport and the built environment, vehicle electrification
Alcazar, S.S.; Olivieri, F.; Neila, J.	2016	Madrid, Spain	Urban heat island
Alford, G.; Whiteman, J.	2009	Melbourne, Australia	Transport and the built environment
Ali-Toudert, F.; Mayer, H.	2007	Ghardaia, Algeria	Active mobility
Ali-Toudert, F.; Mayer, H.	2006	Unspecified	Active mobility, street canyons
Almulhim, A.I.; Bibri, S.E.; Sharifi, A.; Ahmad, S.; Almatar, K.M.	2022	Gulf countries	Developing countries urban energy challenges
Alshehry, A.S.; Belloumi, M.	2017	Saudi Arabia	Developing countries urban energy challenges
Amado, M.; Poggi, F.; Amado, A.R.	2016	Lisbon, Portugal	Urban sprawl
Amado, M.; Poggi, F.; Ribeiro Amado, A.; Breu, S.	2018	Oeiras, Portugal	Urban geometry and buildings energy consumption
Anderson, J.E.; Wulfhorst, G.; Lang, W.	2015	Unspecified	Urban form and policies
Andersson, B.; Place, W.; Kammerud, R.; Scofield, M.P.	1985	USA	Street canyons
Aram, F.; Higueras García, E.; Solgi, E.; Mansournia, S.	2019	Unspecified	Urban heat island
Aram, F.; Solgi, E.; Holden, G.	2019	Hamadan, Iran	Urban heat island
Artmann, M.; Inostroza, L.; Fan, P.	2019	Unspecified	Urban sprawl
Asarpota, K.; Nadin, V.	2020	Unspecified	Urban form
Azevedo, J.A.; Chapman, L.; Muller, C.L.	2016	Birmingham, UK	Urban heat island
Bajracharya, A.R.; Shrestha, S.; Skotte, H.	2020	Kathmandu,, Nepal	Urban public spaces

Authors	Publication date	Location of Research	Article topic
Banister, D.; Watson, S.; Wood, C.	1997	Unspecified	Urban trips and network design
Baruti, M.M.; Johansson, E.; Åstrand, J.	2019	Unspecified	Urban form
Battista, G.; Carnielo, E.; De Lieto Vollaro, R.	2016	Rome, Italy	Urban heat island
Berawi, M.A.; Ibrahim, B.E.; Gunawan; Miraj, P.	2019	Indonesia	Densification and compactification
Besir, A.B.; Cuce, E.	2018	Worldwide	Urban heat island
Bleviss, D.L.	2021	Worldwide	Active mobility
Boakye, K.; Bovbjerg, M.; Schuna, J.; Branscum, A.; Mat-Nasir, N.; Bahonar, A.; Barbarash, O.; Yusuf, R.; Lopez-Jaramillo, P.; Seron, P.; et al.	2023	Worldwide	Active mobility
Bourbia, F.; Awbi, H.B.	2004	Unspecified	Active mobility
Bracco, S.; Delfino, F.; Ferro, G.; Pagnini, L.; Robba, M.; Rossi, M.	2018	Savona, Italy	Eco-districts and built environment towards clean energy
Brandt, L.; Derby Lewis, A.; Fahey, R.; Scott, L.; Darling, L.; Swanston, C.	2016	Chicago, USA	Urban heat island
Brown, R.D.; Vanos, J.; Kenny, N.; Lenzholzer, S.	2015	Worldwide	Urban heat island
Bucher, D.; Buffat, R.; Froemelt, A.; Raubal, M.	2019	Switzerland	Active mobility
Buyadi, S.N.A.; Mohd, W.M.N.W.; Misni, A.	2015	Selangor, Malaysia	Urban heat island
Buyana, K.; Byarugaba, D.; Sseviiri, H.; Nsangi, G.; Kasaija, P.	2019	Africa	Developing countries urban energy challenges
Byrne, J.; Taminiau, J.; Kurdgelashvili, L.; Kim, K.N.	2015	Seoul, South Korea	Urban geometry and buildings energy consumption
C40 Cities	2023	Worldwide	Urban form
Cajot, S.; Peter, M.; Bahu, J.-M.; Guignet, F.; Koch, A.; Maréchal, F.	2017	Switzerland	Urban form
Cao, X.; Yang, W.	2017	Guangzhou, China	Transport and the built environment, urban trips and network design
Caputo, P.; Pasetti, G.	2015	Italy	Urban form
Carboni, A.; Pirra, M.; Costa, M.; Kalakou, S.	2022	Europe	Active mobility
Carter, J.G.	2018	England	Urban public spaces
Castro, L.F.C.; Freitas, B.B.; Carvalho, P.C.M.	2021	Unspecified	Urban form
Cervero, R.	1996	San Francisco, USA	Urban trips and network design
Cervero, R.; Murakami, J.	2010	USA	Transport and the built environment
Charalampopoulos, I.; Tsiros, I.; Chronopoulou-Sereli, A.; Matzarakis, A.	2013	Athens, Greece	Urban heat island
Chen, Y.; Hong, T.; Piette, M.A.	2017	San Francisco, USA	Eco-districts and built environment towards clean energy
Cheng, V., Steemers, K., Montavon, M., Compagnon, R.	2006	Worldwide	Urban geometry and buildings energy consumption
Chilvers, J.	2008	UK	Urban form
Chow, W.T.L.; Brazel, A.J.	2012	Phoenix, USA	Urban heat island
Christiansen, L.B.; Cerin, E.; Badland, H.; Kerr, J.; et al.	2016	Worldwide	Active mobility

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Clark, T.A.	2013	USA	Densification and compactification
Coaffee, J.; Therrien, M.-C.; Chelleri, L.; Henstra, D.; Aldrich, D.P.; Mitchell, C.L.; Tsenkova, S.; Rigaud, É.; Participants, T.	2018	Unspecified	Urban form
Collaço, F.M. de A.; Simoes, S.G.; Dias, L.P.; Duic, N.; Seixas, J.; Bermann, C.	2019	São Paulo, Brazil	Urban form
Collier, M.J.; Nedović-Budić, Z.; Aerts, J.; Connop, S.; Foley, D.; Foley, K.; Newport, D.; McQuaid, S.; Slaev, A.; Verburg, P.	2013	Unspecified	Urban form, urban sprawl and policies
Conticelli, E.; Proli, S.; Tondelli, S.	2017	Italy	Densification and compactification
COP 27	2022	Worldwide	Urban energy consumption data
Cop 27	2022	Worldwide	Urban energy consumption data
Costamagna, F.; Lind, R.; Stjernström, O.	2019	Umeå, Sweden	Urban public spaces
Couto, R.; Duarte, F.; Magalhães, A.	2022	Unspecified	Urban public spaces
Covenant of Mayors	2023	Europe	Urban form
Croce, S.; Vettorato, D.	2021	Unspecified	Eco-districts and built environment towards clean energy
Csuzi, I.; Csuzi, B.	2017	Unspecified	Vehicle electrification and the built environment
Daniel, M.; Lemonsu, A.; Viguié, V.	2018	Paris, France	Urban heat island
Das, M.; Das, A.; Momin, S.	2022	India	Urban heat island
Davidson, K.; Nguyen, T.M.P.; Beilin, R.; Briggs, J.	2019	New York City, USA and Melbourne, Australia	Urban form and policies
De Lotto, R.; Micciché, C.; Venco, E.M.; Bonaiti, A.; De Napoli, R.	2022	Italy	Eco-districts and built environment towards clean energy
de Nazelle, A.; Nieuwenhuijsen, M.J.; Antó, J.M.; Brauer, M.; Briggs, D.; Braun-Fahrlander, C.; Cavill, N.; Cooper, A.R.; Desqueyroux, H.; Fruin, S.; et al.	2011	Worldwide	Active mobility
De Pascali, P.; Bagaini, A.	2019	Unspecified	Urban form
Derix, C.	2012	Unspecified	Urban form
Dias, A.M.; Lopes, M.; Silva, C.	2022	Unspecified	Active mobility
Dias, D.; Pina, N.; Tchepel, O.	2019	Coimbra, Portugal	Transport and the built environment
Ding, C.; Cao, X.; Wang, Y.	2018	Washington, USA	Public transport
Ding, C.; Lin, Y.; Liu, C.	2014	Washington, USA	Urban trips and network design
Ding, C.; Liu, C.; Lin, Y.; Wang, Y.	2014	Maryland, USA	Transport and the built environment
Ding, C.; Liu, C.; Zhang, Y.; Yang, J.; Wang, Y.	2017	Baltimore, USA	Urban trips and network design
Ding, G.; Guo, J.; Pueppke, S.G.; Yi, J.; Ou, M.; Ou, W.; Tao, Y.	2022	CHina	Transport and the built environment
Dingil, A.E.; Schweizer, J.; Rupi, F.; Stasiskiene, Z.	2019	Worldwide	Transport and the built environment
Dittmar, H.; Ohland, G.	2004	Unspecified	Densification and compactification
Duarte, F.; Ferreira, A.	2016	Unspecified	Urban public spaces
Duarte, F.; Ferreira, A.; Fael, P.	2018	Unspecified	Urban public spaces
Dupras, J.; Marull, J.; Parcerisas, L.; Coll, F.; Gonzalez, A.; Girard, M.; Tello, E.	2016	Montreal, Canada	Urban sprawl

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Dydkowski, G.	2020	Poland	Transport and the built environment
Eicker, U.; Monien, D.; Duminil, É.; Nouvel, R.	2015	Munich, Germany	Densification and compactification
Eldeeb, G.; Mohamed, M.; Páez, A.	2021	Hamilton, Canada	Transport and the built environment
Emmanuel, R.; Johansson, E.	2006	Colombo, Sri Lanka	Active mobility
Energy Information Administration	2023	USA	Urban energy consumption data
Engelfriet, L.; Koomen, E.	2018	China	Transport and the built environment
European Comission	2022	Europe	Vehicle electrification and the built environment
Ewing, R.	1997	Los Angeles, USA	Transport and the built environment
Ewing, R.; Handy, S.; Brownson, R.C.; Clemente, O.; Winston, E.	2006	Unspecified	Active mobility
Falahatkar, S.; Rezaei, F.	2020	Iran	Densification and compactification
Farhadi, H.; Faizi, M.; Sanaieian, H.	2019	Tehran, Iran	Urban heat island
Fatone, S.; Conticelli, E.; Tondelli, S.	2012	Italy	Densification and compactification
Fernández-Rodríguez, A.; Fernández-Cardador, A.; Cucala, A.P.; Falvo, M.C.	2019	Italy and Spain	Transport and the built environment, vehicle electrification
Ferrari, S.; Zagarella, F.; Caputo, P.; Bonomolo, M.	2019	Unspecified	Urban form
Ferreira, H.; Rodrigues, C.M.; Pinho, C.	2020	Porto, Portugal	Urban trips and network design
Formolli, M.; Lobaccaro, G.; Kanters, J.	2021	Europe	Eco-districts and built environment towards clean energy
Fremouw, M.; Bagaini, A.; De Pascali, P.	2020	Unspecified	Urban form
Frumkin, H.	2002	Unspecified	Urban sprawl
Fu, J.; Wang, Y.; Zhou, D.; Cao, S.-J.	2022	Xi'na, China	Urban heat island
Fujii, H.; Iwata, K.; Managi, S.	2017	Worldwide	Urban sprawl, The D-variables of compact planning
Gago, E.J.; Roldan, J.; Pacheco-Torres, R.; Ordóñez, J.	2013	Unspecified	Urban heat island
Gattuso, D.; Cassone, G.C.; Malara, M.	2018	Reggio Calabria, Italy	Transport and the built environment
Gebel, K.; Bauman, A.E.; Sugiyama, T.; Owen, N.	2011	Australia	Active mobility
Geertman, S.; Stillwell, J.	2004	Unspecified	Urban form
Georgakis, Ch.; Santamouris, M.	2006	Athens, Greece	Street canyons
GhaffarianHoseini, A.; Tookey, J.; GhaffarianHoseini, A.; Naismith, N.; Bamidele Rotimi, J.O.	2016	Africa	Developing countries urban energy challenges
Giannopoulou, K.; Santamouris, M.; Livada, I.; Georgakis, C.; Caouris, Y.	2010	Athens, Greece	Active mobility
Gil-García, I.C.; García-Cascales, M.S.; Molina-García, A.	2022	Unspecified	Urban geometry and buildings energy consumption
Giménez-Gaydou, D.A.; Cupido dos Santos, A.; Mendes, G.; Frade, I.; Ribeiro, A.S.N.	2019	Coimbra, Portugal	Active mobility
Givoni, B.	1991	Unspecified	Urban heat island
Givoni, B.; Organization (WMO), W.M.	1989	Worldwide	Urban geometry and buildings energy consumption
Glaeser, E.L.; Kahn, M.E.	2010	USA	Urban sprawl

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Gonçalves Duarte Santos, G.; Birolini, S.; Homem de Almeida Correia, G.	2023	Portugal	Vehicle electrification and the built environment
Gossop, C.	2011	Unspecified	Urban form and policies
Gough, M.; Lotfi, M.; Castro, R.; Madhlopa, A.; Khan, A.; Catalão, J.P.S.	2019	Cape Town, South Africa	Urban geometry and buildings energy consumption
Gunawardena, K.R.; Wells, M.J.; Kershaw, T.	2017	Unspecified	Urban heat island
Guo, J.; Bissuel, C.; Courtot, F.	2021	China	Urban form
Gyurov, V.; Bezhanov, N.	2019	Varna, Bulgaria	Vehicle electrification and the built environment
Hamstead, Z.A.; Farmer, C.; McPhearson, T.	2018	USA	Urban heat island
Handy, S.L.; Boarnet, M.G.; Ewing, R.; Killingsworth, R.E.	2002	Florida, USA	Active mobility
Hankey, S.; Marshall, J.D.	2010	USA	Transport and the built environment
Hannan, S.; Sutherland, C.	2015	Durban, South Africa	Developing countries urban energy challenges
Harlan, S.L.; Brazel, A.J.; Prashad, L.; Stefanov, W.L.; Larsen, L.	2006	Phoenix, USA	Urban heat island
Heres-Del-Valle, D.; Niemeier, D.	2011	California, USA	Urban trips and network design
Hickman, R.; Banister, D.	2014	Unspecified	Transport and the built environment
Hoehner, C.M.; Brennan Ramirez, L.K.; Elliott, M.B.; Handy, S.L.; Brownson, R.C.	2005	USA	Active mobility
Hong, J.; Goodchild, A.	2014	Unspecified	Urban sprawl
Howard, E.	2010	Unspecified	Urban sprawl
Hsieh, S.; Schüler, N.; Shi, Z.; Fonseca, J.A.; Maréchal, F.; Schlueter, A.	2017	Singapore	Urban sprawl
Hu, J.; Yu, X.B.	2019	USA	Urban public spaces
Huang, C.; Yang, J.; Jiang, P.	2018	China	Urban heat island
Huang, H.; Li, Q.; Yang, Y.; Zhang, L.; Dong, Z.	2022	China	Urban form
Huchzermeyer, M.	Not specified	Worldwide	Developing countries urban energy challenges
Hukkalainen, M.; Virtanen, M.; Paiho, S.; Airaksinen, M.	2017	Finland	Urban form
ICLEI Europe	2023	Europe	Urban form
IEA	2023	Worldwide	Vehicle electrification and the built environment
International Energy Agency	2022	Worldwide	Urban energy consumption data
International Energy Agency	2023	Worldwide	Transport and the built environment, vehicle electrification
Jackson, R.J.	2003	USA	Urban sprawl
Jacobs, J.	1992	USA	Urban form, urban sprawl
Jamei, E.; Rajagopalan, P.; Seyedmahmoudian, M.; Jamei, Y.	2016	Unspecified	Urban public spaces
Jank, R.	2017	Europe	Urban form and policies
Jha, A.; Preonas, L.; Burlig, F.	2021	India	Urban energy consumption data
Jin, J.	2019	Chicago, USA	Urban sprawl
Johansson, E.	2006	Fez, Morocco	Active mobility

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Johansson, E.; Spangenberg, J.; Gouvêa, M.L.; Freitas, E.D.	2013	São Paulo, Brazil	Active mobility
John, R.	2020	Dar Es Salaam, Tanzania	Developing countries urban energy challenges
Juvara, M.	2022	Worldwide	Urban energy consumption data
Kadaverugu, A.; Kadaverugu, R.; Chintala, N.R.; Gorthi, K.V.	2021	Hyderabad, India	Urban heat island
Kakar, K.A.; Prasad, C.S.R.K.	2020	Kabul, Afghanistan	Urban sprawl
Kaloustian, N.; Diab, Y.	2015	Beirut, Lebanon	Urban heat island
Karan, E.; Mohammadpour, A.; Asadi, S.	2016	Unspecified	Vehicle electrification and the built environment
Kastner-Klein, P.; Berkowicz, R.; Britter, R.	2004	Unspecified	Street canyons
Kaza, N.	2020	USA	Densification and compactification
Keirstead, J.; Jennings, M.; Sivakumar, A.	2012	Unspecified	Urban geometry and buildings energy consumption
Kenworthy, J.R.	2006	Worldwide	Eco-districts and built environment towards clean energy
Kenworthy, J.R.; Laube, F.B.	1996	Worldwide	Transport and the built environment
Khan, M.; M. Kockelman, K.; Xiong, X.	2014	Seattle, USA	Transport and the built environment
Kim, K.; Yi, C.; Lee, S.	2019	Seoul, South Korea	Urban heat island
Kiprop, V.	2017	Unspecified	Street canyons
Klemm, W.; Heusinkveld, B.G.; Lenzholzer, S.; van Hove, B.	2015	Utrecht, Netherlands	Urban heat island
Kosai, S.; Yuasa, M.; Yamasue, E.	2020	Japan	Urban trips and network design
Koutra, S.; Becue, V.; Gallas, M.-A.; Ioakimidis, C.S.	2018	Unspecified	Eco-districts and built environment towards clean energy
Kumar, P.; Morawska, L.; Martani, C.; Biskos, G.; Neophytou, M.; Di Sabatino, S.; Bell, M.; Norford, L.; Britter, R.	2015	Unspecified	Street canyons
Lai, D.; Liu, W.; Gan, T.; Liu, K.; Chen, Q.	2019	Unspecified	Urban geometry and buildings energy consumption
Lawrence, D.P.	2000	Unspecified	Urban form
Layman, C.C.; Horner, M.W.	2010	Leon County, USA	Urban trips and network design
Le Corbusier	1972	Unspecified	Urban sprawl
Lee, J.H.; Lim, S.	2018	South Korea	Densification and compactification
Leichenko, R.	2011	Unspecified	Urban form
Leng, H.; Chen, X.; Ma, Y.; Wong, N.H.; Ming, T.	2020	Harbin, China	Street canyons
Li, H.; Harvey, J.; Kendall, A.	2013	California, USA	Urban heat island
Li, S.; Zhao, P.	2017	Beijing	Urban trips and network design, public transport
Li, X.-X.; Liu, C.-H.; Leung, D.Y.C.; Lam, K.M.	2006	Unspecified	Street canyons
Li, X.; Zhou, W.; Ouyang, Z.	2013	Beijing, China	Urban heat island
Li, Z.; Quan, S.J.; Yang, P.P.-J.	2016	Macau	Urban geometry and buildings energy consumption
Liddle, B.	2014	Unspecified	Densification and compactification
Lim, X.	2019	Unspecified	Urban public spaces
Lin, L.; Moudon, A.V.	2010	Unspecified	Active mobility
Litman, T.	2005	Worldwide	Transport and the built environment
Liu, X.; Huang, B.; Li, R.; Wang, J.	2021	Shenzhen, China	Urban form and policies

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Liu, X.; Sweeney, J.	2012	Dublin, Ireland	Transport and the built environment
Liu, Y.; Huang, L.; Onstein, E.	2020	Norway	Transport and the built environment
Lobaccaro, G.; Acero, J.A.	2015	Bilbao, Spain	Urban heat island
Lobaccaro, G.; Croce, S.; Lindkvist, C.; Munari Probst, M.C.; Scognamiglio, A.; Dahlberg, J.; Lundgren, M.; Wall, M.	2019	Worldwide	Eco-districts and built environment towards clean energy
Loeffler, R.; Österreicher, D.; Stoeglehner, G.	2021	Vienna, Austria	Densification and compactification
Lombardi, P.; Trossero, E.	2013	Europe	Eco-districts and built environment towards clean energy
Lu, I.J.; Lin, S.J.; Lewis, C.	2007	Taiwan, Germany, Japan, South Korea	Transport and the built environment
Luqman, M.; Rayner, P.J.; Gurney, K.R.	2023	Worldwide	Densification and compactification
Lyu, G.; Bertolini, L.; Pfeffer, K.	2016	Beijing, China	Densification and compactification
Ma, L.; Dill, J.	2015	Portland, USA	Active mobility
Ma, Y.; Yang, Y.; Jiao, H.	2021	Wuhan, China	Urban form
Mackey, C.W.; Lee, X.; Smith, R.B.	2012	Chicago, USA	Urban heat island
Mandeli, K.	2019	Jeddah, Saudi Arabia	Urban public spaces
Marrone, P.; Fiume, F.; Laudani, A.; Montella, I.; Palermo, M.; Fulginei, F.R.	2023	Rome, Italy	Eco-districts and built environment towards clean energy
Mastrucci, A.; Baume, O.; Stazi, F.; Leopold, U.	2014	Rotterdam, Netherlands	Eco-districts and built environment towards clean energy
Matzarakis, A.; Rutz, F.; Mayer, H.	2007	Crete, Greece	Active mobility
Maya-Drysdale, D.; Krog Jensen, L.; Vad Mathiesen, B.	2020	Europe	Urban form
McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Maco, S.E.; Xiao, Q.; Hoefer, P.J.	2003	Unspecified	Urban heat island
Mele, C.; McLeskey, M.H.	2018	Unspecified	Urban form and policies
Mendiola, L.; González, P.; Cebollada, À.	2014	Biscay	Urban trips and network design
Meng, T.; Hsu, D.; Han, A.	2017	New York, USA	Eco-districts and built environment towards clean energy
Mills, D.E.	1981	Unspecified	Urban sprawl
Mohsin, M.M.; Beach, T.; Kwan, A.	2017	Bristol, UK	Developing countries urban energy challenges
Monteiro, J.; Carrilho, A.C.; Sousa, N.; Oliveira, L.K. de; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2023	Belo Horizonte, Brazil and Coimbra, Portugal	Urban form
Monteiro, J.; Para, M.; Sousa, N.; Natividade-Jesus, E.; Ostorero, C.; Coutinho-Rodrigues, J.	2023	Coimbra, Portugal	Transport and the built environment, urban sprawl, densification and compactification
Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2023	Coimbra, Portugal	Transport and the built environment, urban sprawl
Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2023	Coimbra, Portugal	Active mobility, urban sprawl
Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2022	Coimbra, Portugal	Urban form, urban sprawl
Monteiro, J.; Sousa, N.; Pais, F.; Coutinho-Rodrigues, J.; Natividade-Jesus, E.	2023	Worldwide	Urban form

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Moraci, F.; Errigo, M.F.; Fazia, C.; Burgio, G.; Foresta, S.	2018	Rotterdam, Netherlands	Urban form
Morrissey, J.; Moore, T.; Horne, R.E.	2011	Unspecified	Urban geometry and buildings energy consumption, street canyons
Motavalli, J.	2021	Unspecified	Vehicle electrification and the built environment, urban form
Moyer, A.N.; Hawkins, T.W.	2017	Pennsylvania, USA	Urban heat island
Muñoz, P.; Zwick, S.; Mirzabaev, A.	2020	Austria	Densification and compactification
Naess, P.	2010	Hangzhou, China	Urban sprawl
Nahlik, M.J.; Chester, M.V.	2014	Los Angeles, USA	Transport and the built environment, densification and compactification
Nasri, A.; Zhang, L.	2014	Washington, D.C. and Baltimore	Transport and the built environment, densification and compactification
Natividade-Jesus, E.	2022	Unspecified	Transport and the built environment
Nechyba, T.J.; Walsh, R.P.	2004	Unspecified	Urban sprawl
Nelson, A.C.	2017	Unspecified	Urban sprawl, The D-variables of compact planning
Net Zero by 2050	2021	Worldwide	Eco-districts and built environment towards clean energy
Neuman, M.	2005	Unspecified	The D-variables of compact planning
Newman, P.	2006	Worldwide	Transport and the built environment
Newman, P.W.G.; Kenworthy, J.R.	1989	Worldwide	Transport and the built environment
Ng, E.; Chen, L.; Wang, Y.; Yuan, C.	2012	Hong Kong	Active mobility
Nkosi, N.P.; Dikgang, J.;	2018	South Africa	Urban energy consumption data
Norton, B.A.; Coutts, A.M.; Livesley, S.J.; Harris, R.J.; Hunter, A.M.; Williams, N.S.G.	2015	Melbourne, Australia	Urban heat island
O'Malley, C.; Piroozfar, P.; Farr, E.R.P.; Pomponi, F.	2015	London, UK	Urban heat island
Oh, M.; Jang, K.M.; Kim, Y.	2021	Seoul, South Korea	Urban geometry and buildings energy consumption, street canyons
Oh, M.; Kim, Y.	2019	South Korea	Urban geometry and buildings energy consumption
Oke, T.R.	1987	Unspecified	Urban heat island
Okeil, A.	2010	Unspecified	Urban heat island
Olgyay, V.	2015	Unspecified	Urban geometry and buildings energy consumption
Osman, T.; Divigalpitiya, P.; Osman, M.M.	2016	Cairo, Egipt	Urban sprawl
Ozgun, K.	2020	Sidney, Australia	Urban public spaces
Paatero, J.V.; Lund, P.D.	2007	Helskinki, Finland	Eco-districts and built environment towards clean energy
Pacheco-Torgal, F.	2015	Worldwide	Urban heat island
Pasichnyi, O.; Levihn, F.; Shahrokni, H.; Wallin, J.; Kordas, O.	2019	Stockholm, Sweeden	Eco-districts and built environment towards clean energy
Patel, Z.; Greyling, S.; Simon, D.; Arfvidsson, H.; Moodley, N.; Primo, N.; Wright, C.	2017	Cape Town, South Africa	Developing countries urban energy challenges
Pei, A.	2023	Worldwide	Active moblity
Perea-Moreno, M.-A.; Hernandez-Escobedo, Q.; Perea-Moreno, A.-J.	2018	Worldwide	Urban form
Perini, K.; Magliocco, A.	2014	Italy	Active mobility

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Petersen, J.-P.; Heurkens, E.	2018	Europe	Urban form
Pieterse, D.E.; Parnell, S.	Not specified	Africa	Developing countries urban energy challenges
Pietrzak, O.; Pietrzak, K.	2021	Szczecin, Poland	Vehicle electrification and the built environment
Pisano, C.	2020	Italy and Spain	Active mobility
Pisello, A.L.	2017	Unspecified	Urban public spaces
Pisello, A.L.; Taylor, J.E.; Xu, X.; Cotana, F.	2012	USA	Densification and compactification
Pizzo, B.	2015	Unspecified	Urban form
Pretty, J.; Toulmin, C.; Williams, S.	2011	Africa	Developing countries urban energy challenges
Priyadarsini, R.; Hien, W.N.; Wai David, C.K.	2008	Singapore	Densification and compactification
Qin, Y.	2015	California, USA	Urban public spaces
Quan, S.J.; Li, C.	2021	Unspecified	Urban form
Ratti, C.; Baker, N.; Steemers, K.	2005	Europe	Urban geometry and buildings energy consumption, street canyons
Redweik, P.; Catita, C.; Brito, M.	2013	Lisbon, Portugal	Urban geometry and buildings energy consumption
Regina de Casas Castro Marins, K.	2014	São Paulo, Brazil	Public transport
Reinhart, C.F.; Cerezo Davila, C.	2016	Worldwide	Urban form
Resch, E.; Bohne, R.A.; Kvamsdal, T.; Lohne, J.	2016	Europe	Densification and compactification
Rickwood, P.; Glazebrook, G., Searle, G.	2008	Unspecified	Urban form
Riley, C.	2019	Unspecified	Vehicle electrification
Rode, P.; Keim, C.; Robazza, G.; Viejo, P.; Schofield, J.	2014	Europe	Densification and compactification
Rodríguez-Álvarez, J.	2016	Europe	Densification and compactification
Rodríguez, D.A.; Evenson, K.R.; Diez Roux, A.V.; Brines, S.J.	2009	USA	Active mobility
Roger-Lacan, C.	2019	Unspecified	Eco-districts and built environment towards clean energy
Rosso, F.; Fabiani, C.; Chiatti, C.; Pisello, A.L.	2019	Unspecified	Urban public spaces
Rosso, F.; Jin, W.; Pisello, A.L.; Ferrero, M.; Ghandehari, M.	2016	Unspecified	Urban public spaces
Rosso, F.; Pisello, A.L.; Cotana, F.; Ferrero, M.	2016	Italy	Urban public spaces
Rydin, Y.; Thomas, S.; Beddington, J.	2010	UK	Urban form
Santamouris, M.	2013	Unspecified	Urban heat island
Santamouris, M.	2014	Unspecified	Urban heat island
Santos, P.	-	Unspecified	Buildings and materials
Santos, T.; Deus, R.; Rocha, J.; Tenedório, J.A.	2021	Algarve, Portugal	The D-variables of compact planning
Sarrat, C.; Lemonsu, A.; Masson, V.; Guedalia, D.	2006	Paris, France	Urban heat island
Saunders, M.J.; Kuhnimhof, T.; Chlond, B.; da Silva, A.N.R.	2008	Unspecified	Transport and the built environment
Shahidan, Mohd.F.; Shariff, M.K.M.; Jones, P.; Salleh, E.; Abdullah, A.M.	2010	Malaysia	Urban heat island

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Shashua-Bar, L.; Hoffman, M.E.	2000	Tel-Aviv, Israel	Active mobility
Shashua-Bar, L.; Potchter, O.; Bitan, A.; Boltansky, D.; Yaakov, Y.	2010	Tel Aviv, Israel	Urban heat island
Shashua-Bar, L.; Tzamir, Y.; Hoffman, M.E.	2004	Israel	Active mobility
Shen, Q.; Chen, P.; Pan, H.	2016	China	Public transport
Shi, F.; Liao, X.; Shen, L.; Meng, C.; Lai, Y.	2022	China	Transport and the built environment
Shim, G.-E.; Rhee, S.-M.; Ahn, K.-H.; Chung, S.-B.	2006	South Korea	Transport and the built environment, urban trips and network design
Shirgaokar, M.; Deakin, E.; Duduta, N.	2013	Jinan, China	Urban geometry and buildings energy consumption
Sikder, S.K.; Eanes, F.; Asmelash, H.B.; Kar, S.; Koetter, T.	2016	Dhaka, Bangladesh	Urban form
Silva, M.; Leal, V.; Oliveira, V.; Horta, I.M.	2018	Porto, Portugal	Densification and compactification
Silva, M.; Oliveira, V.; Leal, V.	2017	Porto, Portugal	Transport and the built environment
Silva, M.C.; Horta, I.M.; Leal, V.; Oliveira, V.	2017	Porto, Portugal	Urban geometry and buildings energy consumption
Sousa, N.; Almeida, A.; Coutinho-Rodrigues, J.	2020	Europe	Vehicle electrification and the built environment
Sousa, N.; Monteiro, J.; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2022	Coimbra, Portugal	Urban sprawl
Sousa, N.; Monteiro, J.; Natividade-Jesus, E.; Coutinho-Rodrigues, J.	2022	Coimbra, Portugal	The D-variables of compact planning
Srivanit, M.; Hokao, K.	2013	Japan	Active mobility
Starace, F.; Tricoire, J.-P.	2021	Worldwide	Urban energy consumption data
Steemers, K.	2003	Worldwide	Densification and compactification
Stelzer, V.; Immendoerfer, A.; Winkelmann, M.	2014	Europe	Urban form and policies
Stevens, M.R.	2017	Unspecified	Urban sprawl, The D-variables of compact planning
Stone, B.; Mednick, A.C.; Holloway, T.; Spak, S.N.	2007	USA	Urban sprawl
Strasser, H.	2015	Salzburg, Austria	Urban form and policies
Strømann-Andersen, J.; Sattrup, P.A.	2011	Copenhagen, Denmark	Urban geometry and buildings energy consumption, street canyons
Swilling, M.; Annecke, E.	2006	South Africa	Developing countries urban energy challenges
Talbi, B.	2017	Tunisia	Developing countries urban energy challenges
Taleghani, M.; Tenpierik, M.; van den Dobbelsteen, A.; de Dear, R.	2013	Netherlands	Urban geometry and buildings energy consumption, street canyons
Taminiau, J.; Byrne, J.; Kim, J.; Kim, M.; Seo, J.	2021	East Asia	Eco-districts and built environment towards clean energy
Tchepel, O.; Monteiro, A.; Dias, D.; Gama, C.; Pina, N.; Rodrigues, J.P.; Ferreira, M.; Miranda, A.I.	2020	Coimbra, Portugal	Urban geometry and buildings energy consumption
Toboso-Chavero, S.; Nadal, A.; Petit-Boix, A.; Pons, O.; J.	2019	Unspecified	Urban form
Tonnelat, S.	2008	Worldwide	Urban public spaces
Tsangas, M.; Papamichael, I.; Zorpas, A.A.	2023	Unspecified	Urban form
U.S. Department of Transportation	2010	United States	Active mobility

Authors	Publication date	Location of Research	Article topic
UN Habitat	2023	Worldwide	Urban energy consumption data
United Nations	2018	Worldwide	Urban energy consumption data
United Nations	2023	Worldwide	Urban energy consumption data
United Nations	2021	Worldwide	Urban energy consumption data
Urban Sprawl in Europe - Joint EEA-FOEN Report	N/A	Europe	Urban sprawl
Vailshery, L.S.; Jaganmohan, M.; Nagendra, H.	2013	Bangalore, India	Active mobility
Van der Borght, R.; Pallares Barbera, M.	2023	Latin America	Transport and the built environment
van Esch, M.M.E.; Looman, R.H.J.; de Bruin-Hordijk, G.J.	2012	Netherlands	Street canyons
Vance, C.; Hedel, R.	2007	Germany	Transport and the built environment
Vardoulakis, S.; Fisher, B.E.A.; Pericleous, K.; Gonzalez-Flesca, N.	2003	Unspecified	Street canyons
Vartholomaios, A.	2017	Thessaloniki, Greece	Urban geometry and buildings energy consumption
Vonk, G.; Ligtenberg, A.	2010	Unspecified	Urban form
Wang, D.; Zhou, M.	2017	China	Urban sprawl
Wang, H.; Ou, X.; Zhang, X.	2017	China	Developing countries urban energy challenges
Wang, P.; Yang, Y.; Ji, C.; Huang, L.	2023	Nanjing, China	Urban heat island
Wang, S.; Lu, C.; Liu, C.; Zhou, Y.; Bi, J.; Zhao, X.	2020	China	Vehicle electrification and the built environment
Wang, S.; Wang, J.; Fang, C.; Li, S.	2019	China	Densification and compactification
Wang, Y.; Yang, L.; Han, S.; Li, C.; Ramachandra, T.V.	2017	Xi'an and Bangalore	Urban trips and network design
Wang, Z.-H.	2022	Unspecified	Urban heat island
Weijs-Perrée, M.; Dane, G.; van den Berg, P.	2020	Eindhoven, Netherlands	Urban public spaces
Weisz, H.; Steinberger, J.K.	2010	Unspecified	The D-variables of compact planning
White, I.; O'Hare, P.	2014	Unspecified	Urban form
Wong, P.P.-Y.; Lai, P.-C.; Low, C.-T.; Chen, S.; Hart, M.	2016	Hong Kong	Urban heat island
Woo, Y.-E.; Cho, G.-H.	2018	Seoul, South Korea	Urban sprawl
Wu, W.; Xue, B.; Song, Y.; Gong, X.; Ma, T.	2023	Ningbo, China	Transport and the built environment, urban sprawl
Xiong, R.; Zhao, H.; Huang, Y.	2024	Guiyang, China	Active mobility
Xu, X.; Sun, S.; Liu, W.; García, E.H.; He, L.; Cai, Q.; Xu, S.; Wang, J.; Zhu, J.	2017	Beijing, China	Urban heat island
Xue, X.; Ren, Y.; Cui, S.; Lin, J.; Huang, W.; Zhou, J.	2015	Xiamen, China	ransport and the built environment
Yan, H.; Wu, F.; Dong, L.	2018	Beijing, China	Urban heat island
Yang, W.; Cao, X.	2018	Guangzhou, China	Urban trips and network design
Yang, W.; Li, T.; Cao, X.	2015	China	Transport and the built environment, The D-variables of compact planning
Yao, X.; Kou, D.; Shao, S.; Li, X.; Wang, W.; Zhang, C.	2018	China	Densification and compactification
Yezioro, A.; Capeluto, I.G.; Shaviv, E.	2006	Unspecified	Urban heat island
Yıldırım, H.H.Y.; Gültekin, A.B.; Tanrıvermiş, H.	2017	Europe	Urban form

Authors	**Publication date**	**Location of Research**	**Article topic**
Zahabi, S.A.H.; Miranda-Moreno, L.; Patterson, Z.; Barla, P.; Harding, C.	2012	Montreal, Canada	Vehicle electrification and the built environment, urban sprawl
Zamanifard, H.; Alizadeh, T.; Bosman, C.; Coiacetto, E.	2019	Brisbane, Australia	Urban public spaces
Zanon, B.; Verones, S.	2013	Italy	Urban form and policies
Zhao, P.; Lü, B.; Roo, G. de	2011	Beijing	Urban trips and network design
Zheng, S.; Kroll; A.	2023	Wordwide	Active mobility
Zhu, P.; Wang, K.; Ho, S.-N. (Rita); Tan, X.	2023	Hong Kong	Transport and the built environment
Zölch, T.; Maderspacher, J.; Wamsler, C.; Pauleit, S.	2016	Munich, Germany	Urban heat island

3. Planning cities for pandemics: Review of urban and transport planning lessons from COVID-19

3.1. Table II.3.1. COVID-19 related research articles in Spatial and Transport Planning

Table II.3.1. Extensive description of the multiple aspects found in COVID-19 research papers related to spatial and transport planning.

						Spatial planning					Transport planning					
	Location	COVID-19 Timeline	Past pandemics, their impacts and timeline	COVID-19 impact on urban areas	COVID-19 consequences on mental health and safety perception	General urban planning considerations	Lessons learned from the COVID-19 pandemic	Urban planning as a tool to fight the COVID-19 and future pandemics	Green areas as physical and mental safety nets during COVID-19 lockdown	The impact of density, compactness, and world connection on the spread of COVID-19	General urban transport considerations	Travel patterns under COVID-19 lockdown	The role of accessibility and proximity	Public transport and COVID-19	Active mobility and COVID-19	COVID-19 and the environment flip side
Abdullah et al., 2020	Malaysia															X
Acuto, 2020	Global	X						X								
Ahsan, 2020	Turkey							X		X						
Allam & Jones, 2020a	Global		X				X	X								
Aloi et al., 2020	Santander										X	X				
Amit et al., 2021	Bangladesh				X											
Antunes, 2021	Global							X	X							
Astroza et al., 2020	Chile											X		X		
Awad-Núñez et al., 2021	Spain					X					X				X	
Badii et al., 2020	Florence											X				
Badr et al., 2020	USA	X										X				
Baldasano, 2020	Barcelona/Madrid															X
Barbarossa, 2020	Italy			X											X	
Bolay, 2006	Slums					X										
Borkowski et al., 2021	Poland										X	X				
Brinkley, 2020	Singapore		X				X									
Brooks et al., 2020	USA										X				X	
Büchel et al., 2022	United Kingdom														X	
Budd & Ison, 2020	Basel/Zurich					X					X				X	
Buehler & Pucher, 2021	Global										X				X	
Buehler and Pucher (2022)	Europe/USA		X	X							X	X			X	
Carozzi et al., 2020	USA										X		X			
Carrión et al., 2021	New York City									X						
Cartenì et al., 2020	Italy	X		X								X				
Cheng et al., 2021	Nanjing City						X		X							
Cheshmehzangi, 2021	Global									X					X	X
Corburn et al., 2020	Slums									X						
Dantas et al., 2020	Rio de Janeiro															X
De Vos, 2020	Global										X				X	
Desai, 2020	Global									X						
Dhilon, 2020	India					X					X					
Dong et al., 2021	China													X		
Eisenmann et al., 2021	Germany											X		X		
Eltarabily & Elgheznawy, 2020	Global		X				X									
Espejo et al., 2020	Global															X
Fatmi, 2020	British Columbia											X				
Füller, 2016	Hong Kong		X													

	Location	COVID-19 Timeline	Past pandemics, their impacts and timeline	COVID-19 impact on urban areas	COVID-19 consequences on mental health and safety perception	Spatial planning					Transport planning					
						General urban planning considerations	Lessons learned from the COVID-19 pandemic	Urban planning as a tool to fight the COVID-19 and future pandemics	Green areas as physical and mental safety nets during COVID-19 lockdown	The impact of density, compactness, and world connection on the spread of COVID-19	General urban transport considerations	Travel patterns under COVID-19 lockdown	The role of accessibility and proximity	Public transport and COVID-19	Active mobility and COVID-19	COVID-19 and the environment flip side
Fumagalli et al., 2021	Curitiba											X		X		
Gama et al., 2020	Portugal															X
Gargoum and Gargoum, 2021	Global	X		X							X	X				
Goetsch & Quiros, 2020	Global					X					X					
Guitíerrez et al., 2020	Global														X	
Hamidi et al., 2020	USA									X						
Harrington & Hadjiconstantinou, 2022	UK														X	
Hatef et al., 2020	USA									X						
Hays, 2005	New York		X													
Hong et al., 2020	Global									X						
Hörcher et al., 2021	Global											X		X		
Huet, 2020	Europe					X					X					
Ibert et al., 2022	Global			X			X									
Javid et al., 2020	Global	X		X												
Jenelius & Cebecauer, 2020	Sweden											X		X		
Klein, 2020	New York								X							
Koehl, 2020	Global													X	X	
Kraus & Koch, 2021	Europe														X	
Krecl et al., 2020	São Paulo															X
Krishna & Kummitha, 2020	Global			X												
Kumar et al., 2015	Global										X					
Lai et al., 2020	Global		X							X						
Lak et al., 2020	Global										X				X	
Laverty et al., 2020	UK										X				X	
Lian et al., 2020	Global															X
Lock, 2020	Australia														X	
Lui, 2020	China									X						
Mahato et al., 2020	India															X
Marques et al., 2021	Rio de Janeiro				X		X		X							
Martínez & Short, 2021	Global		X	X						X						
Mayer, 1999	Global					X										
Mazza et al., 2020	Italy				X											
Meyer & Elrahman, 2020	Global														X	
Molloy et al., 2020	Switzerland											X		X		
Mouratidis & Yiannakou, 2022	Greece												X			
Mouratidis, 2022	Norway									X			X			
Muhammad et al., 2020	Global															X
Musselwhite et al., 2020	Global	X		X						X					X	
Nakada and Urban, 2020	São Paulo															X
Nanisetti, 2020	India		X													

						Spatial planning					Transport planning					
	Location	COVID-19 Timeline	Past pandemics, their impacts and timeline	COVID-19 impact on urban areas	COVID-19 consequences on mental health and safety perception	General urban planning considerations	Lessons learned from the COVID-19 pandemic	Urban planning as a tool to fight the COVID-19 and future pandemics	Green areas as physical and mental safety nets during COVID-19 lockdown	The impact of density, compactness, and world connection on the spread of COVID-19	General urban transport considerations	Travel patterns under COVID-19 lockdown	The role of accessibility and proximity	Public transport and COVID-19	Active mobility and COVID-19	COVID-19 and the environment flip side
Nelson, 2020	Global					X					X				X	
Nikiforiadis et al., 2020	Thessaloniki														X	
Obongha and Ukam, 2020	Nigeria									X						
Osservatorio Audimob, 2020	Italy											X				
Paital, 2020	Global							X								
Parr et al., 2020	Global											X				
Patel, 2020	India									X						
Peng et al., 2020	Wuhan									X						
Poortinga, 2021	UK						X		X							
Przybylowski et al., 2021	Gdansk													X		
Ro, 2020	Global					X					X					
Rojas-Ruedas & Morales-Zamora, 2021	Global			X		X	X	X			X					X
Rubin et al., 2020	Global				X							X			X	
Salama, 2020	Global						X	X		X						
Samedi et al., 2021	Global South				X									X		
Sasidharan et al., 2020	London															X
Scorrano and Danielis, 2021	Trieste											X			X	
Setti et al., 2020	Bergamo															X
Shabbir & Ahmad, 2010	Pakistan										X					
Shaer et al., 2021	Shiraz					X					X					
Sharifi & Khavarian-Garmsir, 2020	India												X			X
Sharma et al., 2020	Global										X					X
Singh et al., 2020	Global				X						X	X		X	X	
Slater et al., 2020	Global						X	X	X							
Sui & Prapavessis, 2020	Canada					X					X					
Teixeira & Lopes, 2020	New York															
Teixeira et al., 2021	Lisbon											X		X	X	
Tešić & Lukić, 2020	Global			X			X	X								
Thomas et al., 2021	New Zealand													X		
Thombre & Agarwal, 2021	India											X		X		
Tirachini & Cats, 2020	Global											X		X		
Tomikawa et al., 2021	Tokyo				X											
Ugolini et al., 2020	Europe						X					X				
UN, 2018	Global					X										
Valenzuela-Levi et al., 2021	Santiago Chile											X				
Venter et al., 2021	Norway				X				X							
Waka Kotahi NZ Transport Agency, 2020	New Zealand													X		

						Spatial planning					Transport planning					
	Location	COVID-19 Timeline	Past pandemics, their impacts and timeline	COVID-19 impact on urban areas	COVID-19 consequences on mental health and safety perception	General urban planning considerations	Lessons learned from the COVID-19 pandemic	Urban planning as a tool to fight the COVID-19 and future pandemics	Green areas as physical and mental safety nets during COVID-19 lockdown	The impact of density, compactness, and world connection on the spread of COVID-19	General urban transport considerations	Travel patterns under COVID-19 lockdown	The role of accessibility and proximity	Public transport and COVID-19	Active mobility and COVID-19	COVID-19 and the environment flip side
WHO, 2020	Global	X		X										X		
Wood, 2020	Global					X					X					
Xie et al., 2020	Chengdu						X	X	X			X				
Xu et al., 2020	China															X
Zhang & Zhang, 2021	Global											X			X	
TOTAL	-----	7	9	12	8	14	13	10	8	17	25	26	4	17	25	17

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4. Benchmarking city layouts – A methodological approach and an accessibility comparison between a real city and the Garden City

4.1. Garden City living space calculation

Garden City living space per inhabitant was calculated as follows.

- Measure all the Garden City land plots areas allocated to residential buildings;

- To ensure space for a fluid and spacious movement, a gap between buildings was assumed, consisting of a 2 m strip for gardens, plus 4 m for a sidewalk and 2 m for a cycling lane. This area was removed from the land plot area of above, yielding the implantation area;

- After considering gap space, the area left on the residential land plots had associated floor area ratios of 1.3 and 1.8 (ratio of a building's total floor area to the area of the land plot upon which it is built), which are the two values stated in the municipal city plan of Coimbra for residential areas. Howard suggested the most central residential buildings to be more spacious, thus a ratio of 1.3 was assumed for these land plots. Residential buildings in the outward ring would be more compact and for these land plots a ratio of 1.8 was assumed;

- The total construction area for residential purposes on one Garden City is 2,145,825 m2, obtained by multiplying the implantation area by the corresponding floor area ratio. Considering the three Garden Cities and dividing by 104,643 inhabitants yields an average 61.5 m2 living space available per in habitant;

- For each land plot, multiplying its implantation area by area ratio and dividing by 61.5 yields the number of inhabitants in that land plot, which ranges from 27 in the inner rings to 43 in the outer rings.

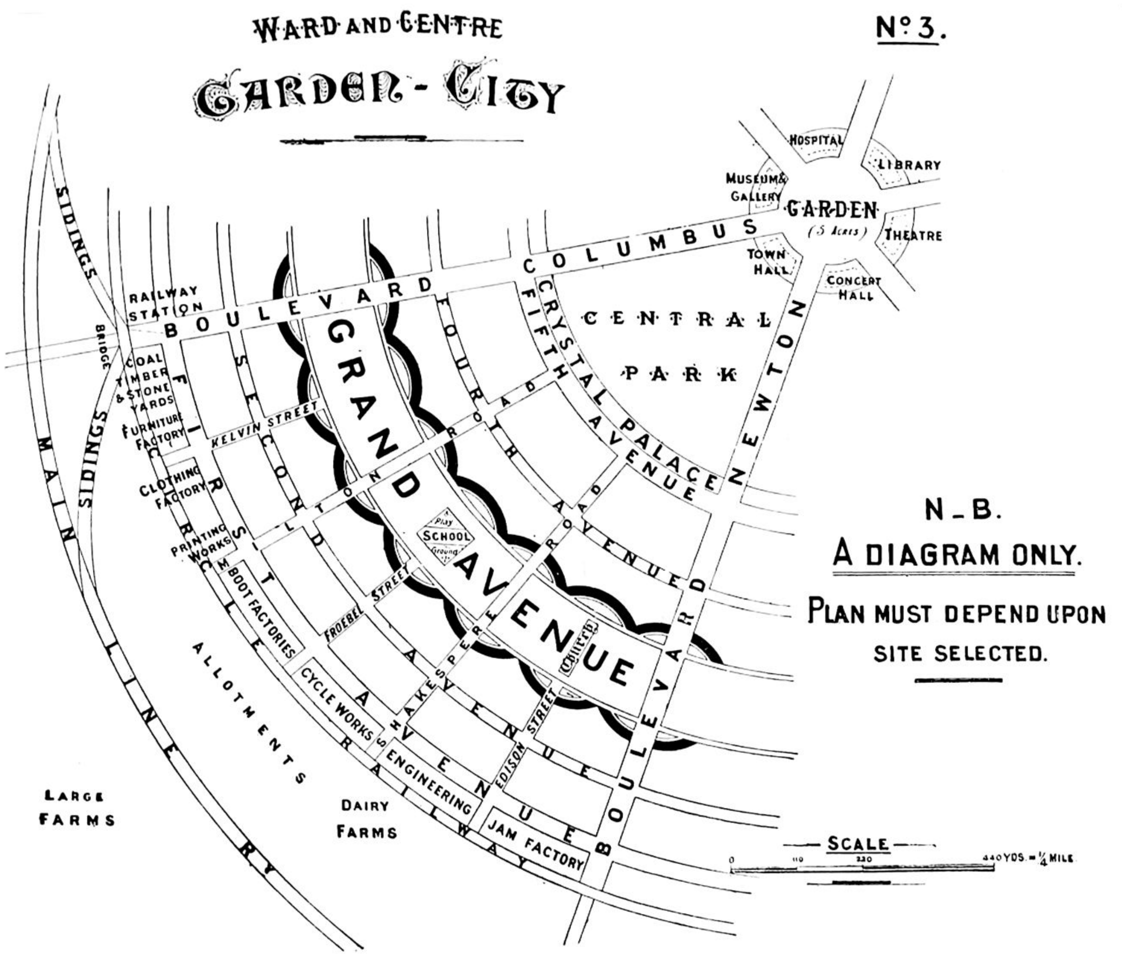


Figure II.4.1 – (a) Layout of a Garden City ward [1].

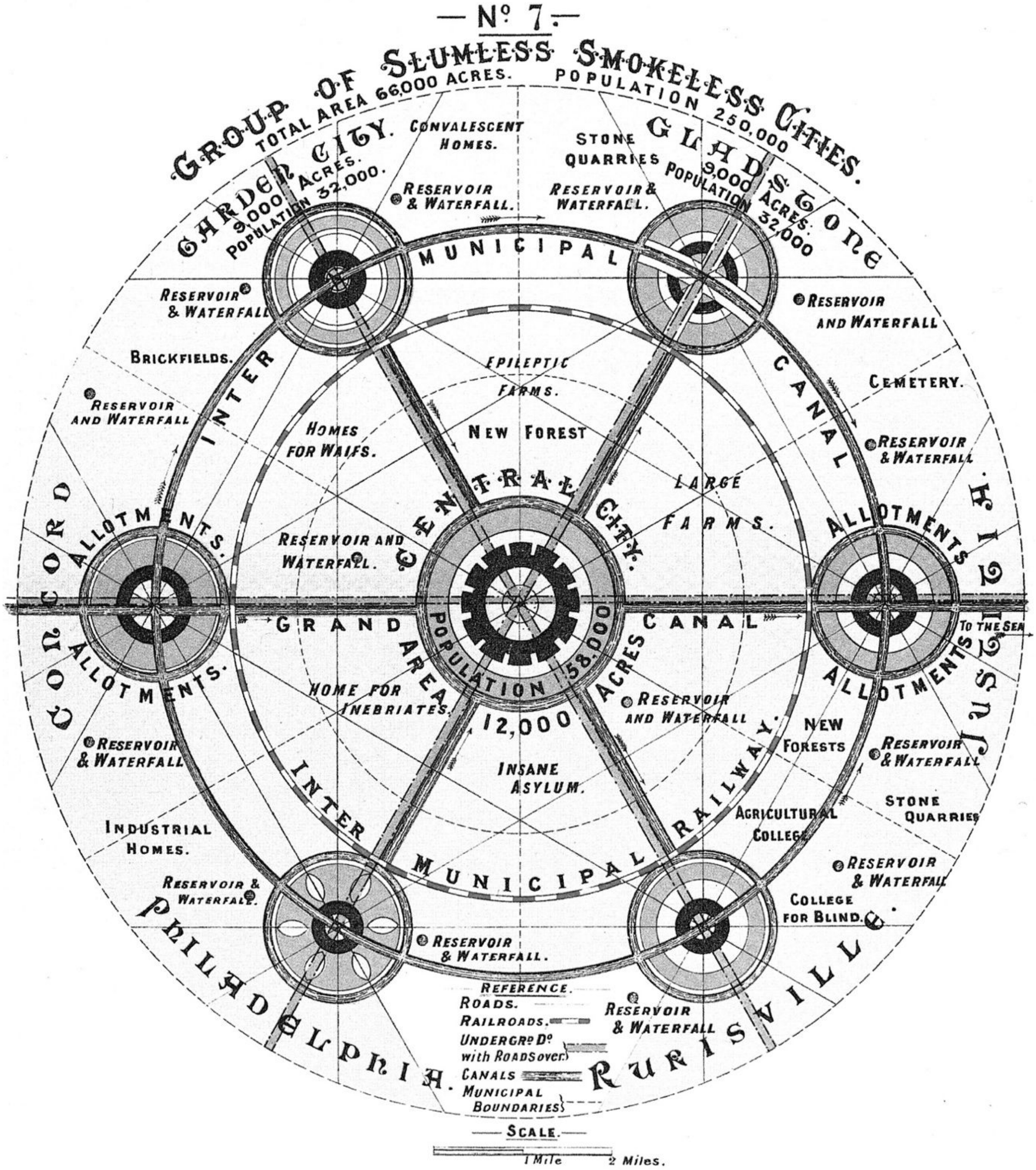
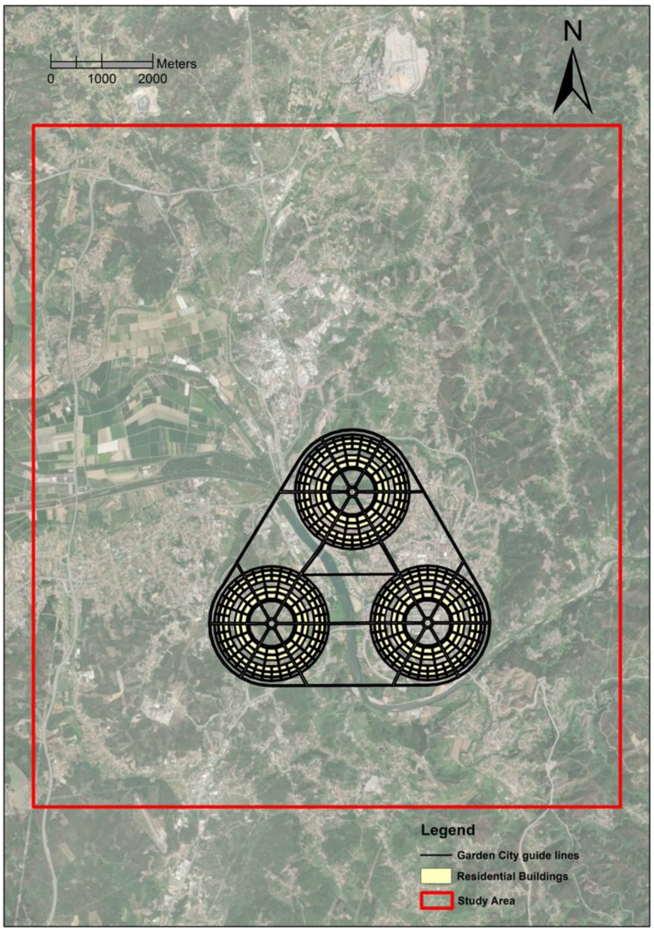


Figure II.4.1 (continuation) – (b) Social City [1].

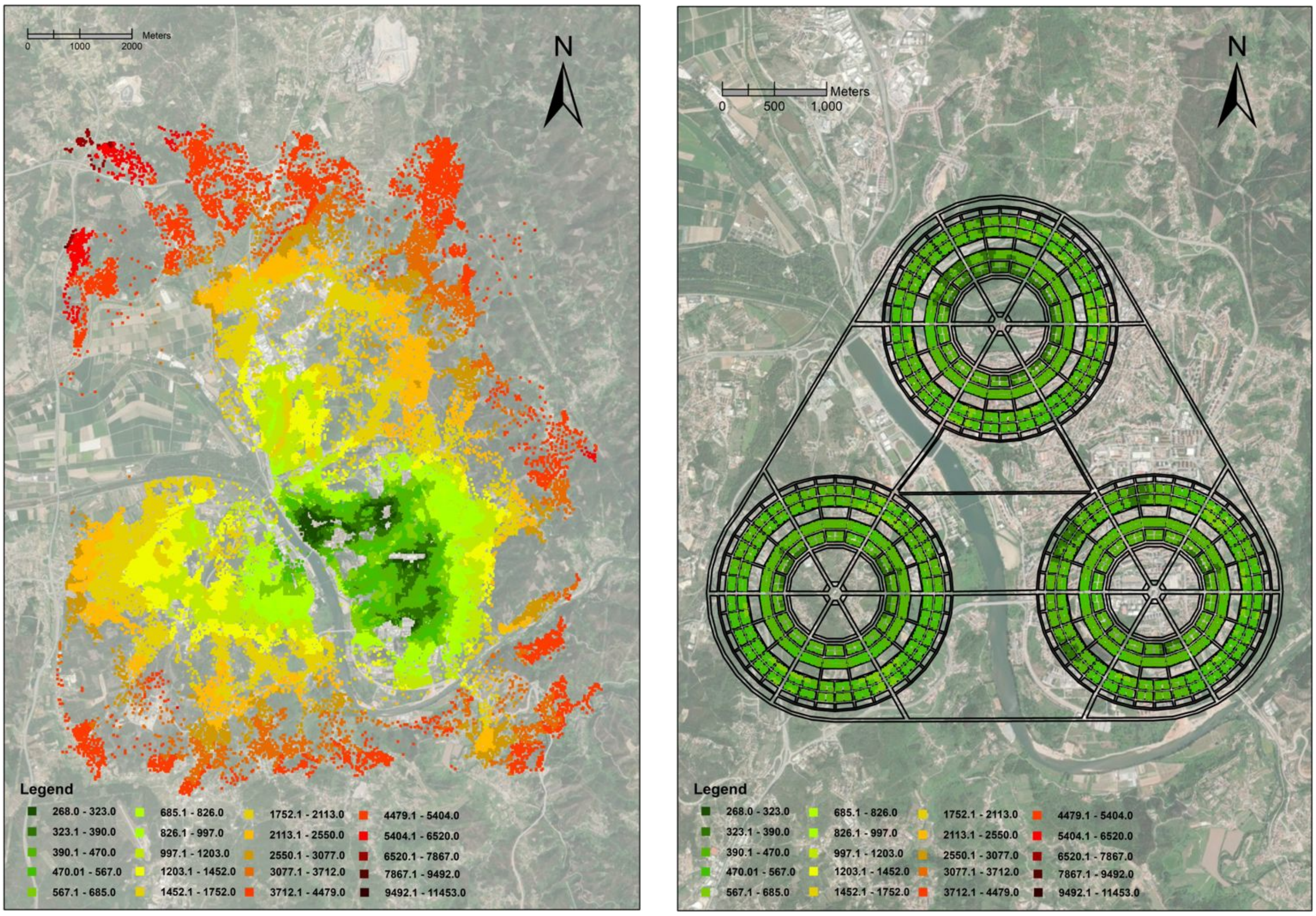
4.2. Supplemental maps

(**a**)



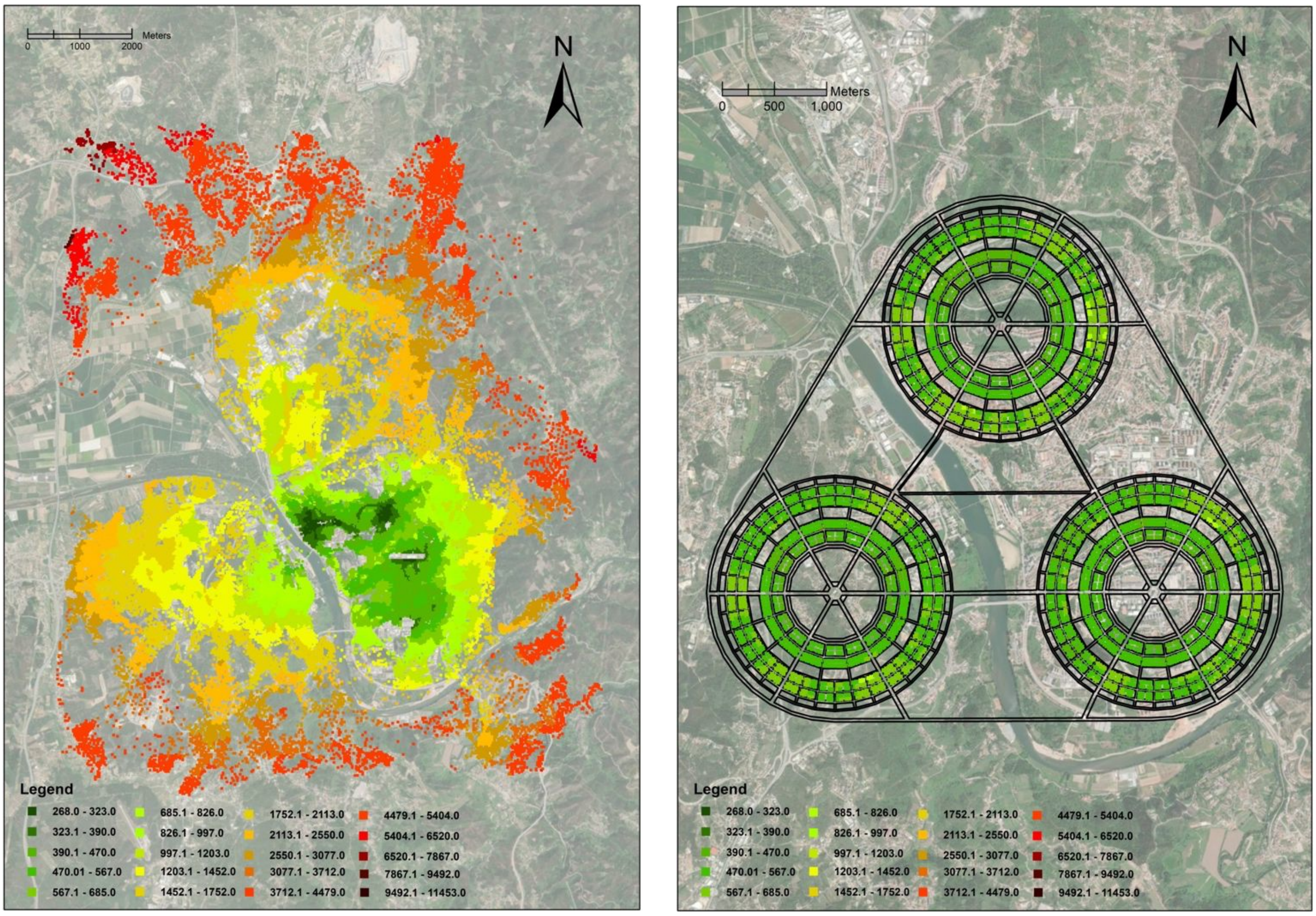
(**b**)

Figure II.4.2. Comparison in size between the city of Coimbra (**a**), and Coimbra as Garden City (**b**).



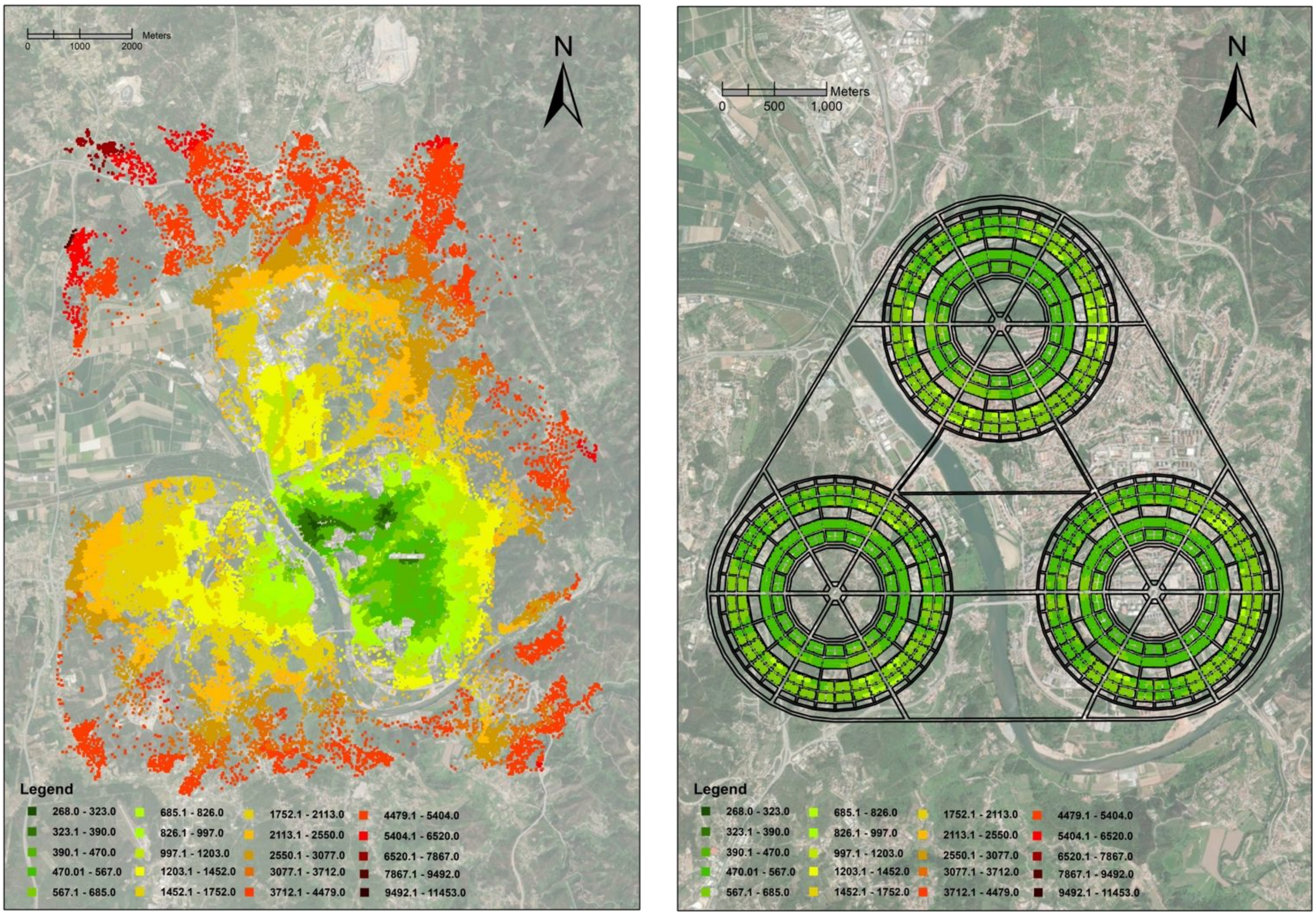
(**a**) (**b**)

Figure II.4.3. Accessibility to urban facilities for $L_k(j_3)$ 100/0/0, Coimbra (**a**), and Coimbra as Garden City (**b**).



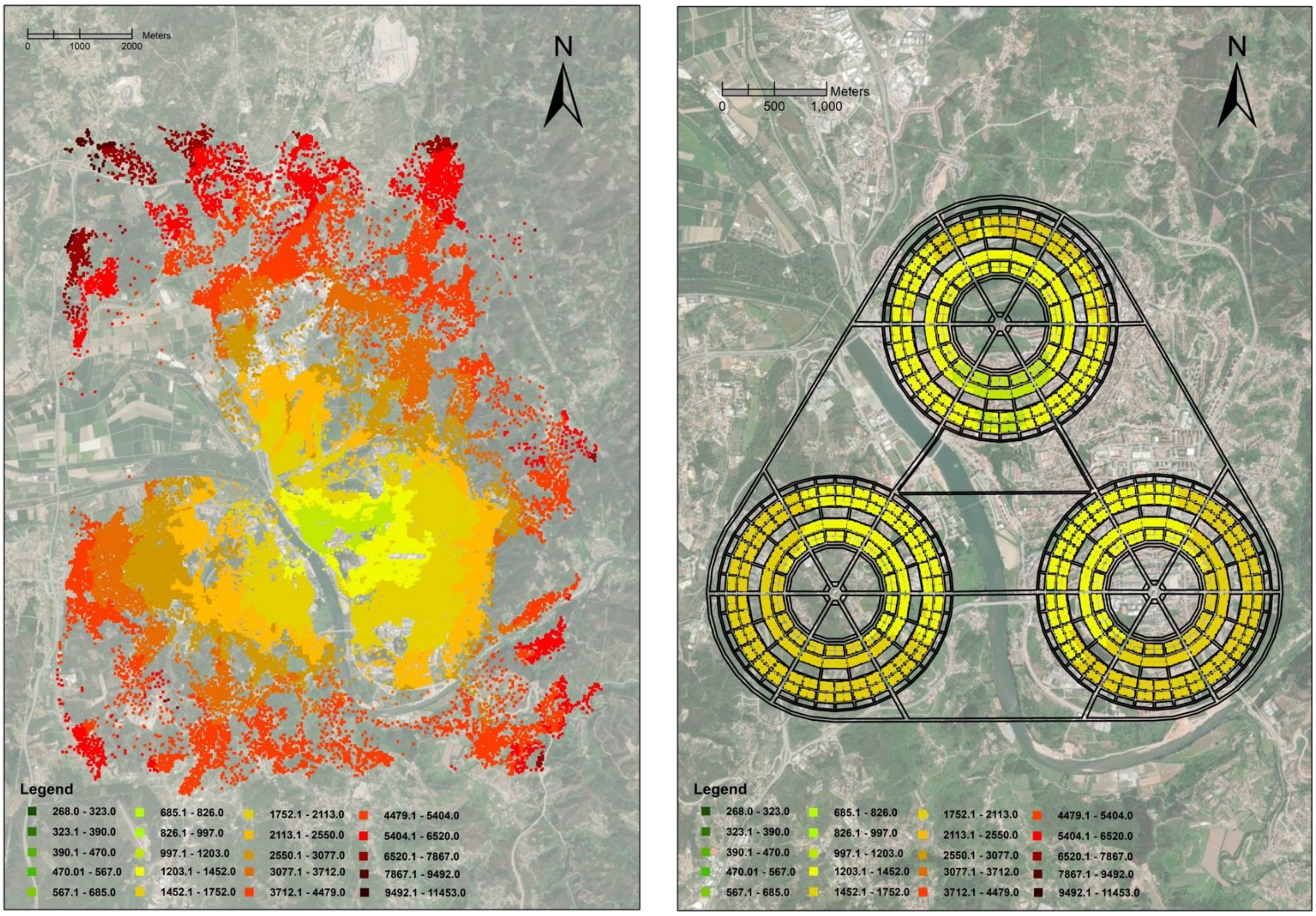
(**a**) (**b**)

Figure II.4.4. Accessibility to urban facilities for $L_k(j_3)$ 70/20/10, Coimbra (**a**), and Coimbra as Garden City (**b**).



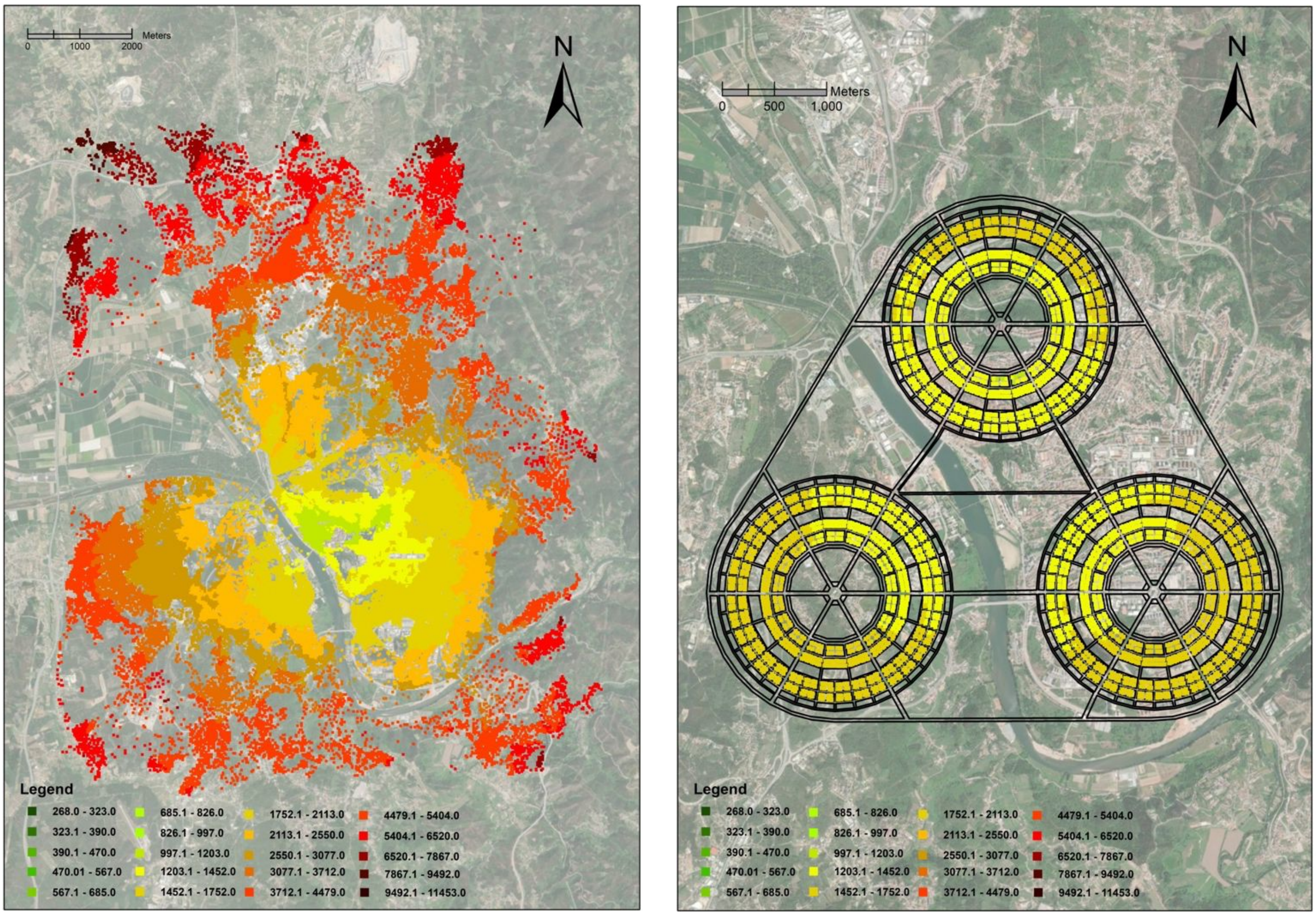
(**a**) (**b**)

Figure II.4.5. Accessibility to urban facilities for $L_k(j_3)$ 50/35/15, Coimbra (**a**), and Coimbra as Garden City (**b**).



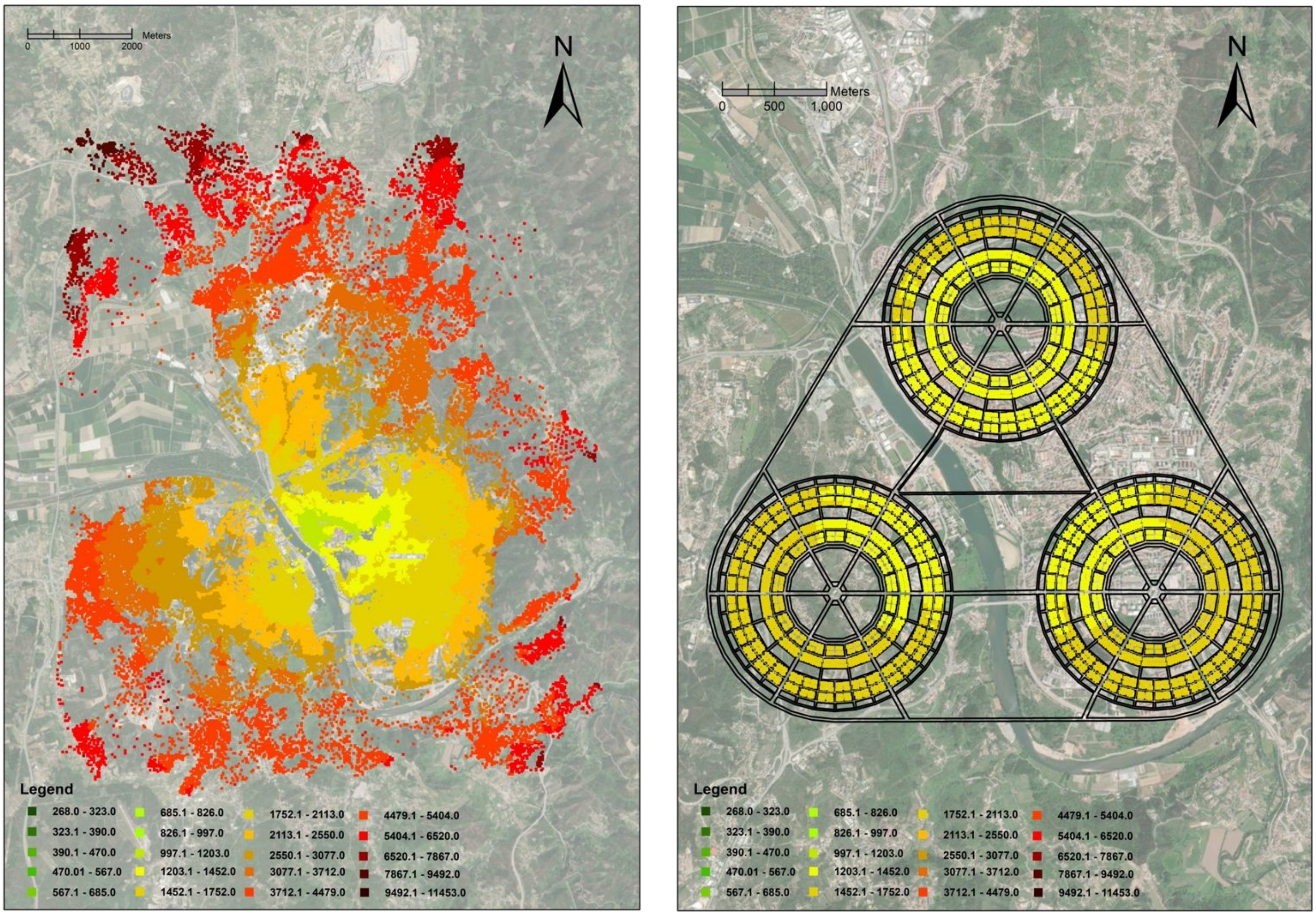
(**a**) (**b**)

Figure II.4.6. Overall accessibility for $L_k(j_3)$ 100/0/0, Coimbra (**a**), and Coimbra as Garden City (**b**).



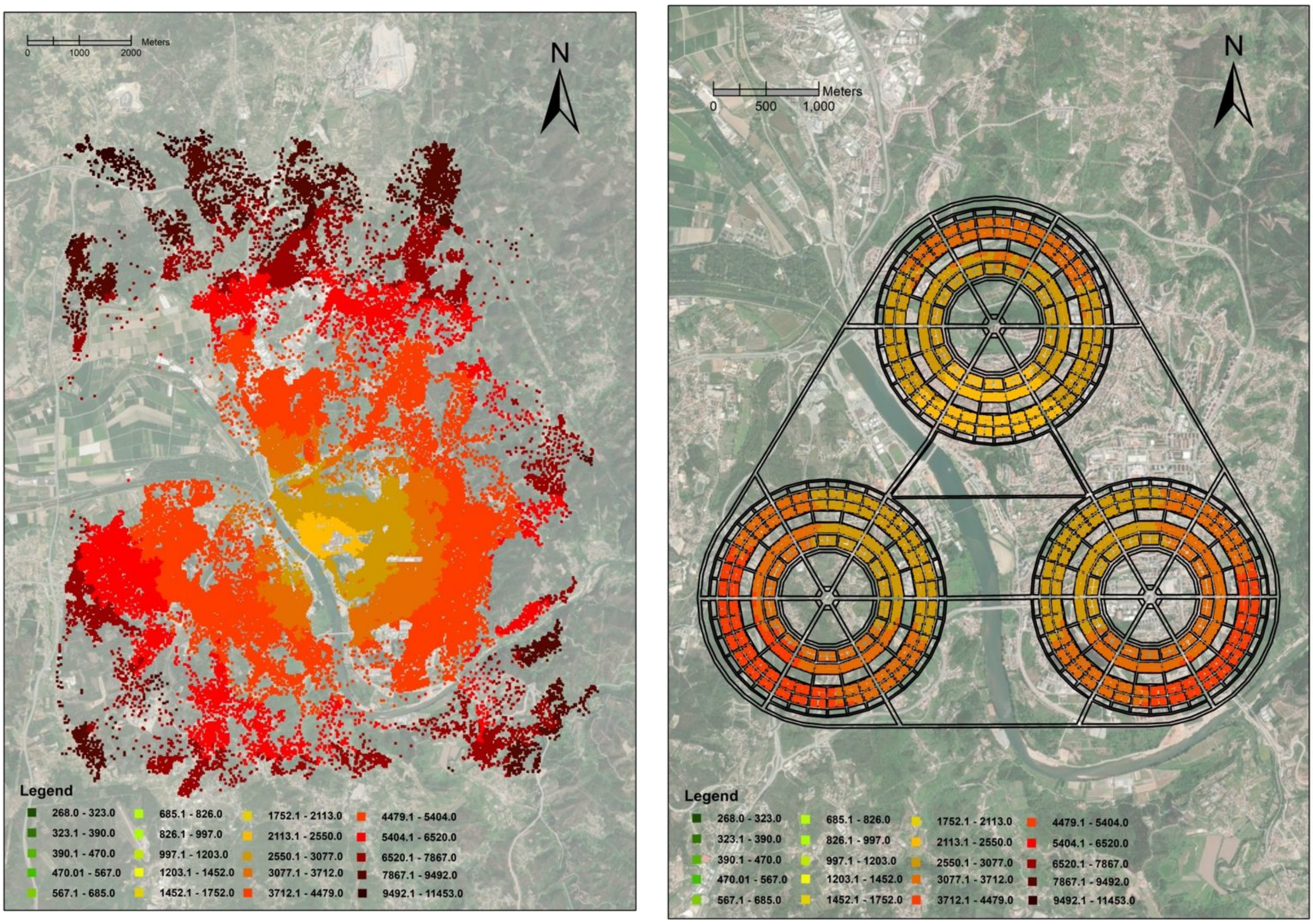
(**a**) (**b**)

Figure II.4.7. Overall accessibility for $L_k(j_3)$ 70/20/10, Coimbra (**a**), and Coimbra as Garden City (**b**).



(**a**) (**b**)

Figure II.4.8. Overall accessibility for $L_k(j_3)$ 50/35/15, Coimbra (**a**), and Coimbra as Garden City (**b**).



(**a**) (**b**)

Figure II.4.9. Job accessibility; Coimbra (**a**), and Coimbra as Garden City (**b**).

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5. THE POTENTIAL IMPACT OF CYCLING ON URBAN TRANSPORT ENERGY AND MODAL SHARE: A GIS-BASED METHODOLOGY

5.1. Sensitive analysis on L_{kj} and job data statistics

Table II.5.1. Active modal share summarizing statistics.

Active modal share per inhabitant (%)		Urban facilities		Urban facilities and jobs	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	3.3	0.5	3.5	0.4
	Max	94.3	71.8	73.7	48.0
	Average	45.8	18.6	35.6	12.7
	Average per inhabitant	55.3	24.7	42.6	16.8
	Standard deviation	24.9	15.9	18.7	10.6
	Coef. of variation	0.54	0.9	0.52	0.87
50/35/15	Min	92.9	69.6	73.2	46.7
	Max	3.2	0.4	3.4	0.4
	Average per inhabitant	53.9	23.5	41.7	16.0
	Average	44.5	17.6	34.8	12.1
	Standard deviation	24.5	15.3	18.5	10.2
	Coefficient of variation	55%	87%	55%	83%

Table II.5.2. Transport fossil energy spending summarizing statistics.

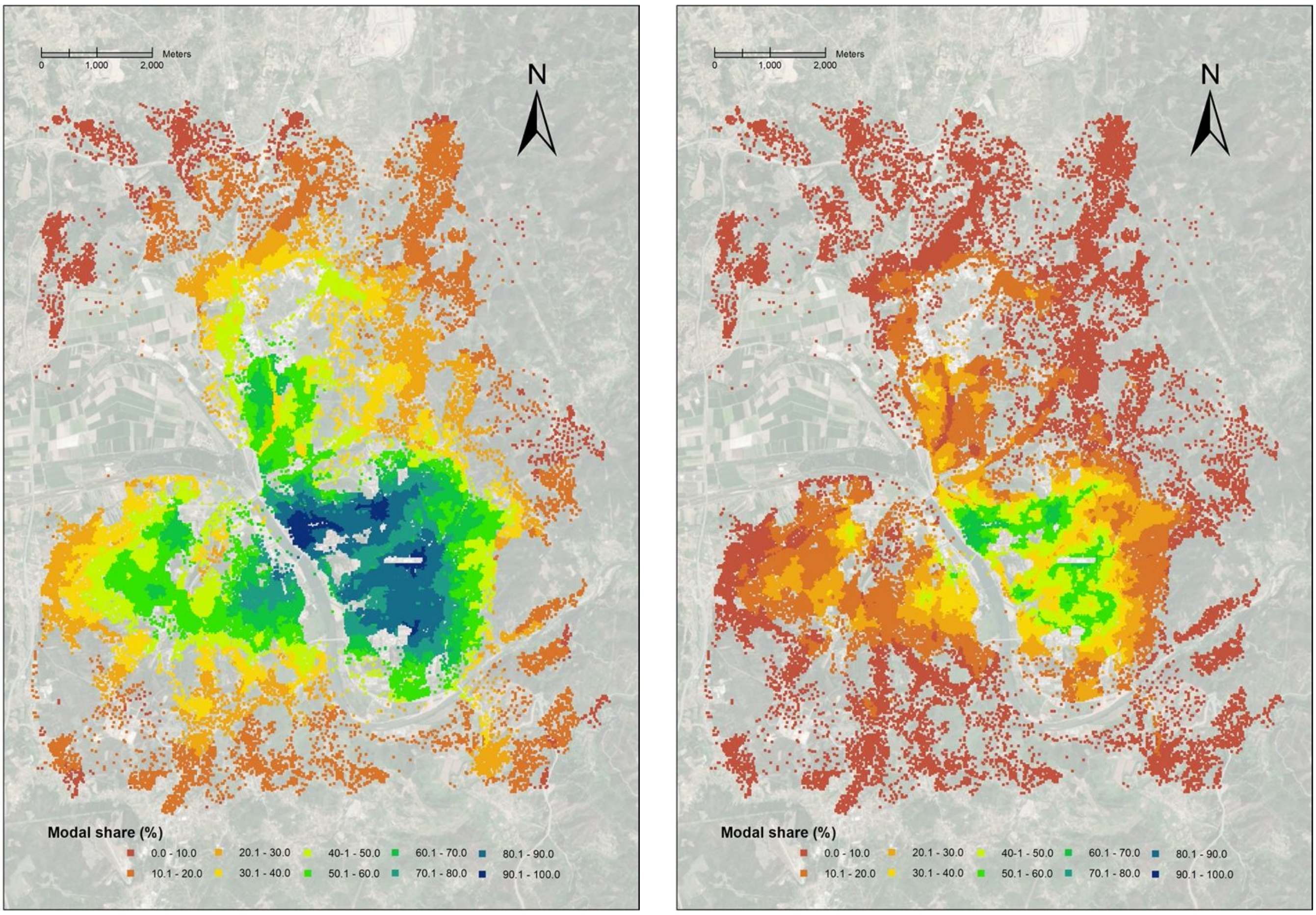
Transport fossil energy spending (MJ/passenger-trip)		Urban facilities		Urban facilities and jobs	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	0.19	0.69	3.29	5.32
	Max	35.37	36.34	46.16	47.59
	Average	6.70	8.18	13.54	15.88
	Average per inhabitant	4.53	5.90	10.69	13.01
	Standard deviation	6.17	6.21	7.97	7.69
	Coef. of variation	0.92	0.76	0.59	0.48
50/35/15	Min	0.24	0.85	3.34	5.38
	Max	35.85	36.89	46.47	47.94
	Average per inhabitant	4.75	6.16	10.82	13.17
	Average	6.97	8.48	13.71	16.08
	Standard deviation	6.27	6.31	7.94	7.75
	Coefficient of variation	90%	74%	58%	48%

Table II.5.3. Accessibility to jobs only summarizing statistics.

Accessibility to jobs only	Active modal share per inhabitant (%)		Transport fossil energy spending (MJ/passenger-trip)	
Measure	**full cycling**	**no cycling**	**full cycling**	**no cycling**
Min	3.8	0.4	8.55	13.21
Max	40.1	7.5	64.81	67.03
Average	18.0	2.7	25.39	29.2
Average per inhabitant	21.2	3.9	23.25	27.47
Standard deviation	8.7	1.6	11.15	10.55
Coef. of variation	48%	59%	44%	36%

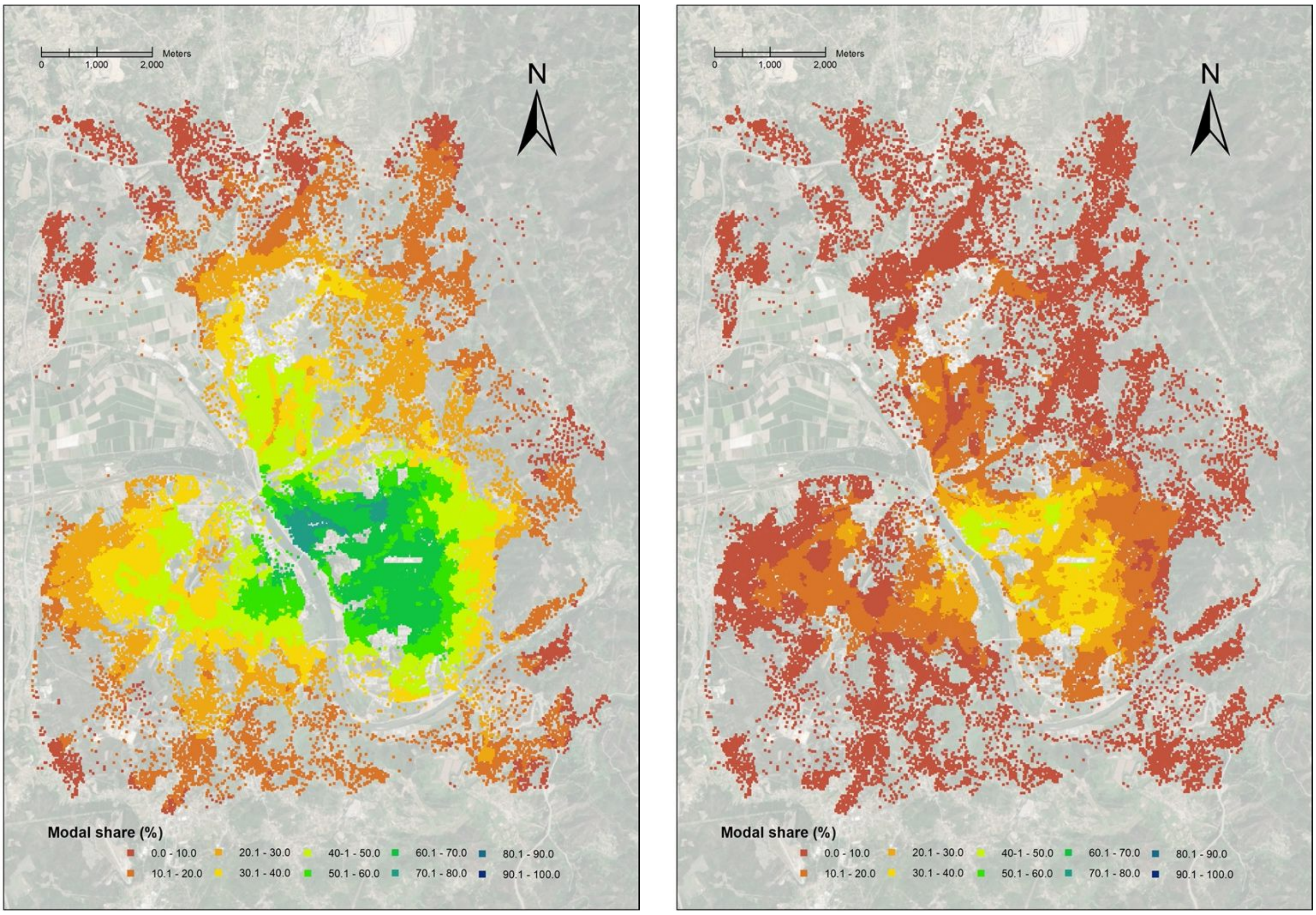
5.2. Full maps for L_{kj} = 70/20/10.

The maps below are full/no-cycling modal share and energy spending maps for three types of accessibility trips: urban facilities, facilities plus jobs, and jobs only. Differential maps between scenarios are also presented for the two indicators.



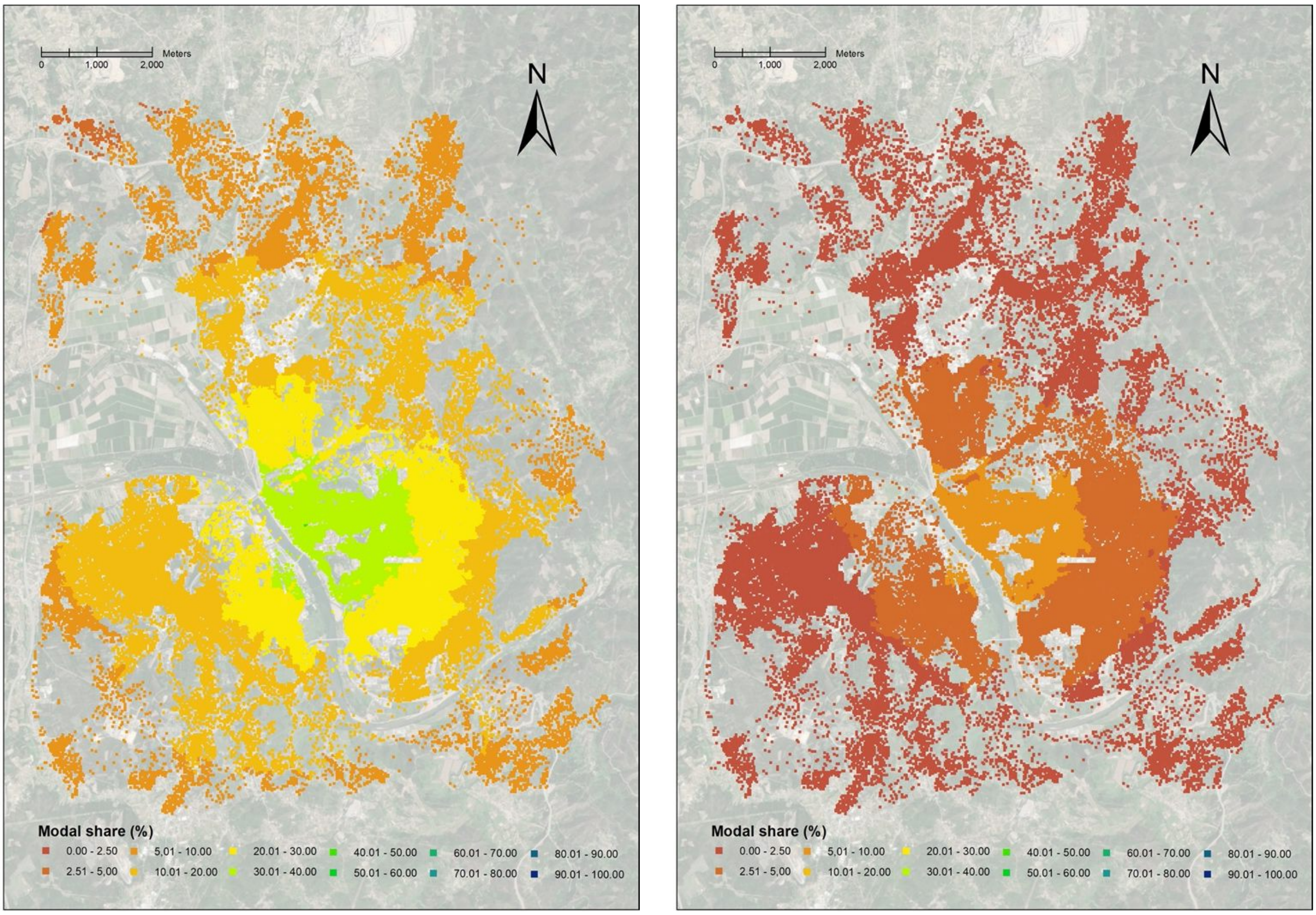
(**a**) (**b**)

Figure II.5.1. (a) Full cycling modal share to urban facilities; (b) No cycling modal share to urban facilities.



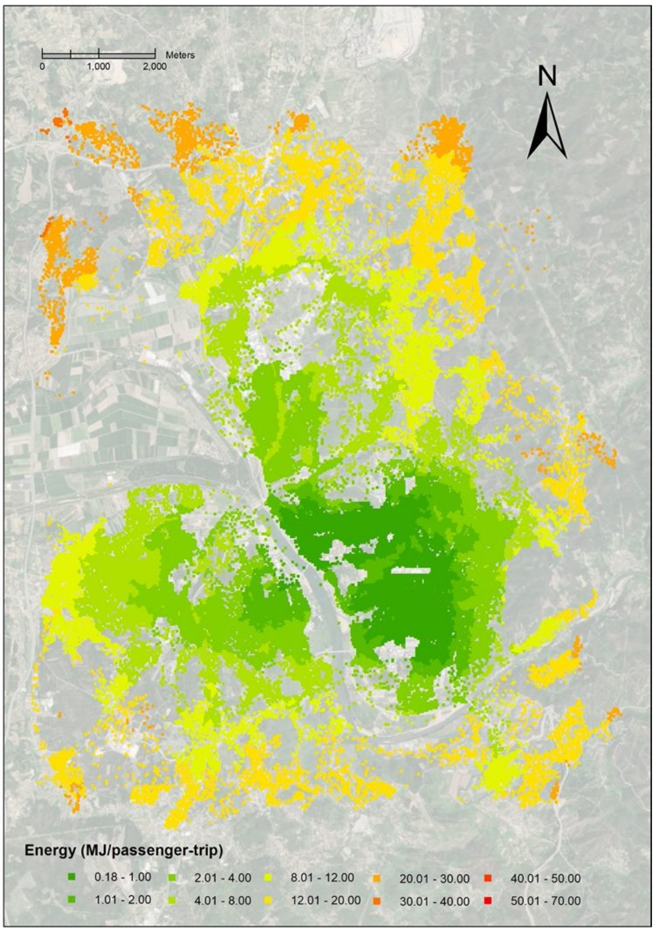
(**a**) (**b**)

Figure II.5.2. (a) Full cycling modal share to urban facilities plus jobs; (b) No cycling modal share to urban facilities plus jobs.

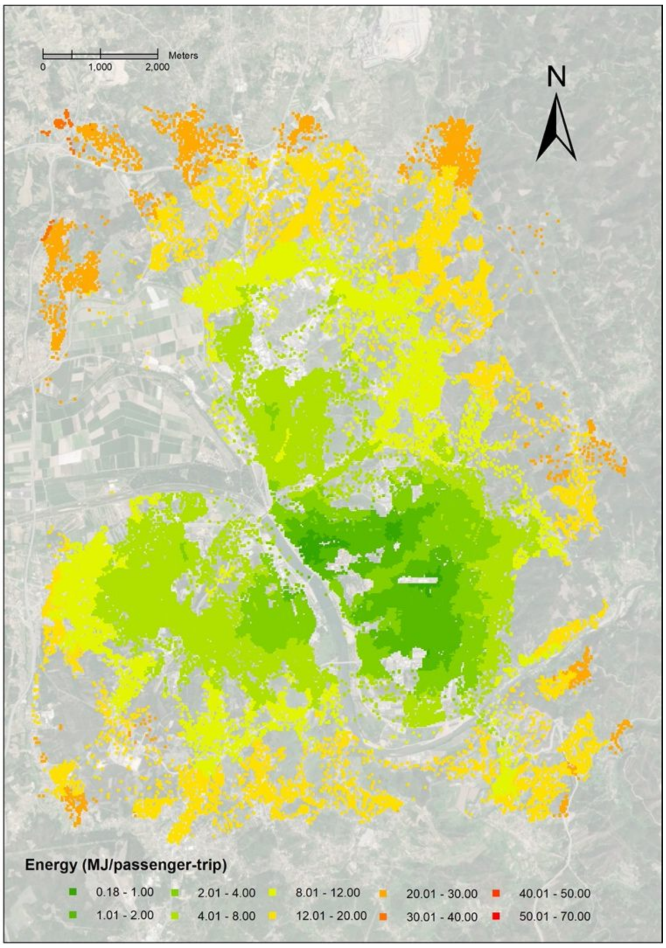


(**a**) (**b**)

Figure II.5.3. (a) Full cycling modal share to jobs; (b) No cycling modal share to jobs.

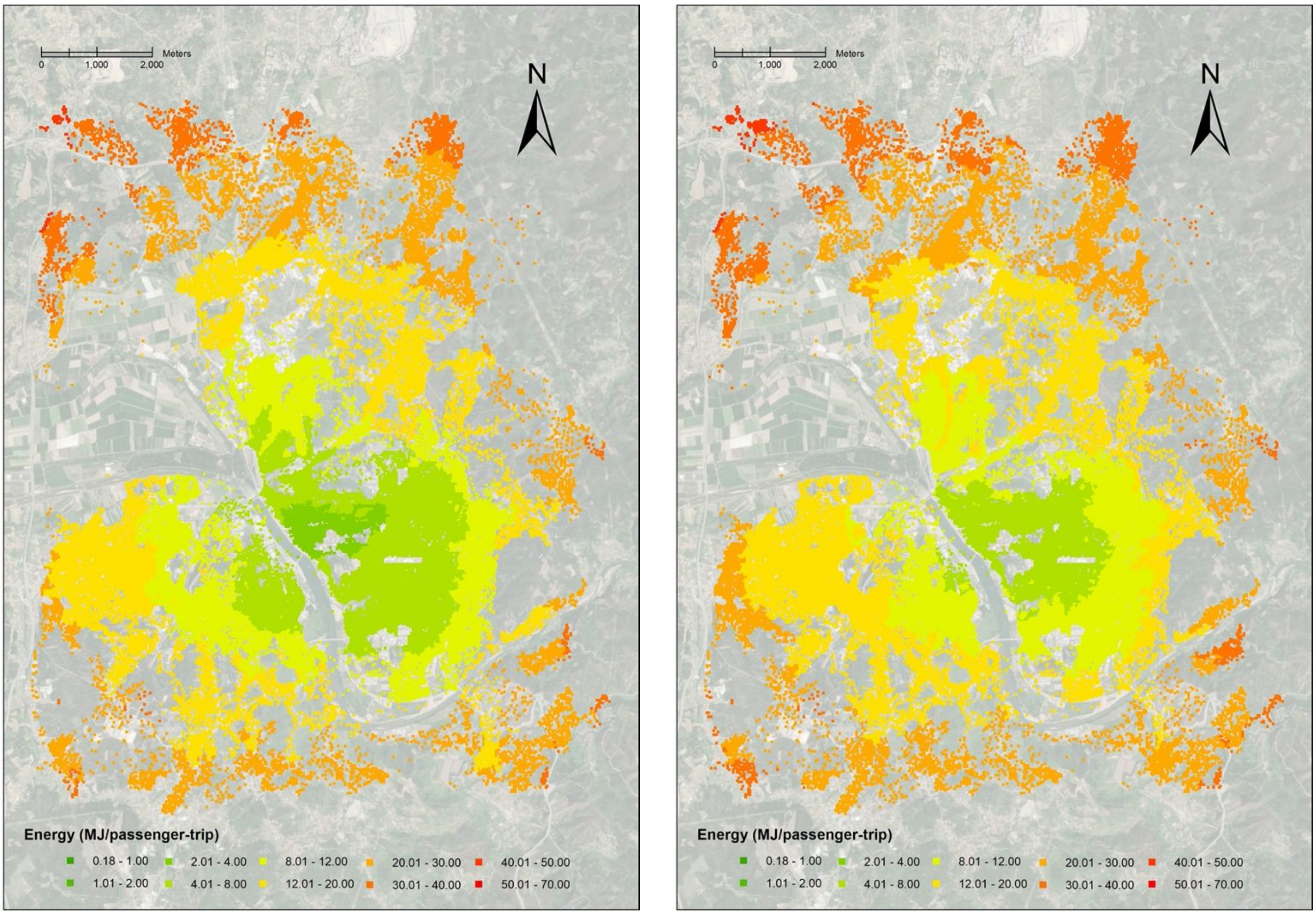


(a)



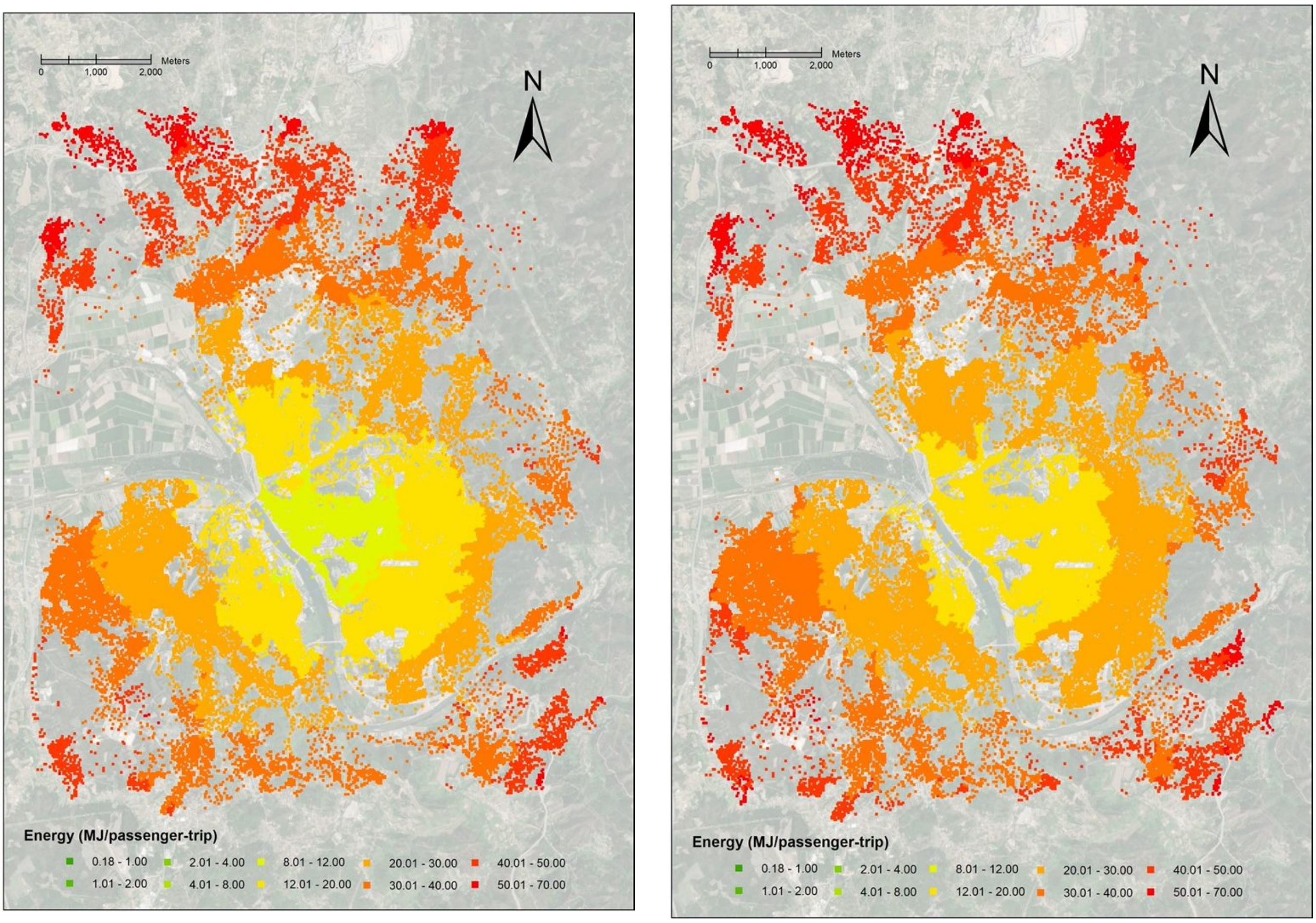
(b)

Figure II.5.4. (a) Full cycling fossil energy spending to urban facilities; (b) No cycling fossil energy spending to urban facilities.



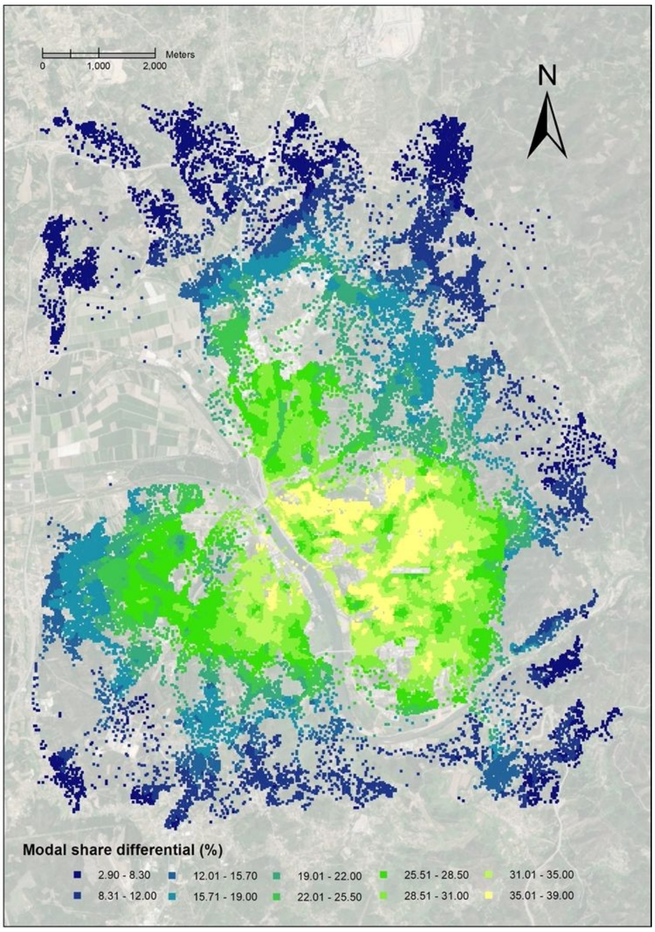
(**a**) (**b**)

Figure II.5.5. (a) Full cycling fossil energy spending to urban facilities plus jobs; (b) No cycling fossil energy spending to urban facilities plus jobs.

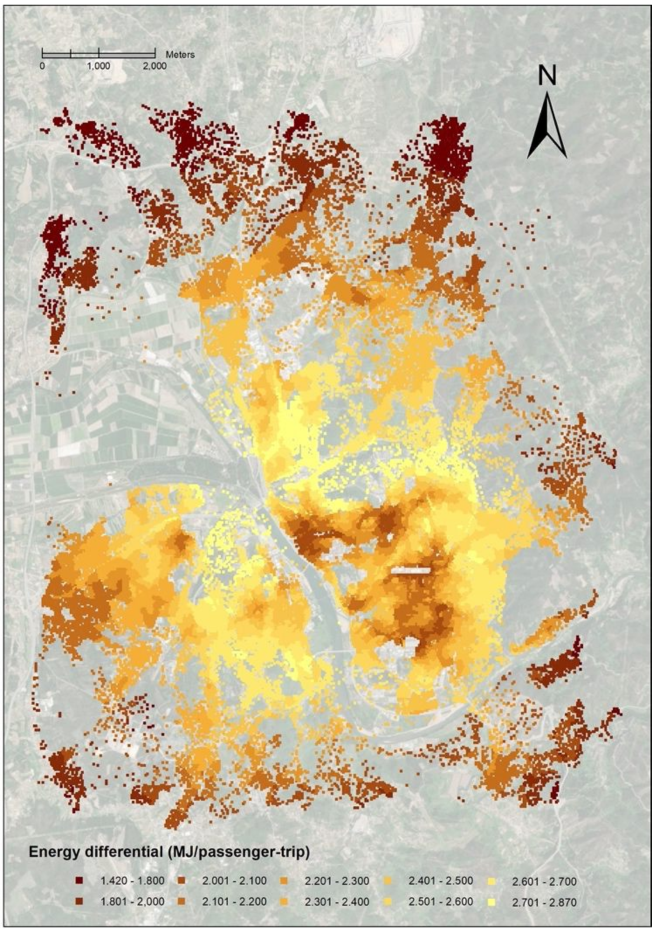


(**a**) (**b**)

Figure II.5.6. (a) Full cycling fossil energy spending to jobs; (b) No cycling fossil energy spending to jobs.



(**a**)



(**b**)

Figure II.5.7. (a) Full cycling/no cycling modal share differential to urban facilities plus jobs; (b) Full cycling/no cycling fossil energy spending differential to urban facilities plus jobs.

6. FILLING IN THE SPACES: COMPACTIFYING CITIES TOWARDS ACCESSIBILITY AND ACTIVE TRANSPORT

6.1. Evaluation of active travel probability

Evaluation of active travel probability from origin-to-destination (OD) follows the methodology of [2]. The discussion below summarizes the methodology and follows that reference closely. Based on the OD distance, a probability for carrying out the trip in active mode, i.e., either by walking or cycling, is calculated as follows.

First, trip probability for individual walking and cycling modes is modelled via a log-logistic distribution:

$$p(x) = \frac{1}{1 + \exp(a + b \ln x)} \qquad \text{(II.6.1)}$$

where a, b are parameters and x the network distance for the respective travel mode. Log-logistic parameter values depend on destination type and can be obtained indirectly from the negative exponential law for the walk mode of Yang and Diez-Roux [3] by calculating the distances for which the Yang and Diez-Roux law yields 10% and 90% walk probabilities, inserting these benchmarks in eq. (II.6.1), and solving for a, b for each destination type. This yields the parameters shown in Table II.6.1 below. Trip probabilities for the cycling mode are derived assuming that users typically spend a similar time buffer in cycling trips as in walking trips [4]. However, since the distance ridden by a bicycle is longer due to its higher speed, the effect on (II.6.1) is that, for cycling, the trip probability is given simply by changing the distance by $x \to x \cdot \frac{v_{\text{walk}}}{v_{\text{cycle}}}$. Using the walking speed of Tobler [5] and cycling speed of Parkin and Rotheram [6] yields a ratio of circa $\frac{v_{\text{walk}}}{v_{\text{cycle}}} \approx 0.233$.

The second step in obtaining an active trip probability requires combining walking and cycling probabilities into one single probability. This is done considering three distance regimes: short, long, and medium distances, defined respectively as distances for which walk probability < 50%, < 10%, and in-between [1]. For short distances one has the choice to either walk or use a bicycle and the active trip probability, p_{A}, can be modeled by $p_{\text{A}} = 1 - (1 - p_{\text{W}})(1 - p_{\text{C}})$, with p_{W} and p_{C} obtained applying eq. (II.6.1) for distances x and $0.233x$ respectively, as prescribed above. Extending this reasoning for all distances would lead to an excessively optimistic trip probability for long distances [4,7], so in that the simplifying assumption is made that all active trips are done cycling. Finally, trips in the medium range are modelled by a linear interpolation between the short and long-distance expressions. The mathematical expression for the unified active trip probability is given in eq. (II.6.2) below:

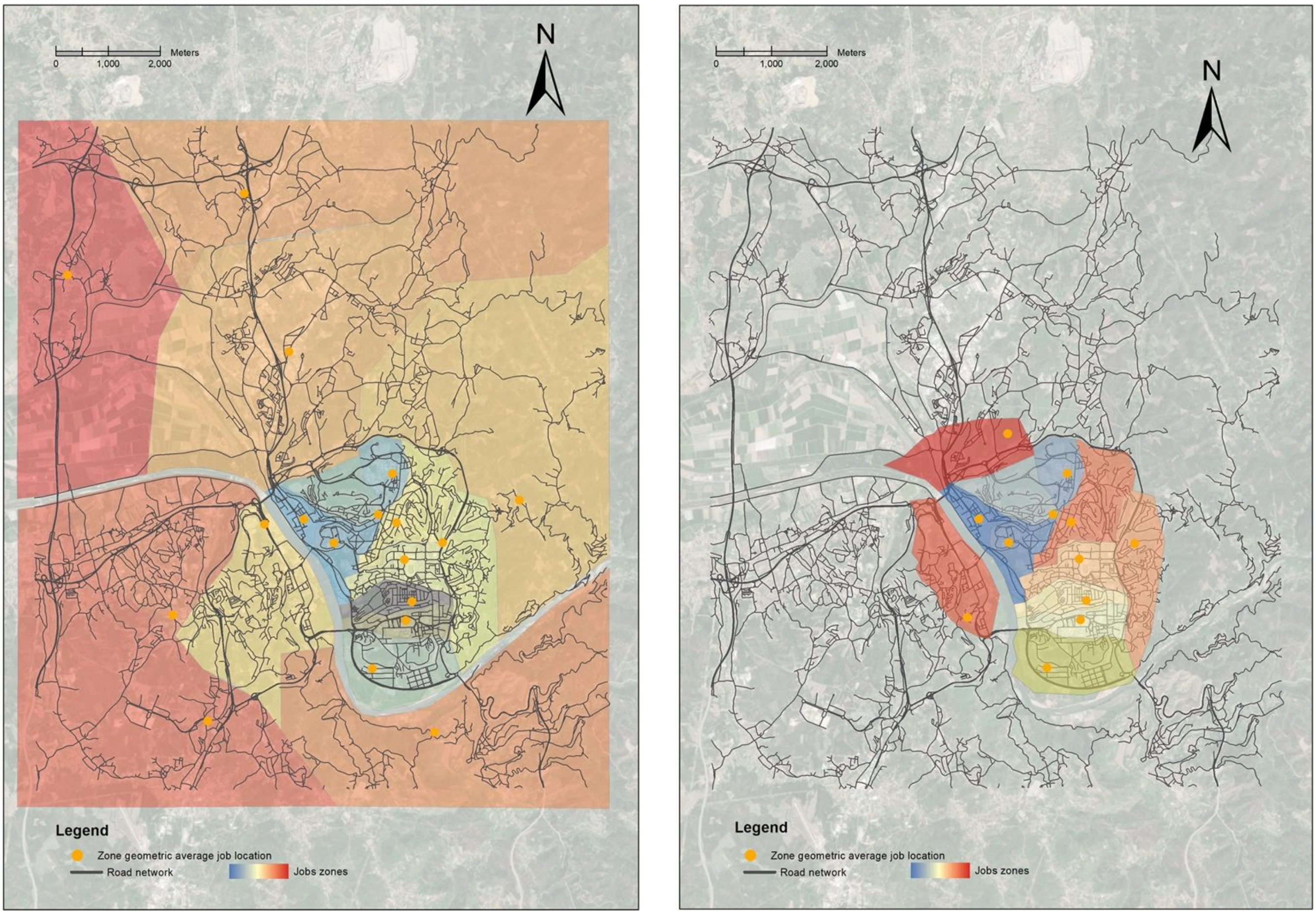
$$p_{\mathrm{A}}(x) = \begin{cases} 1-(1-p_{\mathrm{W}})(1-p_{\mathrm{C}}) & p_{\mathrm{W}} \geq 0.50 \\ p_{\mathrm{C}} + \dfrac{1-(1-p_{\mathrm{W}})(1-p_{\mathrm{C}})-p_{\mathrm{C}}}{0{,}5-0{,}1}(p_{\mathrm{W}}-0{,}1) & 0.10 \leq p_{\mathrm{W}} \leq 0.50 \\ p_{\mathrm{C}} & p_{\mathrm{W}} \leq 0.10 \end{cases} \quad \text{(II.6.2)}$$

Because p_{W} and p_{C} depend on destination type j, the active trip probability in the manuscript reads $p_{\mathrm{A}j}(x)$ to reflect this dependence. For further details and motivation, the reader is referred to [2].

Table II.6.1. Log-logistic parameters for walking.

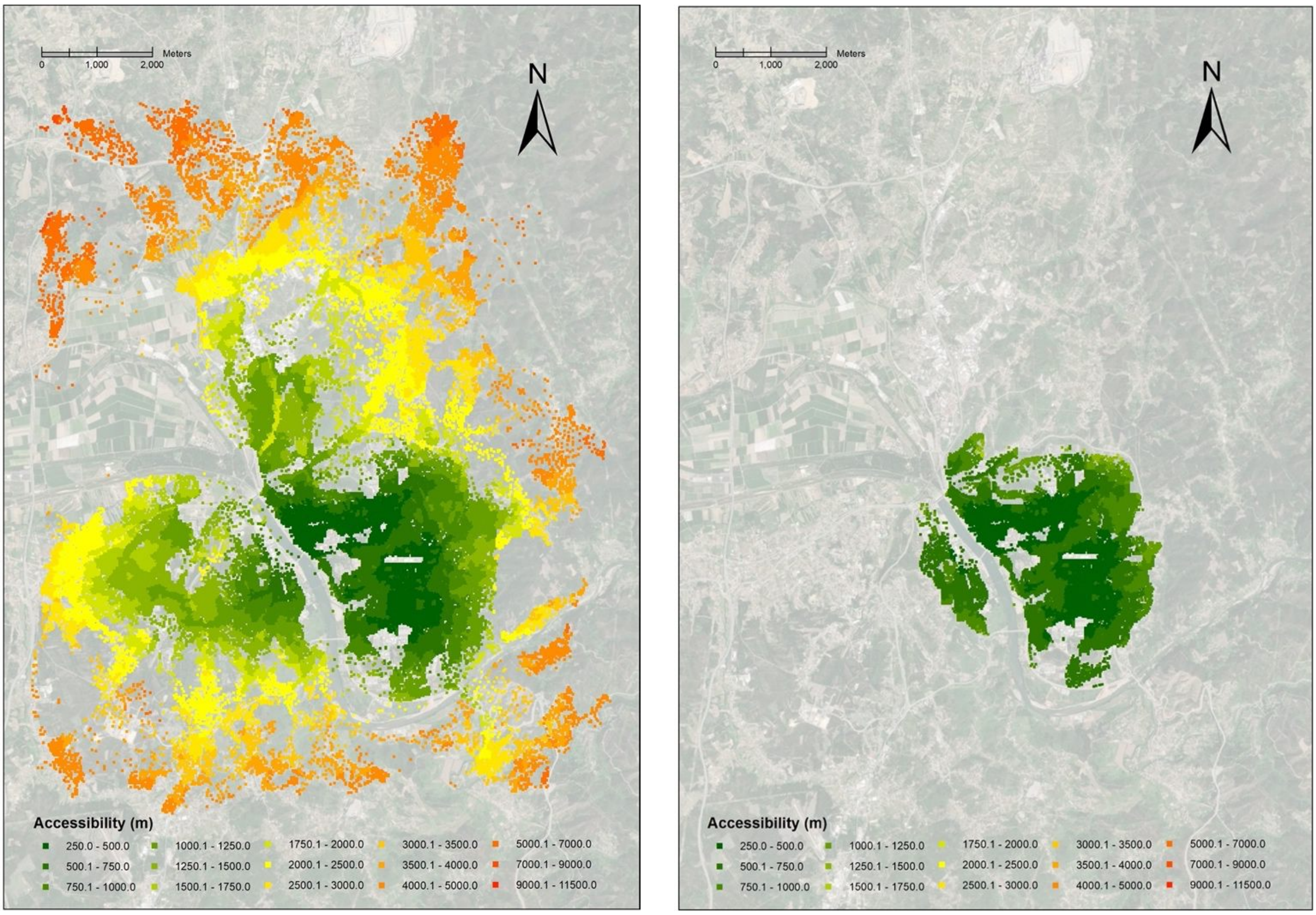
Destination type	a_j (distance: km)	b_j (distance: km)
Post offices	1.19225	1.83021
Sports facilities	0.05574	1.83013
Cultural organizations	1.00344	1.82990
Universities and institutes	1.07775	1.82989
Elderly care centres	1.19225	1.83021
Churches	1.00344	1.82990
High Schools	1.07775	1.82989
Shopping centres	1.19225	1.83021
Entertainment sites	1.00344	1.82990
Primary healthcare services	1.19225	1.83021
Pharmacies	1.19225	1.83021
Restaurants	1.46215	1.83009
Parks and green areas	1.00344	1.82990
Kindergartens	1.46215	1.83009
Primary schools	1.46215	1.83009
Middle Schools	1.46215	1.83009
Grocery stores	1.19225	1.83021
Supermarkets	1.19225	1.83021
Bakeries and pastries	1.46215	1.83009
Jobs	0.89627	1.83017

6.2. Maps



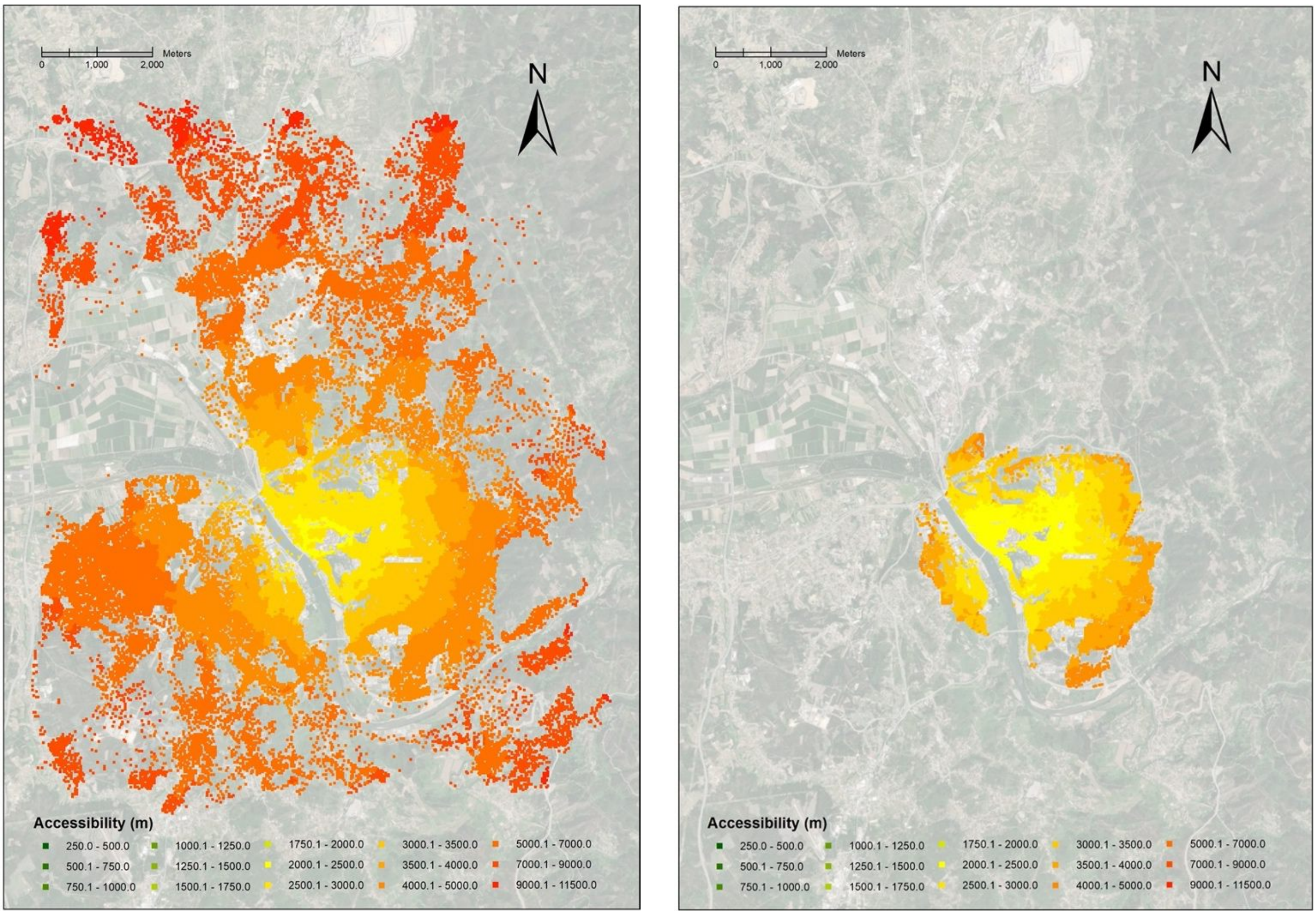
(**a**) (**b**)

Figure II.6.1. Job zones: (a) Coimbra; (b) Infill Coimbra.



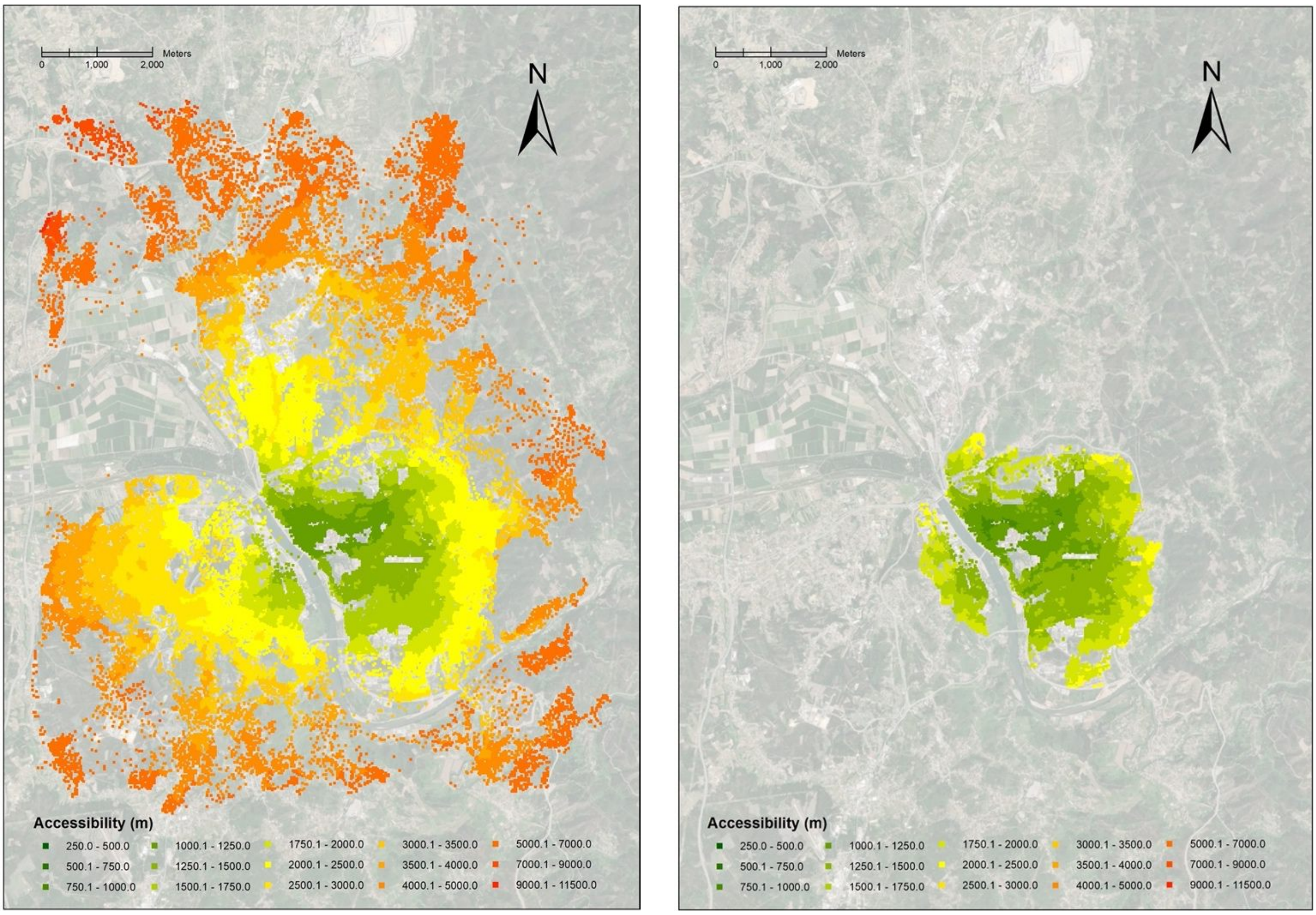
(**a**) (**b**)

Figure II.6.2. Accessibility to urban facilities (m): (a) Coimbra; (b) Infill Coimbra.



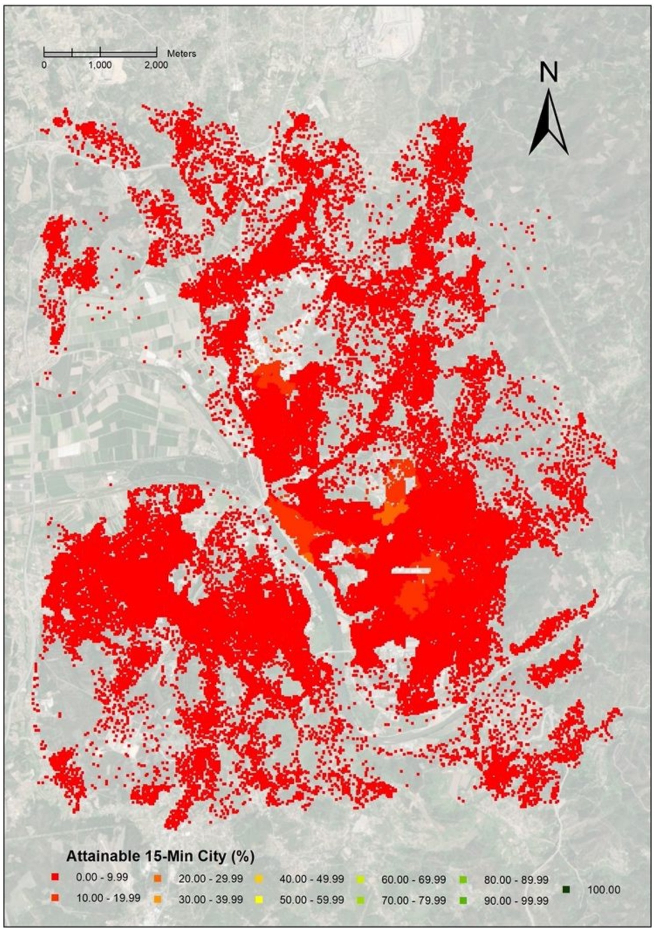
(**a**) (**b**)

Figure II.6.3. Accessibility to jobs (m): (a) Coimbra; (b) Infill Coimbra.



(**a**) (**b**)

Figure II.6.4. Total accessibility [facilities plus jobs] (m): (a) Coimbra; (b) Infill Coimbra.



(**a**)

(**b**)

Figure II.6.5. 15-Minute City by walking [jobs only] (%): (a) Coimbra; (b) Infill Coimbra.

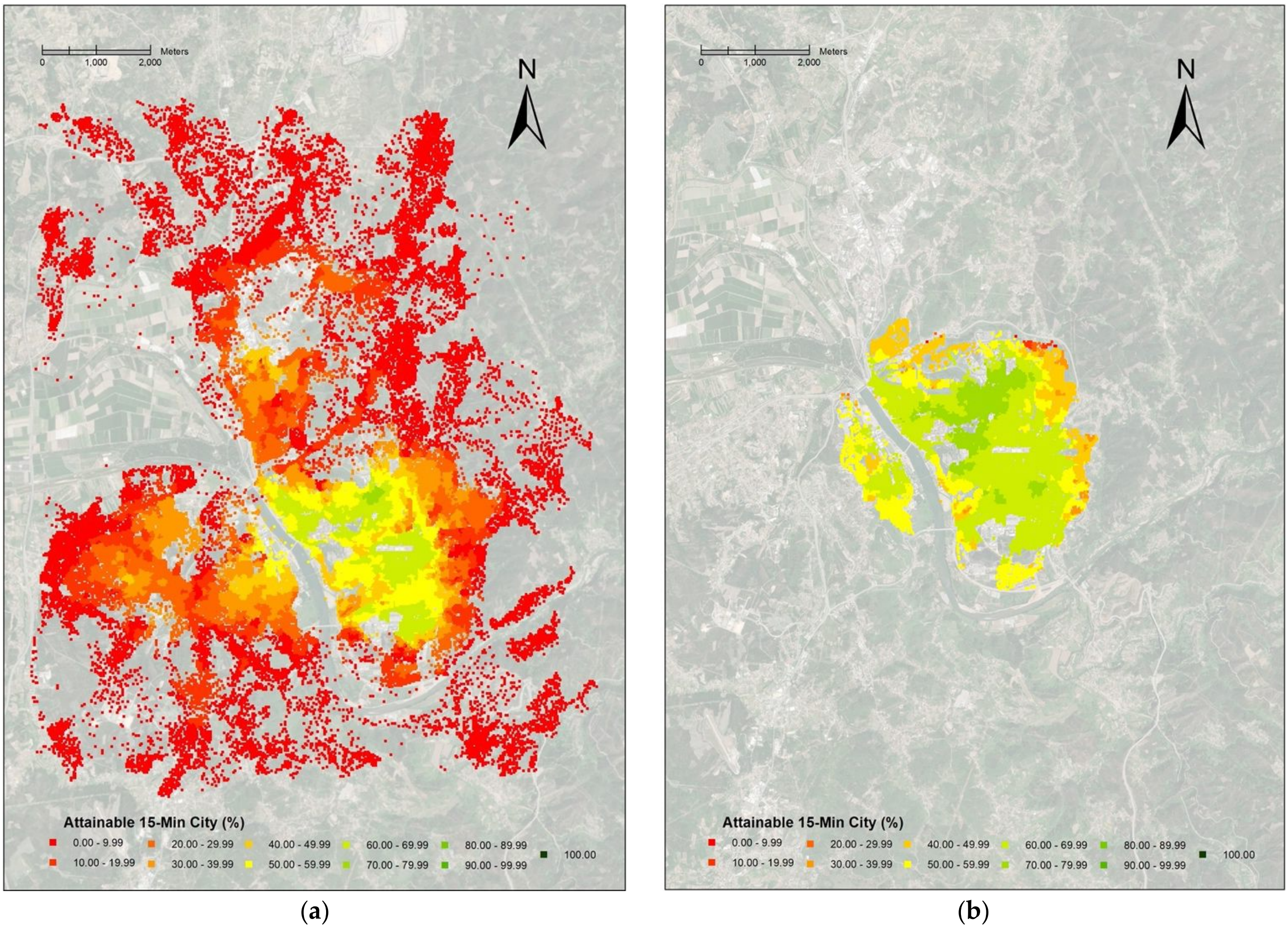
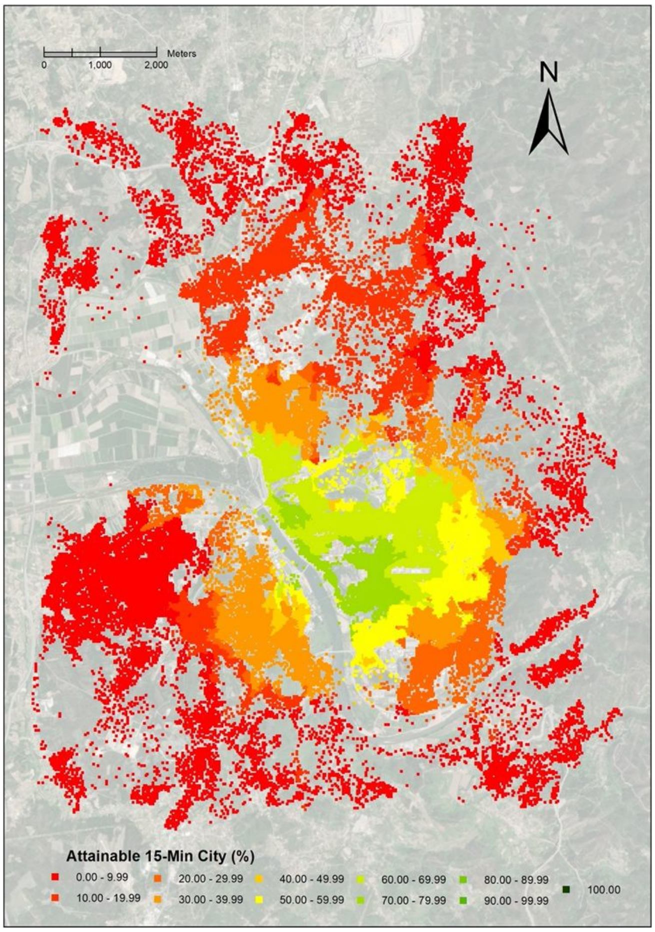
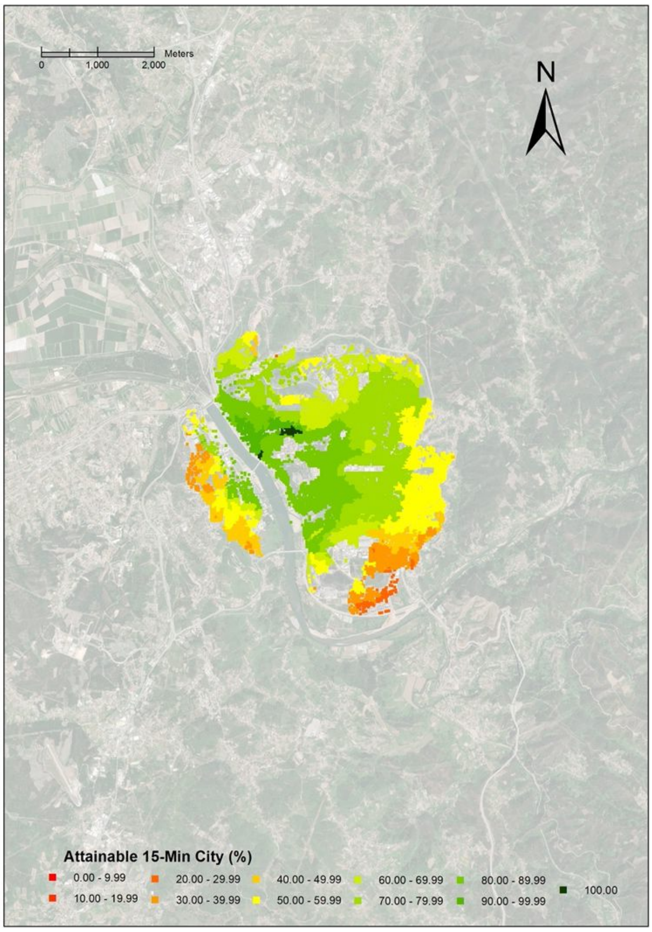


Figure II.6.6. 15-Minute City by walking [facilities plus jobs] (%): (a) Coimbra; (b) Infill Coimbra.

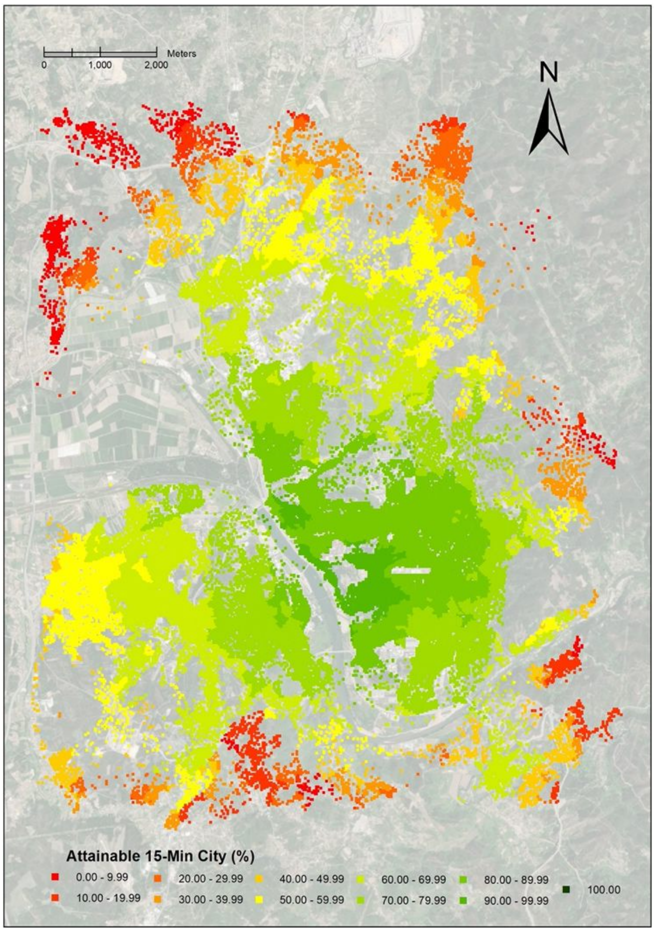


(**a**)



(**b**)

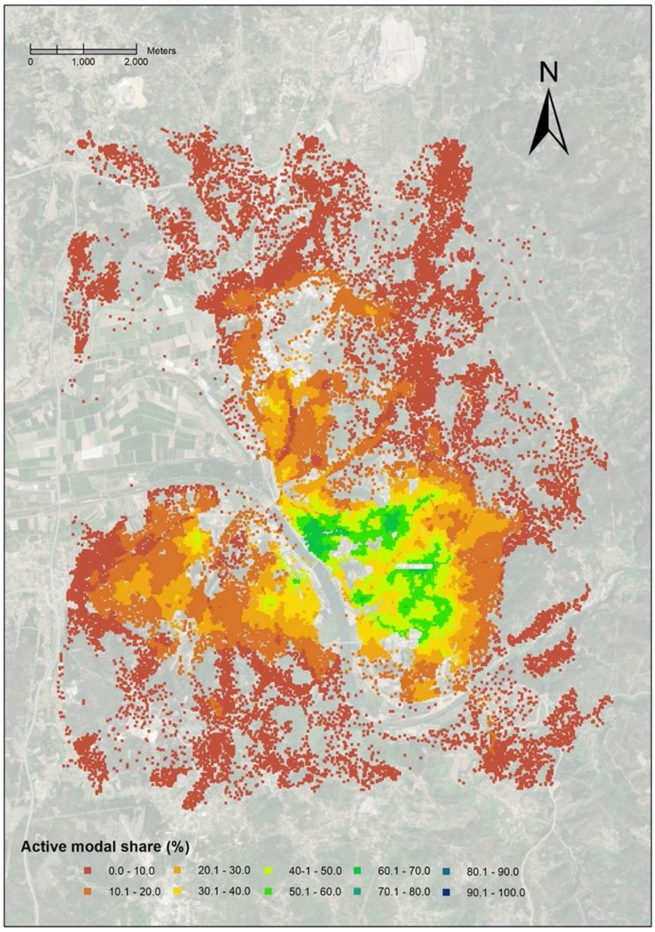
Figure II.6.7. 15-Minute City by active modes (walking/cycling) [jobs only] (%): (a) Coimbra; (b) Infill Coimbra.



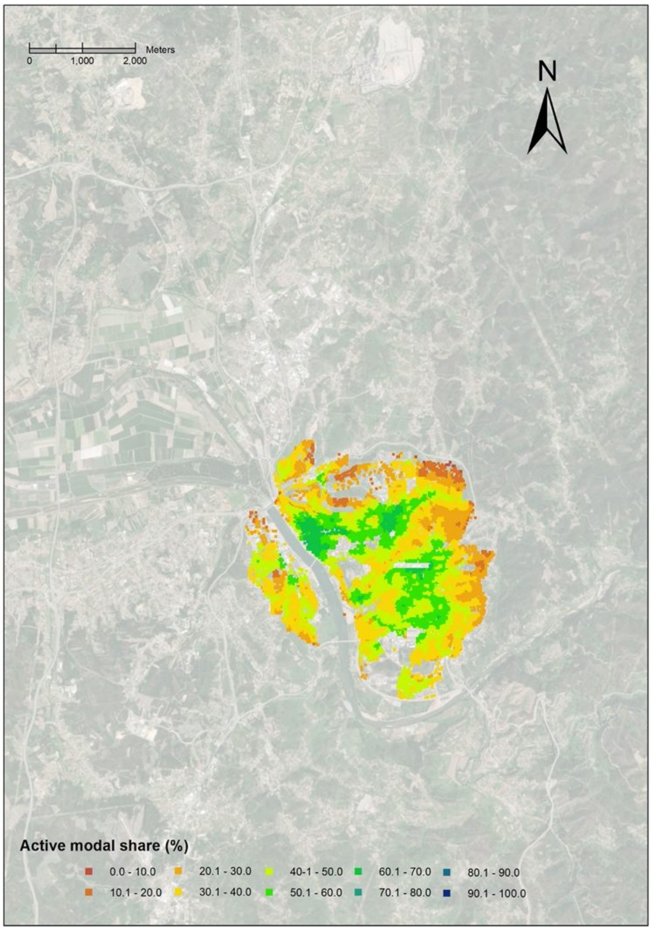
(**a**)

(**b**)

Figure II.6.8. 15-Minute City by active modes (walking/cycling) [facilities plus jobs] (%): (a) Coimbra; (b) Infill Coimbra.



(**a**)



(**b**)

Figure II.6.9. Walk modal share to facilities (%): (a) Coimbra; (b) Infill Coimbra.

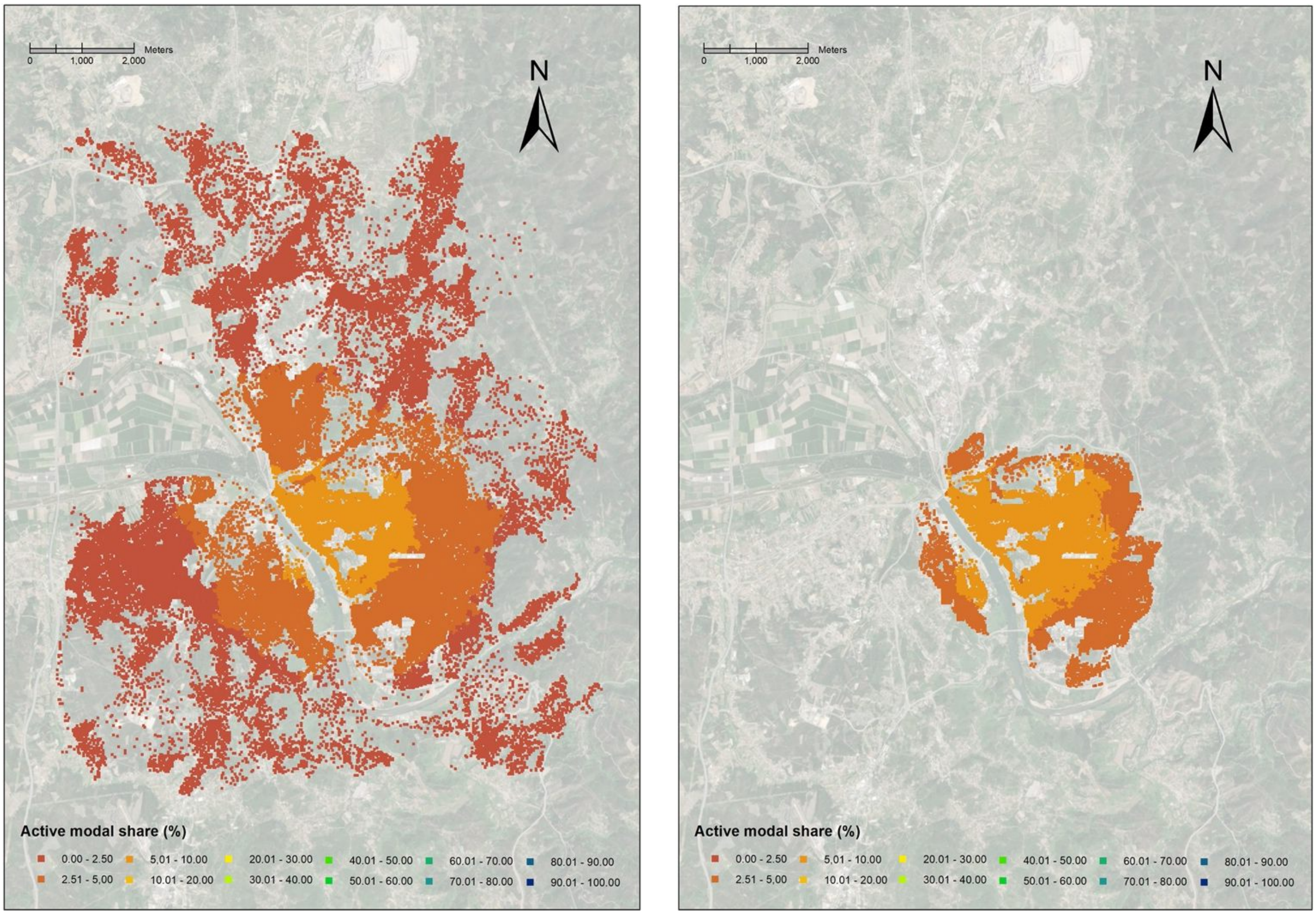
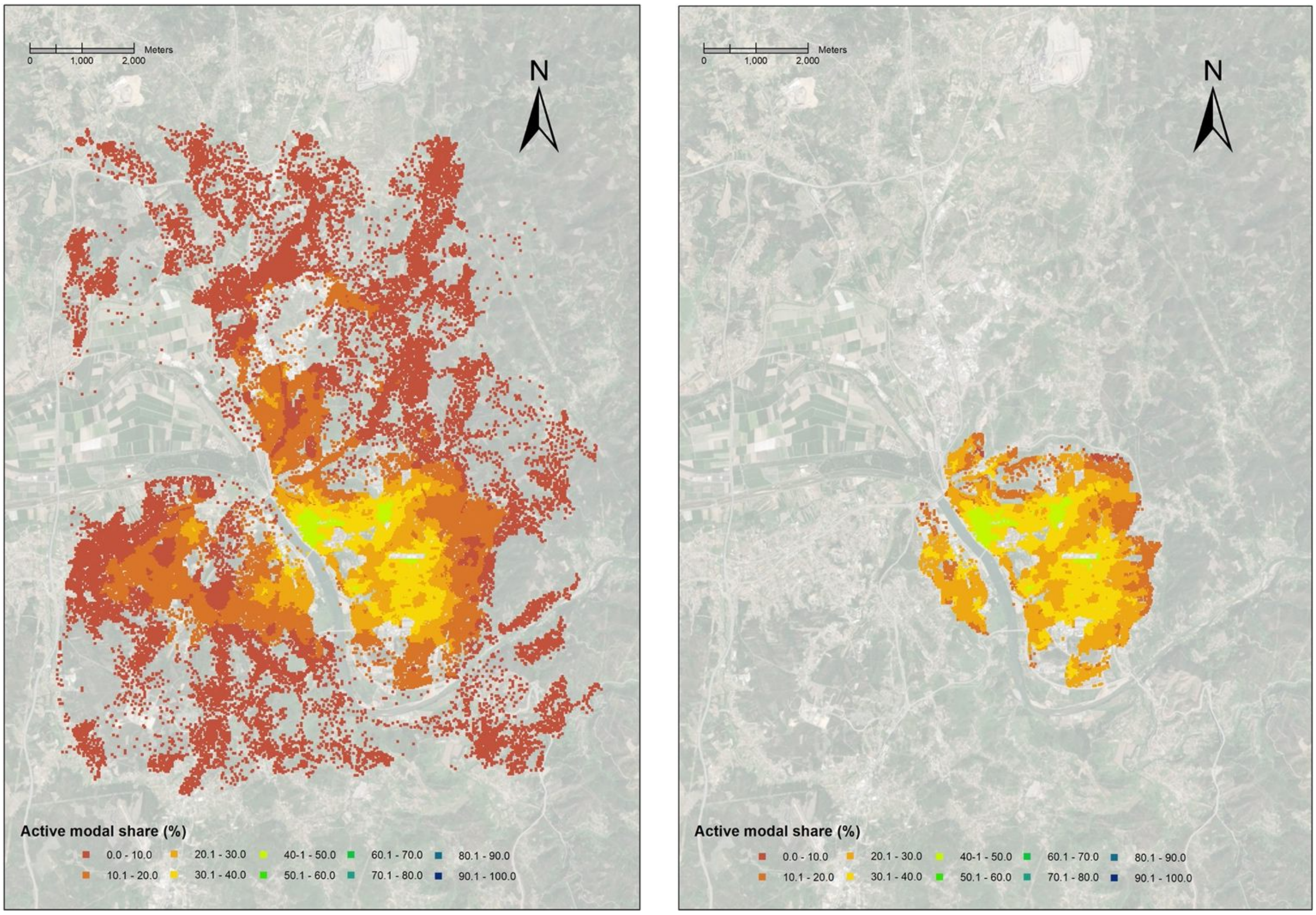


Figure II.6.10. Walk modal share to jobs (%): (a) Coimbra; (b) Infill Coimbra.



(**a**) (**b**)

Figure II.6.11. Walk modal share to facilities plus jobs (%): (a) Coimbra; (b) Infill Coimbra.

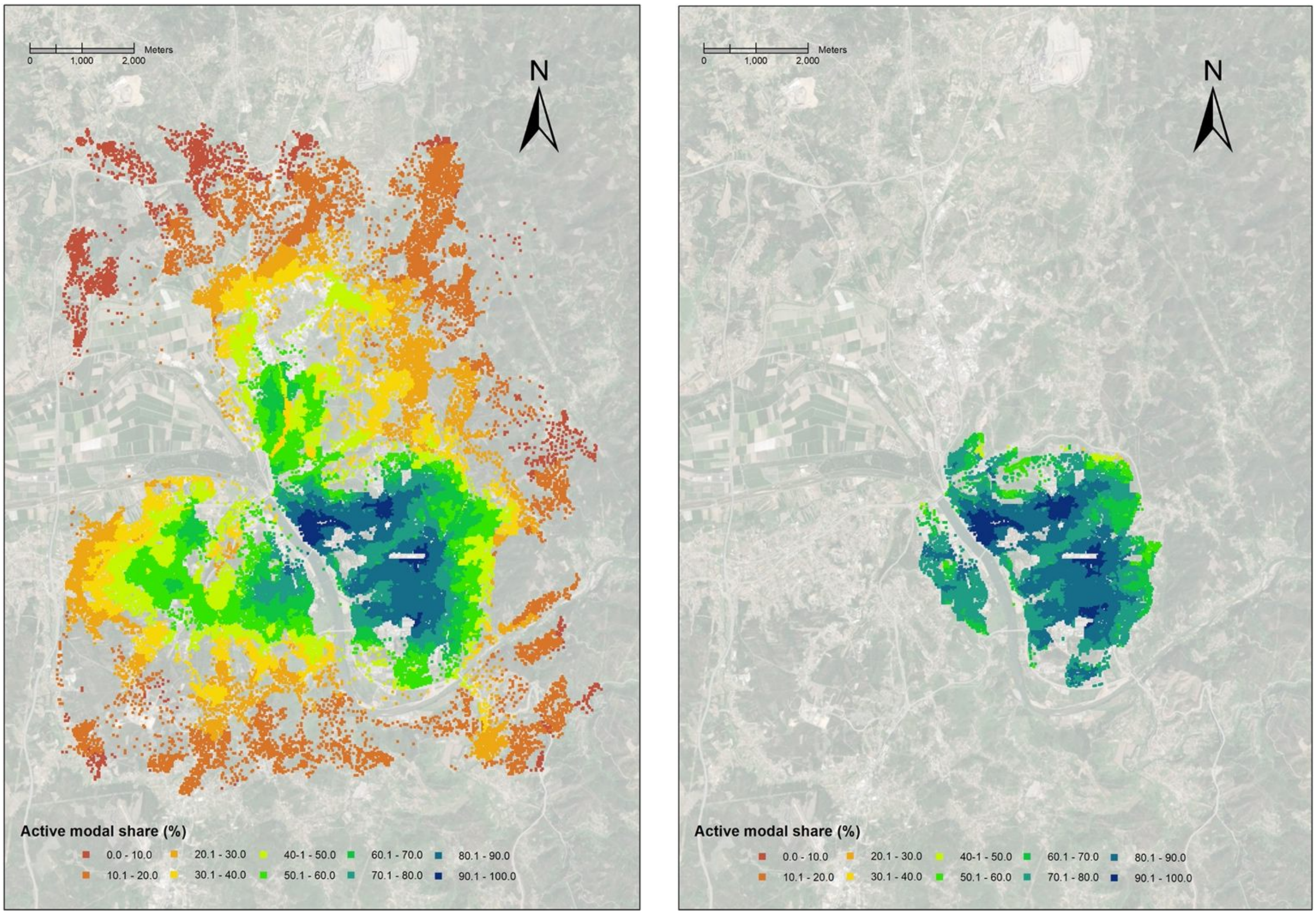
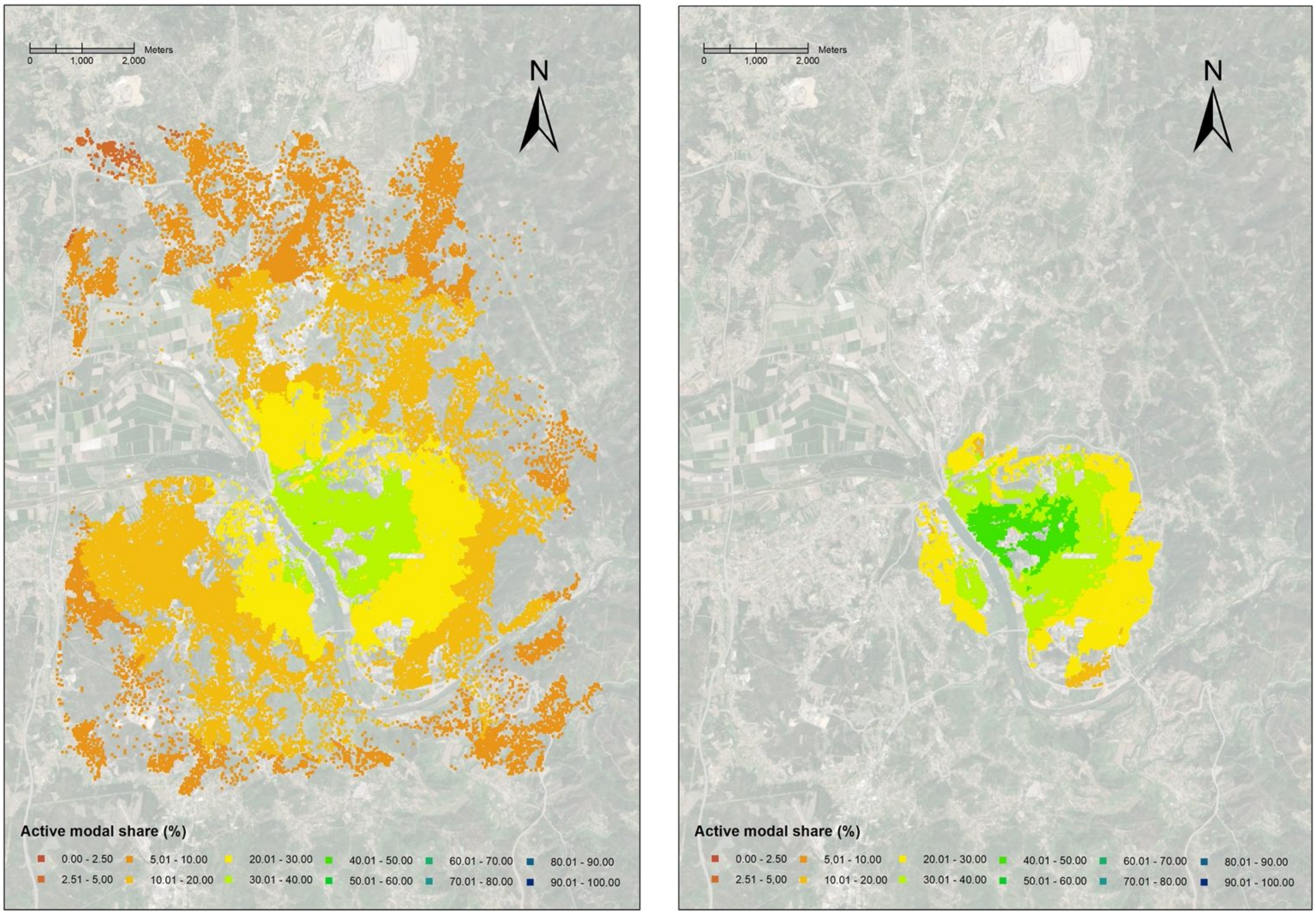
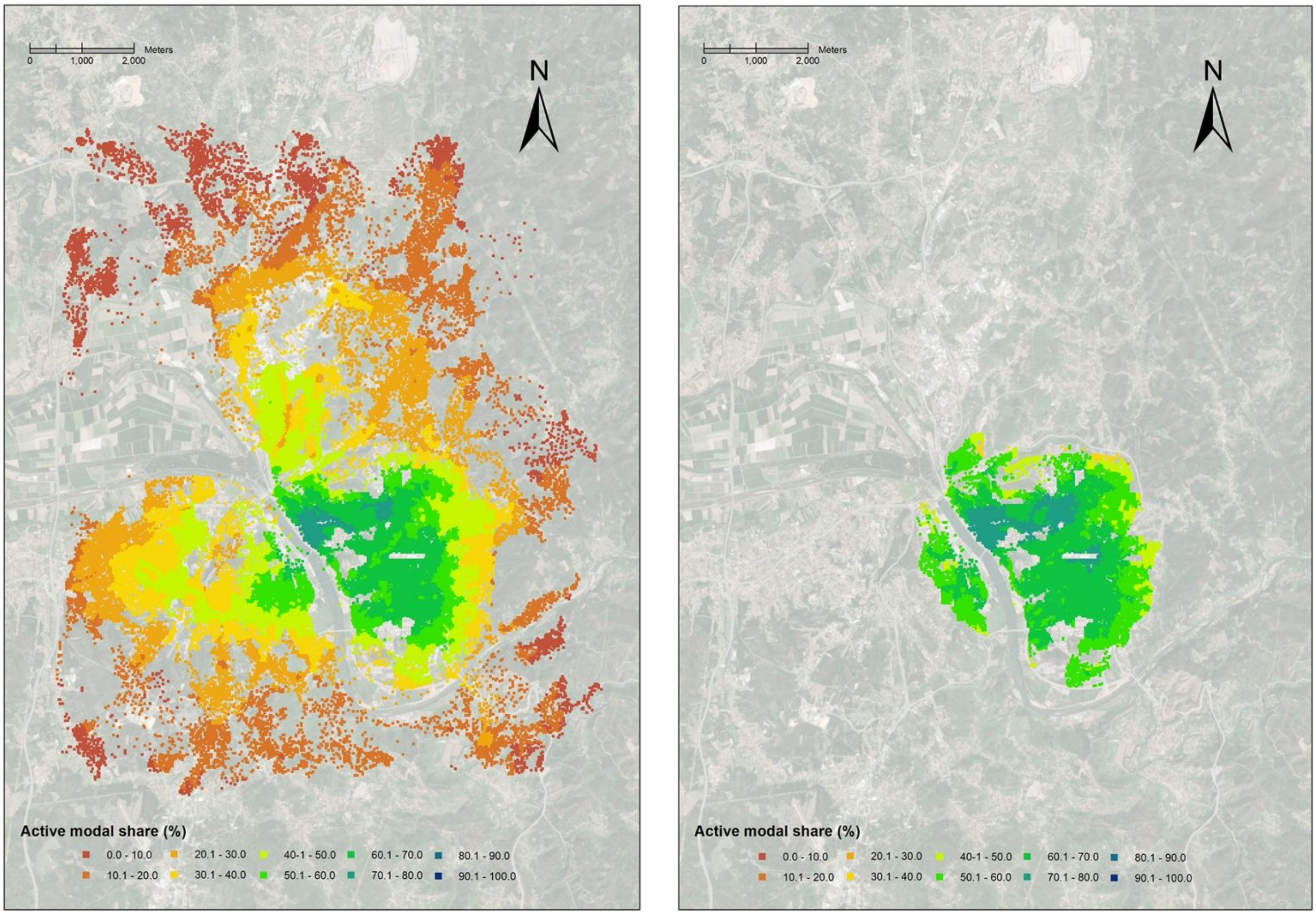


Figure II.6.12. Active modal share (walking/cycling) to facilities (%): (a) Coimbra; (b) Infill Coimbra.



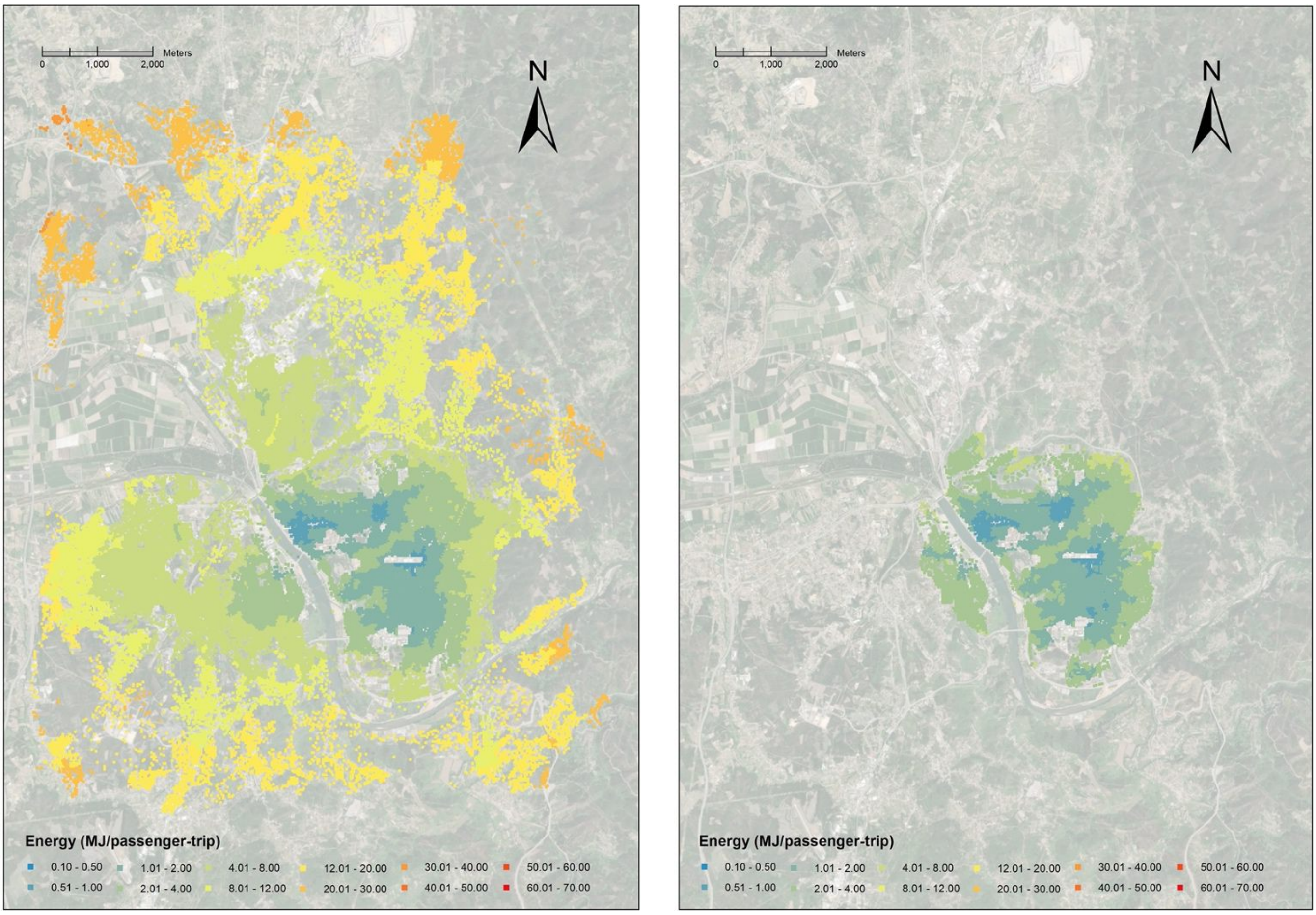
(**a**) (**b**)

Figure II.6.13. Active modal share (walking/cycling) to jobs (%): (a) Coimbra; (b) Infill Coimbra.



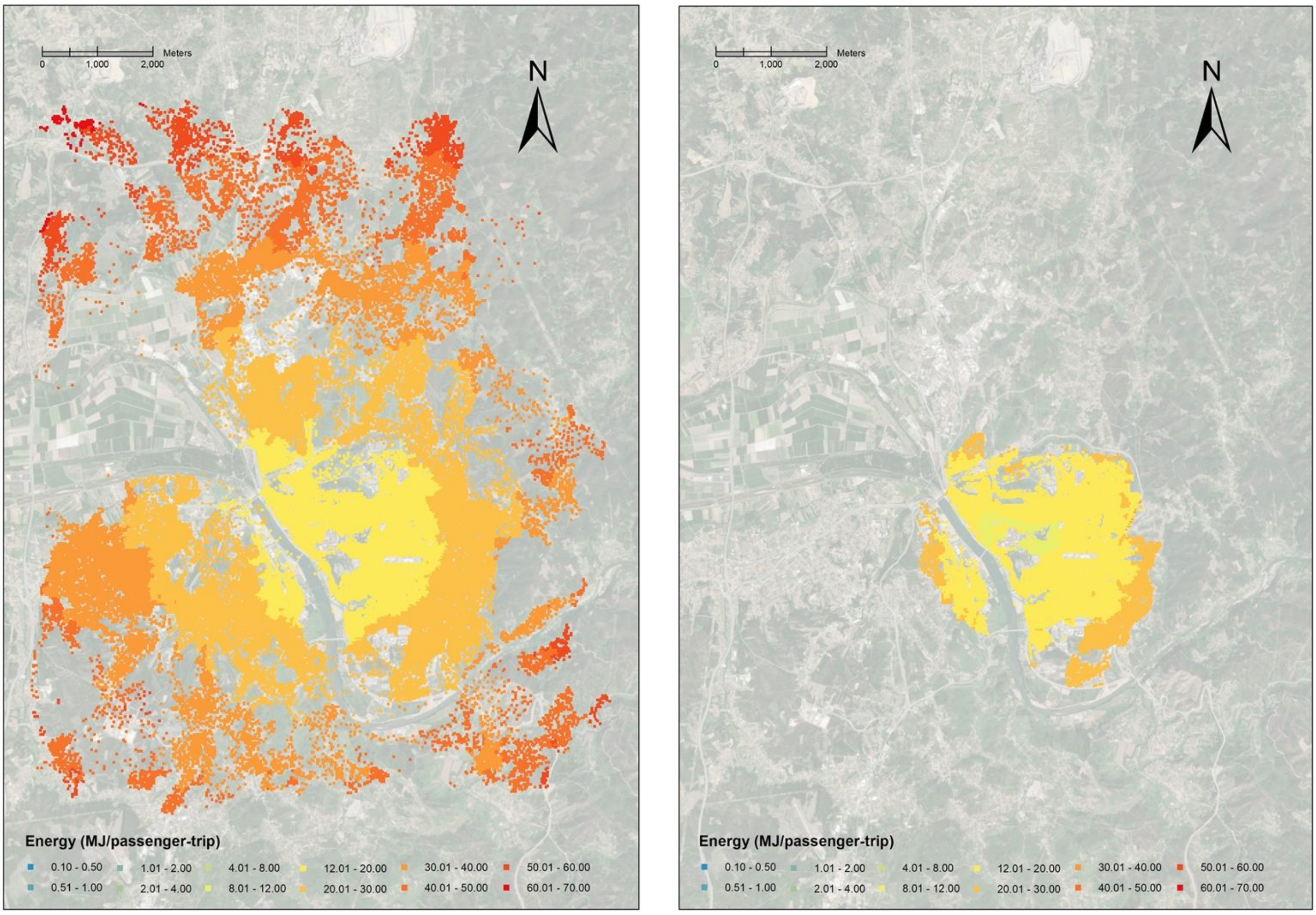
(**a**) (**b**)

Figure II.6.14. Active modal share (walking/cycling) to facilities plus jobs (%): (a) Coimbra; (b) Infill Coimbra.



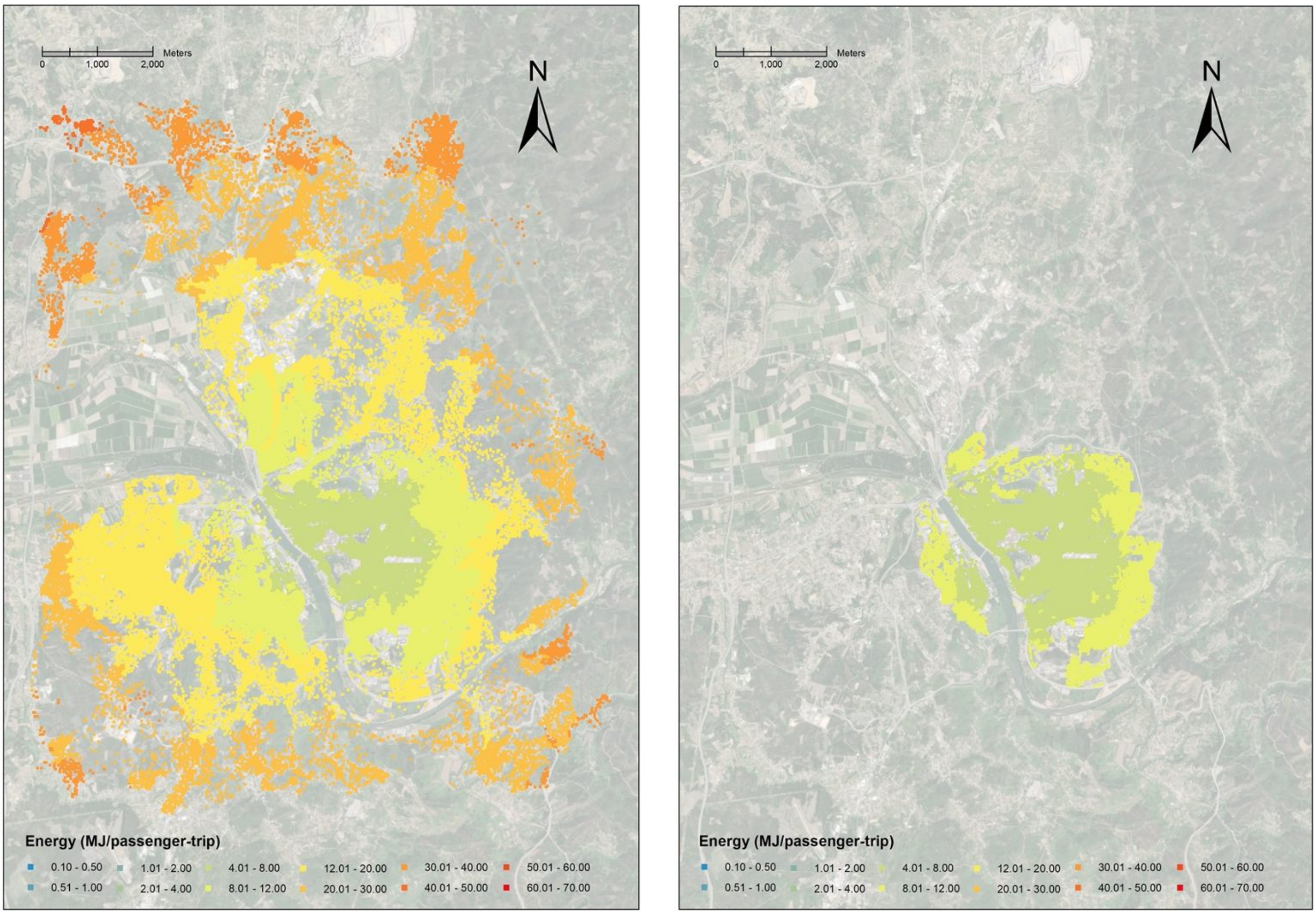
(**a**) (**b**)

Figure II.6.15. Transport energy spending to facilities [active: walk only] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.



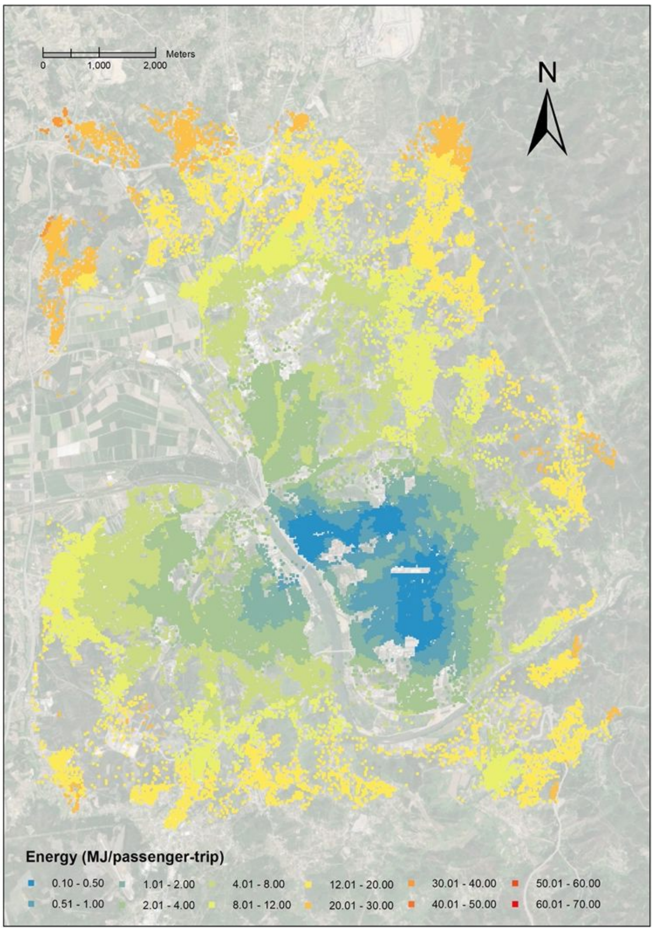
(**a**) (**b**)

Figure II.6.16. Transport energy spending to jobs [active: walk only] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.



(**a**) (**b**)

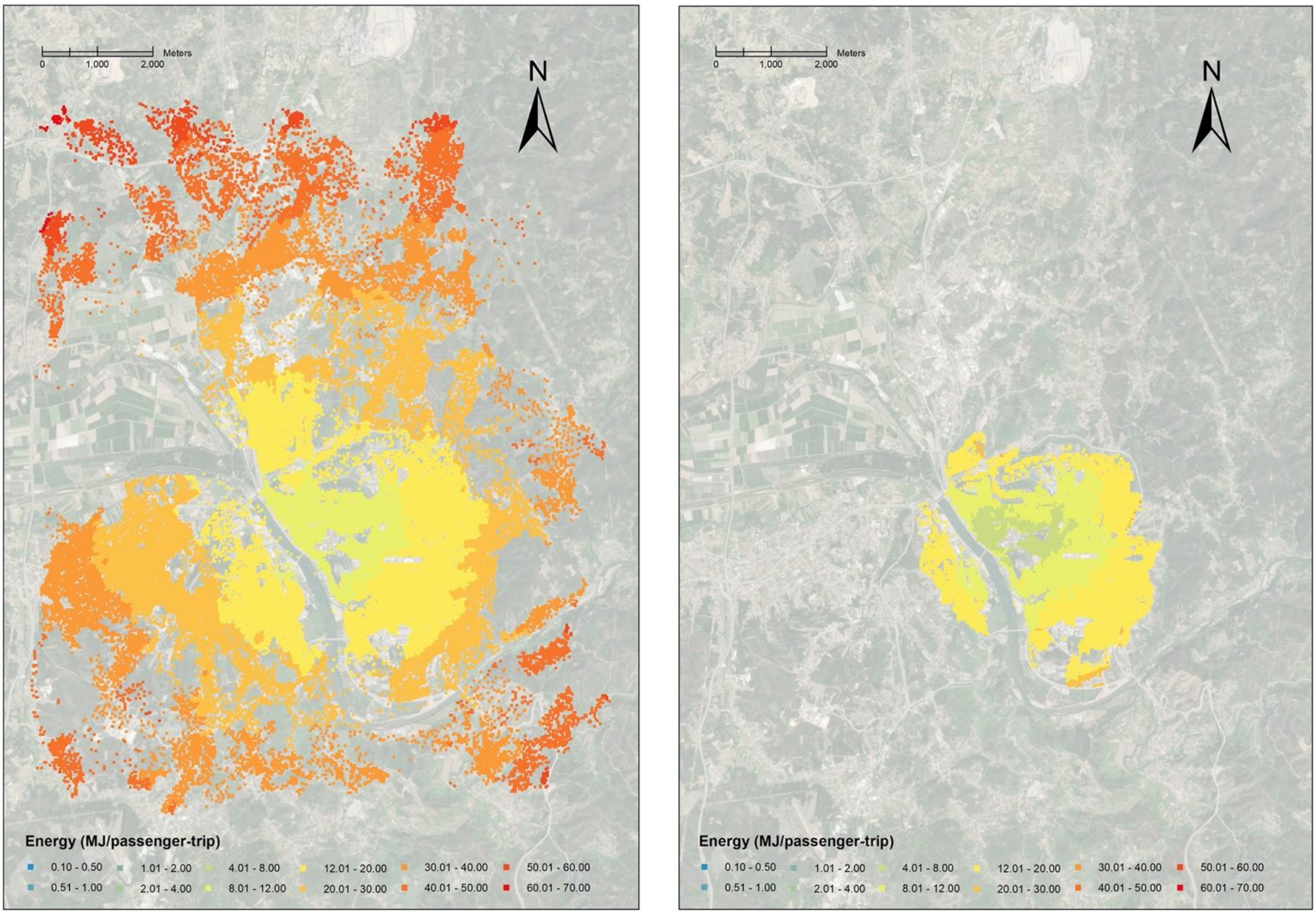
Figure II.6.17. Transport energy spending to facilities plus jobs [active: walk only] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.



(**a**)

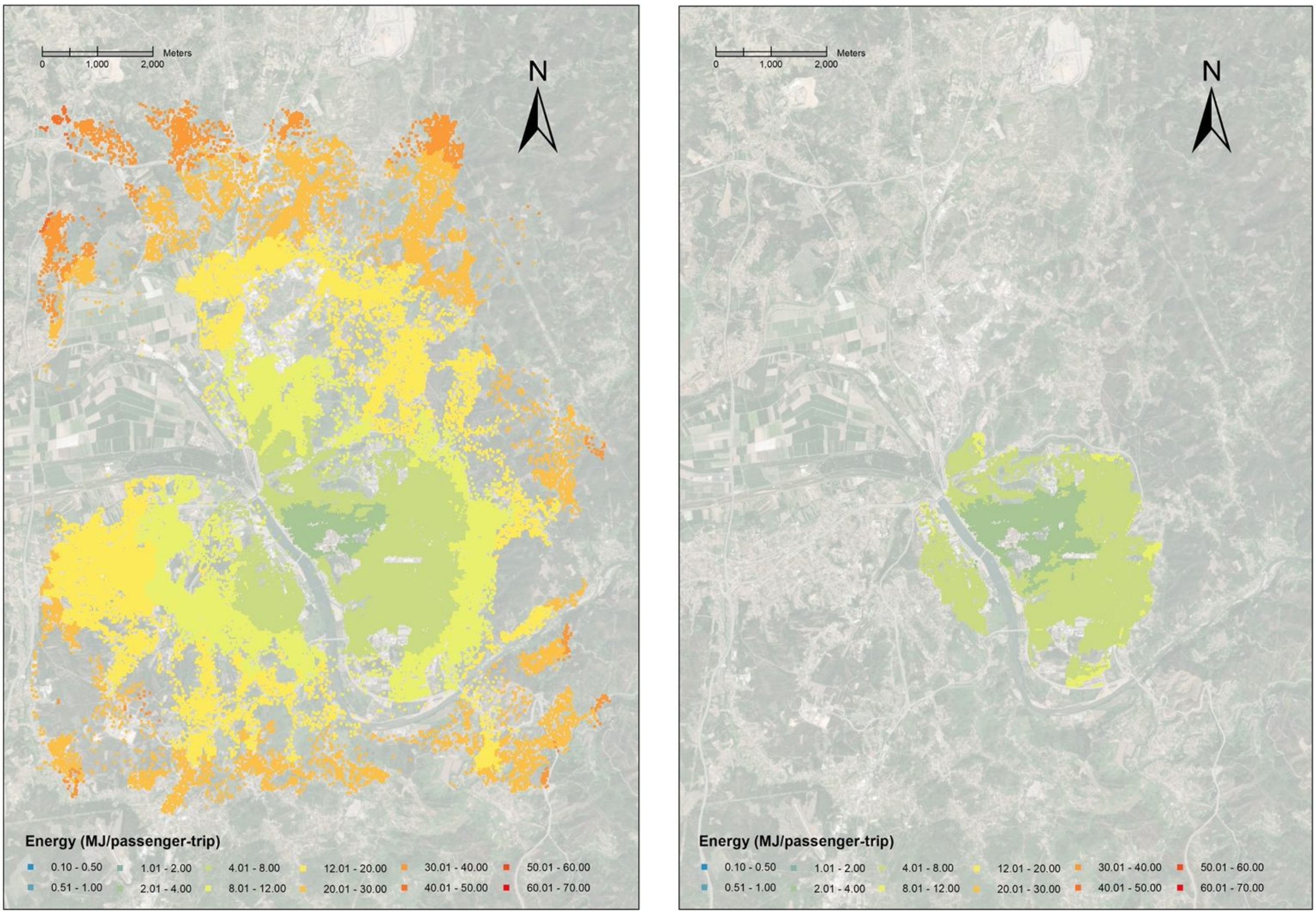
(**b**)

Figure II.6.18. Transport energy spending to facilities [active: walking/cycling] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.



(**a**) (**b**)

Figure II.6.19. Transport energy spending to jobs [active: walking/cycling] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.



(**a**) (**b**)

Figure II.6.20. Transport energy spending to facilities plus jobs [active: walking/cycling] (MJ/passenger.trip): (a) Coimbra; (b) Infill Coimbra.

7. THE IMPACT OF GEOMETRIC AND LAND USE ELEMENTS ON PERCEIVED PLEASANTNESS OF URBAN LAYOUTS

7.1. Survey images summarizing data

Table II.7.1. Survey images summarizing data.

Image	GreenArea	StreetWidth	NrFloors	BuildingDist	GreenPrivArea
1	small	narrow	med	compact	none
2	med	narrow	tall	sprawl	none
3	small	wide	house	compact	backyard
4	med	narrow	short	compact	backyard
5	high	narrow	house	spaced	backyard
6	med	wide	short	compact	backyard
7	med	wide	short	sprawl	none
8	med	very_wide	tall	sprawl	none
9	high	wide	tall	sprawl	none
10	small	wide	tall	sprawl	none
11	high	wide	skyscraper	sprawl	none
12	none	wide	tall	compact	none
13	med	narrow	house	spaced	backyard
14	none	narrow	house	compact	none
15	high	narrow	med	compact	none
16	none	very_wide	skyscraper	compact	none
17	none	wide	med	compact	none
18	small	wide	short	spaced	none
19	med	very_wide	med	sprawl	none
20	high	narrow	house	spaced	backyard
21	small	very_wide	short	compact	none
22	small	narrow	house	compact	none
23	high	narrow	house	spaced	backyard
24	small	very_wide	skyscraper	sprawl	none
25	small	narrow	house	spaced	backyard

7.2. Survey images (by order of appearance)

Figure II.7.1. Survey image 1.

Figure II.7.2. Survey image 2.

Figure II.7.3. Survey image 3.

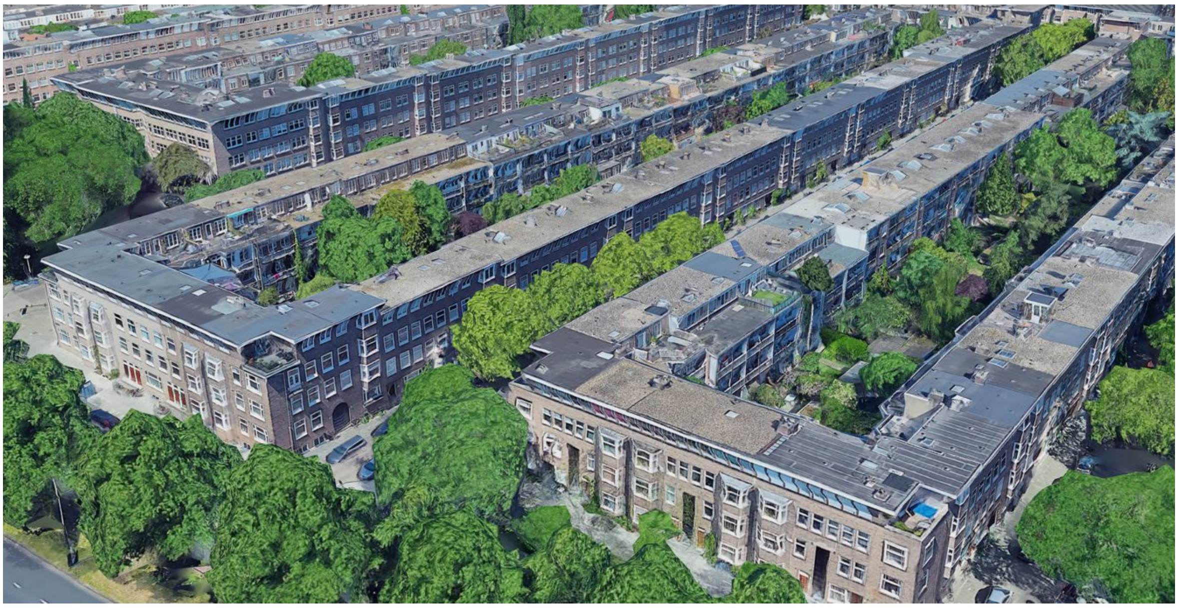


Figure II.7.4. Survey image 4.

Figure II.7.5. Survey image 5.

Figure II.7.6. Survey image 6.

Figure II.7.7. Survey image 7.

Figure II.7.8. Survey image 8.

Figure II.7.9. Survey image 9.

Figure II.7.10. Survey image 10.

Figure II.7.11. Survey image 11.

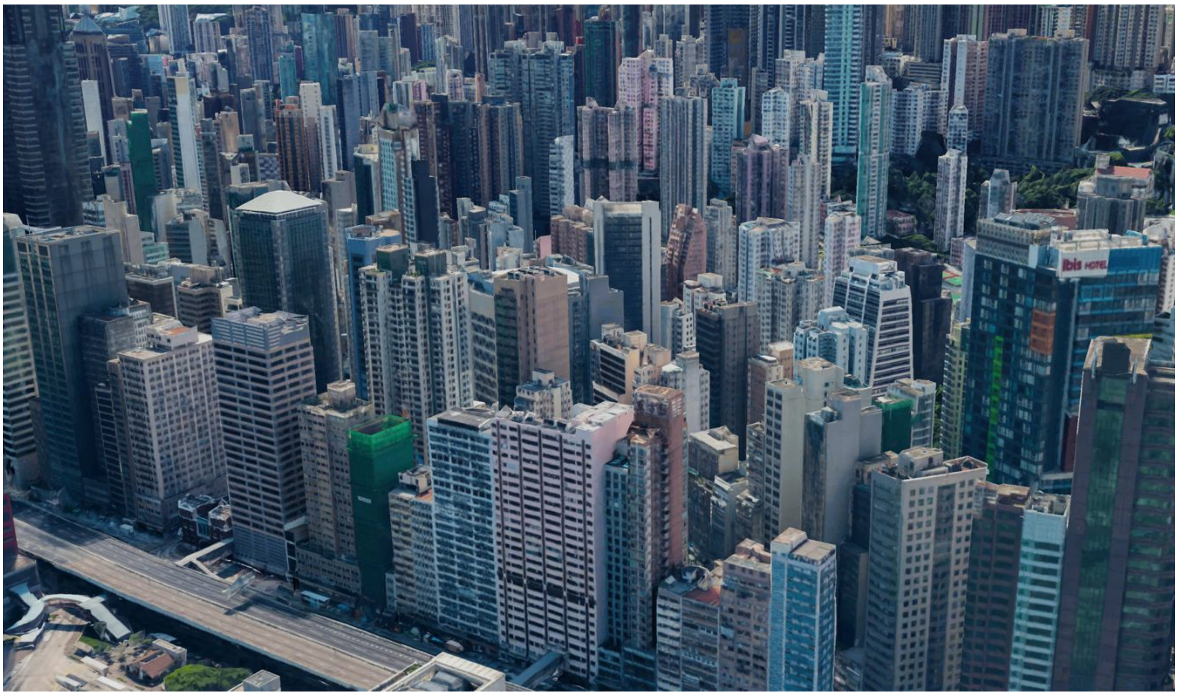


Figure II.7.12. Survey image 12.

Figure II.7.13. Survey image 13.

Figure II.7.14. Survey image 14.

Figure II.7.15. Survey image 15.

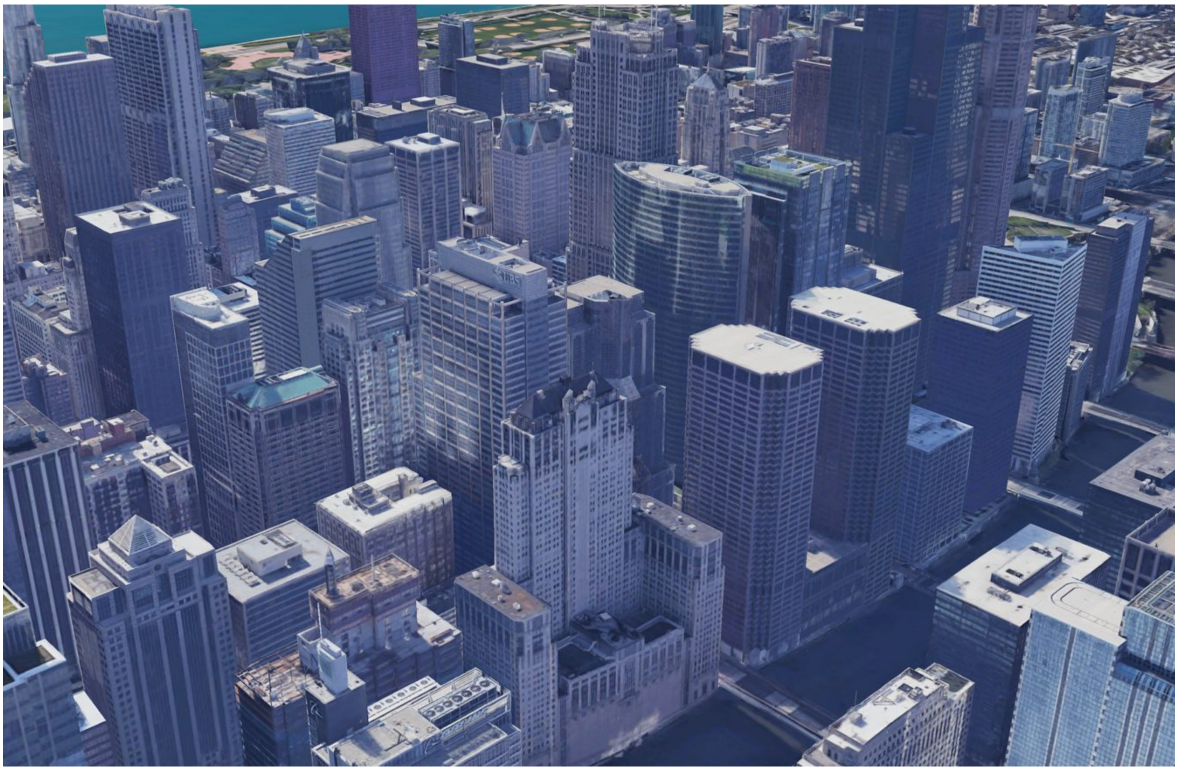


Figure II.7.16. Survey image 16.

Figure II.7.17. Survey image 17.

Figure II.7.18. Survey image 18.

Figure II.7.19. Survey image 19.

Figure II.7.20. Survey image 20.

Figure II.7.21. Survey image 21.

Figure II.7.22. Survey image 22.

Figure II.7.23. Survey image 23.

Figure II.7.24. Survey image 24.

Figure II.7.25. Survey image 25.

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8. Do we live where it is pleasant? Correlates of perceived pleasantness with socioeconomic variables

Figure II.8.1. Favela image 1.

Figure II.8.2. Favela image 2.

Figure II.8.3. Favela image 3.

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