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DOCTORAL (PhD) DISSERTATION

Decision-Support Approaches for Urban Climate Action Planning and Environmental Assessment

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DECISION-SUPPORT APPROACHES FOR URBAN CLIMATE ACTION PLANNING AND ENVIRONMENTAL ASSESSMENT

This dissertation was prepared in fulfillment of the requirements for obtaining the Doctor of Philosophy (PhD) degree within the framework of the Chemical Engineering and Material Sciences Doctoral School of the University of Pannonia.

in the discipline of Bioengineering, Environmental Engineering, and Chemical Engineering.

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List of Publications Strongly Related to the Research Theses

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Conference papers

1. **Rjiba, I.B**., Tóth-Nagy, G., Sebestyén, V.: Cities strategies to protect their energy and climate security, VII. Turizmus és Biztonág Nemzetközi Tudományos Konferencia, Tanulmánykötet, pp. 357-364, 2023.
2. **Rjiba, I.B**., Kristófné Makó, É., Tóth-Nagy, G., Sebestyén, V.: Life Cycle Assessment of Construction Materials in Climate Action Projects, 1st African Conference on Sustainable Development of Energy, Water and Environment Systems, Oujda-Saidia, Morocco, May, 27-31, 2025.

International Conference presentations

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4. **Rjiba, I.B**., Sebestyén, V., Tóth-Nagy, G.: Impacts of public awareness on climate adaptation, 26th Spring Wind Conference, Miskolc, május 5-7, 2023.
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7. **Rjiba, I.B**., Sebestyén, V., Tóth-Nagy, G.: Data-driven climate action plans: Fostering sustainable resilience through innovative models, 52th Chemical Engineering Days, Veszprém, April, 16-17, 2024.
8. Tóth-Nagy, G., **Rjiba, I.B**., Sebestyén, V.: Climate adaptation in urban environments: Practical examples and lesson learned, IX. International Symposium 2025, Budapest May, 8-9, 2025.
9. **Rjiba, I.B**., Tóth-Nagy, G., Sebestyén, V.: A Spatially Driven Framework for Data-Based Climate Action Planning in Cities. Materials science day XXV of PhD students, Veszprém, november 17, 2025.
10. **Rjiba, I.B**., Sebestyén, V., Tóth-Nagy, G.: Sustainable Tourism and Urban Safety Through Spatial Analysis, X. International Scientific Conference on Tourism and Security, Zalakaros, December, 5, 2025.

UNIVERSITY OF PANNONIA

Abstract

Chemical Engineering and Material Sciences Doctoral School

Decision-Support Approaches for Urban Climate Action Planning and Environmental Assessment

By Iskander BEN RJIBA

Urban areas play a central role in addressing climate change, both as major sources of emissions and as key actors in mitigation and adaptation efforts. However, planning effective climate actions remains complex due to the diversity of urban contexts and available interventions. This thesis aims to support urban climate action planning by combining analytical, data-driven, and environmental assessment approaches.

The research is structured around four main components. First, a systematic analysis of published climate action plans was conducted to develop a structured categorization of climate actions, enabling clearer comparison across cities. Second, the role of public awareness was examined by analysing the relationship between awareness-related measures, education levels, and environmental indicators such as air quality and emissions. Third, a data-driven decision-support model based on a decision tree was developed using a large dataset of European climate action plans to guide the selection of appropriate actions based on city characteristics. Finally, the environmental impacts of construction materials used in climate action projects were evaluated through a comparative, project-level framework. The results highlight the importance of public awareness and education as supporting factors in environmental performance. The decision-support model demonstrates the value of using empirical data to guide climate action planning. In addition, the material-based analysis shows that environmental impacts are strongly influenced by material intensity, emphasizing the need to consider construction materials in project evaluation.

This thesis contributes to the development of more structured, evidence-based, and comprehensive approaches to urban climate action planning.

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Résumé

École doctorale de génie chimique et des sciences des matériaux

Approches d'aide à la décision pour la planification de l'action climatique urbaine et l'évaluation environnementale

Par Iskander BEN RJIBA

Les zones urbaines jouent un rôle central dans la lutte contre le changement climatique, à la fois comme principales sources d'émissions et comme acteurs clés des efforts d'atténuation et d'adaptation. Cependant, la planification d'actions climatiques efficaces reste complexe en raison de la diversité des contextes urbains et des interventions possibles. Cette thèse vise à soutenir la planification de l'action climatique urbaine en combinant des approches analytiques, fondées sur les données et d'évaluation environnementale.

La recherche s'articule autour de quatre composantes principales. Premièrement, une analyse systématique des plans d'action climatique publiés a été menée afin d'élaborer une catégorisation structurée des actions climatiques, permettant une comparaison plus claire entre les villes. Deuxièmement, le rôle de la sensibilisation du public a été examiné en analysant la relation entre les mesures de sensibilisation, les niveaux d'éducation et des indicateurs environnementaux tels que la qualité de l'air et les émissions. Troisièmement, un modèle d'aide à la décision fondé sur les données, reposant sur un arbre de décision, a été développé à partir d'un vaste ensemble de plans d'action climatique européens, afin d'orienter le choix des actions appropriées en fonction des caractéristiques des villes. Enfin, les impacts environnementaux des matériaux de construction utilisés dans les projets d'action climatique ont été évalués au moyen d'un cadre comparatif à l'échelle des projets. Les résultats mettent en évidence l'importance de la sensibilisation du public et de l'éducation comme facteurs favorisant la performance environnementale. Le modèle d'aide à la décision démontre l'intérêt

d'utiliser des données empiriques pour orienter la planification de l'action climatique. En outre, l'analyse fondée sur les matériaux montre que les impacts environnementaux sont fortement influencés par l'intensité matérielle, soulignant la nécessité de prendre en compte les matériaux de construction dans l'évaluation des projets.

Cette thèse contribue au développement d'approches plus structurées, fondées sur des données probantes et plus complètes pour la planification de l'action climatique urbaine.

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List of Abbreviations

Abbreviation	Definition
API	Application Programming Interface
BEI	Baseline Emission Inventory
BIM	Building Information Modelling
CO_2	Carbon Dioxide
CoM	Covenant of Mayors
COP21	2015 United Nations Climate Change Conference
CRF	Common Reporting Framework
EC	European Commission
EU	European Union
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDI	Human Development Index
HT	Human Toxicity
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MDS	Multidimensional Scaling
MEI	Monitoring Emission Inventory
MWh	Megawatt-hour
ODP	Ozone Depletion Potential
OSM	OpenStreetMap
PhD	Doctor of Philosophy
SDG	Sustainable Development Goal
SECAP	Sustainable Energy and Climate Action Plan
SHAP	SHapley Additive exPlanations
TE2100	Thames Estuary 2100 Plan
UNFCCC	United Nations Framework Convention on Climate Change

Climate action category codes

Abbreviation	Definition
Br	Buildings retrofit and renovations
Ci	Involving the community in the decision-making phase
Da	Enhance monitoring systems and data analysis
Fa	Flood avoidance
Fi	Seeking financial investments and joining projects
Hi	Heat control and improvement of heating systems
Re	Transition to renewable energy
Str	Street light replacement
To	Optimizing transportation
Tp	Adding green areas, parks and planting trees

Climate class

Köppen-Geiger climate classification code	**Definition**
Am	Tropical monsoon climate
BSk	Cold semi-arid (steppe) climate
BWh	Hot desert climate
BWk	Cold desert climate
Cfb	Temperate oceanic climate
Cfc	Subpolar oceanic climate
Csc	Cold-summer Mediterranean climate
Cwb	Subtropical highland climate
Dfb	Warm humid continental climate
Dsa	Hot, dry-summer continental climate
Dsb	Warm-summer Mediterranean continental climate
Dsc	Cold-summer Mediterranean continental climate
Dwc	Cold-winter subarctic continental climate (dry winters)

1. Introduction

Climate change has emerged as one of the most pressing challenges of the twenty first century, exerting profound pressures on both natural systems and human societies. Among human settlements, cities stand at the front line of climate impacts. According to the United Nations' Sustainable Development Goals Report, more than half of the world's population (around 55%) currently lives in urban areas, and this share is projected to increase to about 68% by 2050. Urban areas are the engines of economic activity and resource consumption, accounting for approximately 67% of global primary energy use and about 70% of global greenhouse gas emissions. At the same time, cities are increasingly vulnerable to climate-related hazards such as heat waves, flooding, air pollution, and resource scarcity, with impacts concentrated in densely populated infrastructure and communities (UN-Habitat, 2024).

Because of this dual role, cities have become central actors in the global climate agenda, developing and implementing local climate strategies. The challenge, however, lies in identifying which actions are most effective, in what contexts, and with what long term implications for environmental and social outcomes.

1.1. Research gap

Over the past decades, municipalities across Europe and beyond have begun to design and implement climate action plans that combine adaptation and mitigation measures. These strategies range from large scale flood protection infrastructures to energy retrofitting of historical buildings, from the expansion of urban parks to the improvement of insulation and heating systems. Such initiatives are often presented as exemplary pathways toward more resilient and sustainable cities (Bulkeley, 2013). However, despite the large number of initiatives, there is still a significant challenge: The diversity of climate actions makes them difficult to compare, evaluate, or prioritize. While some cities have invested in ambitious technological solutions, others emphasize social participation or ecosystem-based approaches. This diversity reflects the creativity of local actors, but it also creates difficulties for decision makers who must decide which actions are most suitable for their local context. Existing studies often document these actions individually or within specific sectors, but they rarely provide systematic tools to compare different types of interventions across cities or to support structured decision-making processes (Castán Broto, 2013).

This difficulty is compounded by a second challenge: The knowledge generated through climate action plans is fragmented. Each municipality develops its own strategy, often reporting it in ways that differ in terminology, scope, and emphasis. While this provides a rich diversity of experiences, it makes it extremely difficult to extract general lessons. As a result, decision makers cannot easily benefit from the accumulated knowledge of other municipalities, and researchers cannot readily systematize the large body of evidence emerging from practice (Satterthwaite, 2008). In addition, current research tends to separate analytical dimensions, focusing either on governance processes, technical performance, or environmental impacts, without integrating these perspectives into a unified framework that can support practical decision-making (Rosenzweig, 2018).

More specifically, several shortcomings can be identified in the existing literature. First, many studies remain limited to qualitative or sector-specific analyses, without developing analytical methods capable of systematically comparing climate actions across a large number of municipalities. Second, although extensive datasets of climate action plans are publicly available through initiatives such as the Covenant of Mayors, these datasets are still underused in the development of operational and data-driven decision-support tools. Existing studies frequently use these reports for descriptive purposes only, rather than transforming them into structured analytical models capable of supporting urban climate planning. Third, environmental evaluations of climate actions are often conducted separately from governance and planning studies, particularly regarding the role of construction materials and their environmental impacts within urban climate projects. As a result, there is still a lack of integrated approaches that combine action categorization, decision-support modelling, and environmental assessment within a single analytical framework.

It is in this context that the present research positions itself. This thesis addresses these limitations by developing a structured and data-driven approach for analysing, categorizing, and evaluating urban climate actions. By doing so, it addresses a critical gap: while many studies exist on individual sectors, such as energy efficiency, transport, or flood management, there are relatively few that attempt to integrate these several actions into a common framework. This integration is important for supporting municipal decision makers, who must select among competing priorities with limited resources and under significant uncertainty. The research further contributes by transforming published climate action plans into a structured dataset that supports the development of decision-support approaches based on empirical municipal experiences. The novelty of this research therefore lies in its systematic approach to categorization and its development of decision-support methods rooted in real municipal experiences. By combining action categorization, data-driven modelling, and material-based environmental assessment within a single framework, this research directly addresses the identified gaps and provides a more integrated and practical approach to urban climate action planning.

1.2. Thesis motivation

This thesis is motivated by the growing need for integrated approaches to urban climate action. Current research on urban climate governance tends to follow one of two distinct paths. On the one hand, policy-oriented studies emphasize participation processes, institutional arrangements, and the political dynamics of climate action (Anguelovski, 2011). On the other hand, technical assessments, such as life cycle analyses of buildings or energy-efficiency modelling, provide detailed environmental evaluations but rarely connect these findings to the decision-making processes used by municipalities (Cabeza, 2014). The separation between these perspectives limits the capacity of cities to translate scientific knowledge into actionable and context-sensitive strategies. Bridging this divide represents a central motivation for the present research.

The work is further motivated by the recognition that important dimensions of climate planning remain under explored despite their influence on project outcomes. For example, Awareness raising is frequently included in municipal climate plans but is rarely assessed in terms of measurable environmental impact. Similarly, construction materials play a decisive role in the environmental footprint of many projects, yet they are often overlooked in urban governance discussions. Addressing these blind spots expands the analytical framework used to evaluate climate actions and supports a more comprehensive understanding of effectiveness, one that includes social engagement, material efficiency, and spatial context alongside technical performance.

The significance of this research is therefore threefold. First, it responds to the need for knowledge integration by systematizing the different experiences of municipalities into a coherent categorization of climate actions. Second, it contributes to the development of decision support methods that can guide local authorities in selecting strategies suited to their specific contexts. Third, it enriches the debate on impact assessment by demonstrating how social and material factors interact with climate strategies. Together, these motivations position the thesis as a step toward more informed urban climate governance and support the transition toward resilient and sustainable cities.

1.3. Personal motivation

This doctoral research also builds on my personal academic trajectory. Having completed a master's degree in environmental engineering at the University of Pannonia, I developed a strong foundation in the assessment and management of environmental challenges, with my final thesis focusing on air quality. That work introduced me to the complex interactions between urban systems and environmental pressures, as well as to the importance of reliable data and methodological rigor in understanding these dynamics. Continuing my studies at the same university through a PhD has provided me with the opportunity to expand this perspective beyond a single environmental issue toward the broader question of how cities can design and implement effective strategies to cope with climate change. This progression reflects both an intellectual continuity and a deep personal commitment to advancing the tools and approaches that support municipalities in building more sustainable and resilient futures.

1.4. Research objectives

The objective of this thesis is to develop an analytical and practical framework that supports cities in designing and evaluating climate strategies aligned with the goals of sustainable and resilient urban development. Building on the principles articulated in Sustainable Development Goals 11 and 13, the research seeks to systematize the wide range of urban climate actions into a structured categorization that allows comparison, knowledge transfer, and prioritization throughout several municipal contexts. The thesis further aims to translate experimental evidence from existing practices into decision-support tools capable of assisting local authorities in navigating the technical and strategic complexity of climate planning.

Particular attention is given to dimensions that remain insufficiently examined in current urban climate research, including the measurable effectiveness of awareness raising initiatives and the environmental implications of construction materials. By integrating these aspects, the research clarifies how social, material, and spatial factors interact within climate action frameworks. Together, these objectives position the thesis as a contribution to both conceptual understanding and operational guidance, supporting municipalities in advancing toward the targets of sustainable and climate resilient urban development.

1.5. Research questions

The research questions are formulated to provide a more focused, precise and researchable framework in contrast to the broader research objectives. In the dissertation, these research questions are addressed through a literature review and the development of a theoretical background. Based on this foundation, a research assumption is elaborated in subsequent chapters. Through the implementation of the research addressing the main points of the thesis, the assumptions are confirmed or rejected, and the corresponding research theses are articulated.

Taking into account the above issues and their relevance, the current study seeks to answer the following research questions.

RQ1: To what extent can systematic analytical approaches be used to identify and categorize recurring climate action patterns from published urban climate action plans?

RQ2: How does increasing public awareness through climate actions targeting the population, together with higher education levels, influence air quality and emission reduction outcomes in urban areas?

RQ3: What kind of decision-support tools can be developed from the analysis of existing climate action plans to help cities identify more appropriate and evidence-based climate actions?

RQ4: How does the use and intensity of construction materials influence the environmental impacts of different types of climate action projects?

This thesis makes several contributions to the study of urban climate action. From a methodological perspective, it develops a structured approach that combines the analysis of climate action plans, data-driven modelling, and material-based environmental evaluation. From a scientific perspective, the research provides new vision into how different types of climate actions can be categorized, compared, and assessed within a common framework, while also highlighting the role of public awareness and material selection in shaping environmental outcomes. From a practical point of view, the thesis offers tools and approaches that can support decision-makers, urban planners, and local authorities in selecting and evaluating climate actions in a more structured and evidence-based way.

1.6. Thesis structure

This thesis is organized into several chapters that follow a logical progression from background to analysis and conclusions. After a brief introduction, the literature review presents the related works and findings and, on this basis, characterizes the research assumptions. The methodology chapter then describes the approaches used to investigate the research questions and is structured into four interconnected parts. The first part applies systematic analytical approaches to published climate action plans in order to identify and categorize recurring climate actions. Building on this categorization, which showed public awareness to be among the most frequently adopted recent climate actions, the second part examines the role of public awareness and its relationship with environmental outcomes such as air quality and emissions. The third part develops a data-driven decision-support model that draws on the analysis of existing action plans to guide the selection of appropriate climate actions, and the fourth part evaluates the environmental performance of climate action projects through a material-based assessment at the project level. The results and discussion chapter presents and interprets the findings of these components, linking them to the corresponding research assumptions. Finally, the conclusion summarizes the main contributions of the thesis, discusses its implications for climate action planning, and outlines limitations and directions for future research. The overall logic connecting the four parts is summarized in Figure 1.

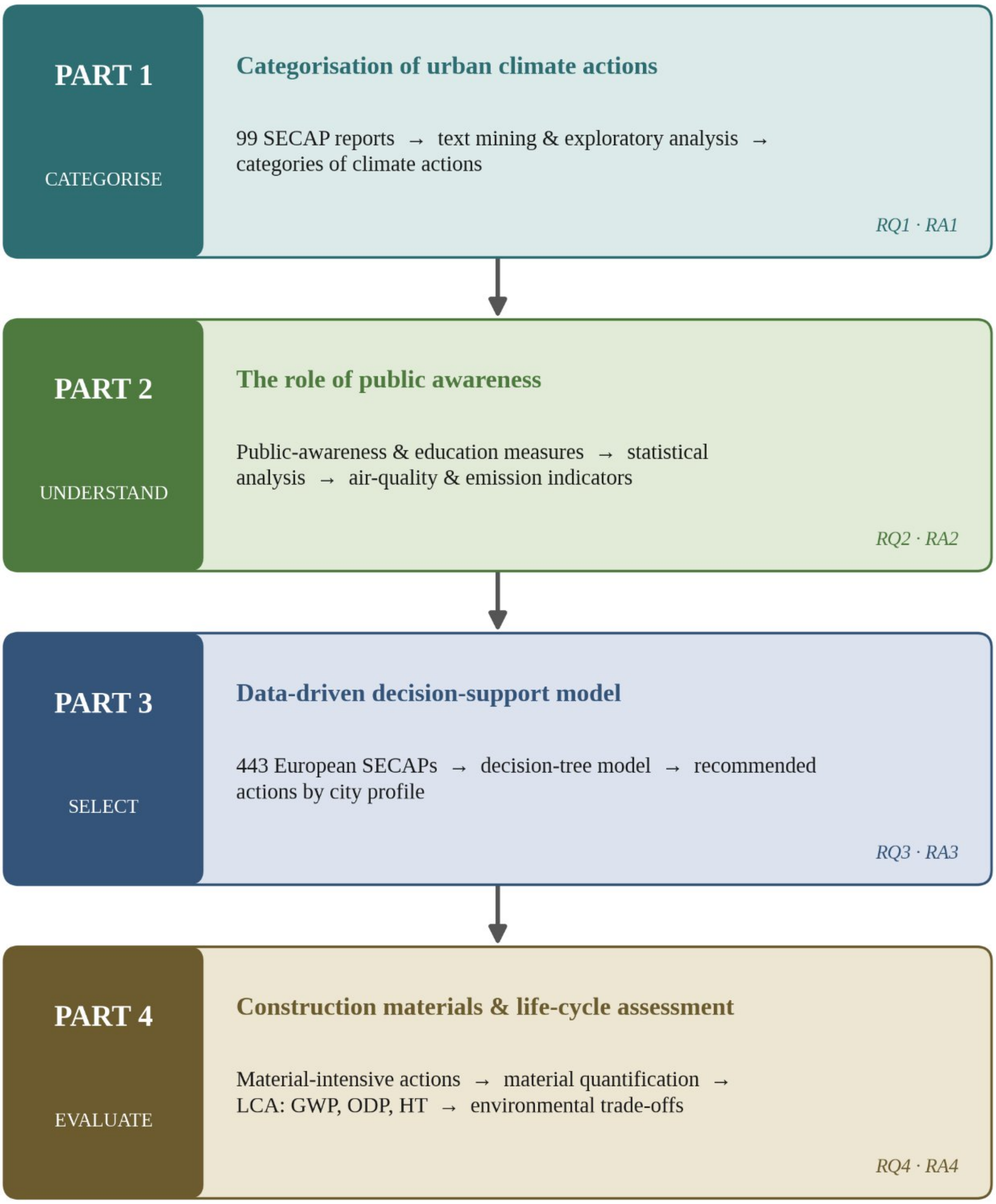


Figure 1: Integrated research framework linking the four parts of the thesis into a single workflow for urban climate action planning (categorise → understand → select → evaluate).

2. Literature review

This chapter presents a review of the existing literature related to climate change and urban climate action. It first outlines the main impacts of climate change and the challenges faced by cities, highlighting their central role in mitigation and adaptation efforts. It then introduces key initiatives such as the Covenant of Mayors, which provide a basis for the data used. The chapter also discusses analytical approaches used to study climate action plans, including data-driven methods, in order to position the contribution of this thesis within the existing body of knowledge. At the end of the chapter, the research assumptions are presented based on the research questions and the findings from the literature.

2.1. Climate change impacts

European cities face a range of challenges over the coming decades that will influence the nature of urban growth and development across the continent. Climate change is central amongst these and is having direct implications for urban processes through changes to temperature and precipitation patterns (Carter, 2011). The impacts of climate change are increasingly evident at the urban level such as the rise of sea level, accentuation of the climatic events (flooding's, droughts...), forest destabilization, quantitative and qualitative impacts on the water resources (Smerdon, 2017), Agricultural difficulties (Nelson G.C, 2013), reduction of the biodiversity (de La Rocque S, 2008) and extension of tropical sickness (Actu-environnement, 2019).

The impacts of climate change on cities can be grouped into a few recurring themes: rising temperatures and the urban heat island effect, water-related hazards such as flooding and drought, and broader ecological and health consequences. During the last thirty years, the number of disasters related to climate has tripled. Several popular natural events, caused by the climatic change, affected many cities like the bush fires in Australia (2020), drought in eastern Africa (2011, 2017 and 2019), the storm in Copenhagen (2011), and floodings in Southern Asia (2020). The Disasters related to climate change are pushing 20 million person/ year to move (Oxfam, 2021).

Recent observations indicate that global mean sea level is rising at a markedly accelerated pace: between 2006 and 2018, the rate increased to about 3.7 mm/year, more than twice the average rate of the 20th century (around 1.0–2.0 mm/year), and satellite records from 1993 to 2023 show that the annual rate has more than doubled from around 2.1 to 4.5 mm/year in recent decades (IPCC, 2021) (Hamlington, 2024). The study of the trend of the climate change effects shows that more harms will be caused on several countries. Some of these harms are: The decrease of 17.5% of the area of Bangladesh and 1% for Egypt, intense reduction of the biodiversity, and re-appearance of some sickness such as cholera (Santamaría-Gómez, 2017).

This critical situation makes the set of strategies and elaborates sustainable models to avoid natural disasters related to climate change an obligation. Cities started to build a strong strategy to improve their local air quality and to enhance their resilience which became widely cited as a key goal for both adaptation and mitigation efforts in cities and urban regions (Leichenko, 2011). Frequently used terms such as ‘climate resilient,’ and the ‘resilient city’ emphasize the idea that cities, urban systems, and urban constituencies need to be able to quickly bounce back from climate-related shocks and stresses (Boyd.E, 2008). Most studies describe the impacts of climate change in cities, but they do not clearly link these impacts to how climate actions should be selected or prioritized. This shows the need for more structured approaches that connect climate impacts with urban decision-making.

2.2. Climate related challenges in cities

Cities are central to the fight against climate change (Gouldson, 2016), and a powerful force in meeting this global challenge (van den Bergh, 2023). The principal physical risks that climate change poses to urban areas can be summarised under three main headings: the urban heat island effect and heatwaves, flooding from intense rainfall and rising sea levels, and drought and water scarcity, each threatening urban infrastructure, public health, and economic activity. Building on this overview of the physical challenges, Local governments are now expected more than ever to lead climate action planning as climate change intensifies and urbanization increases rapidly (Aboagye, 2024). Cities, industries and communities that dwell with overlap are critical for the future of life on earth (Gupta, 2024). With the majority of the global population living in urban areas, people are a key contributor to global GHG emissions (Hoornweg, 2010), rendering action plans by cities with great potential to build resilience to climate change (Betsill, 2006). In addition, cities, as local actors, can play a key role in developing and implementing climate change programs because they are located at the interface between local action and national- as well as level climate change adaptation and mitigation commitments (Heidrich, 2016). The importance of local actions as a means of securing global sustainable development was first highlighted, in the 1987 Brundtland Report and at the 1992 UNCED held in Rio de Janeiro, Brazil (the Rio Convention) (Betsill M. B., 2003), before being underscored at the 2015 UN Climate Change Conference (COP21) in Paris, where commitments made by cities to act were registered at the United Nations Framework Convention on Climate Change (UNFCCC) (Rosenzweig, 2018). The development of a climate action plan is an iterative process that involves ongoing stakeholder engagement, regular updates, as well as adaptability to changing conditions and knowledge (Harrison, 2013). Collaboration among government agencies, non-governmental organisations, businesses, and the communities is essential for successful climate action planning and implementation (Harangozo, 2015). Although the literature highlights the important role of cities in climate action, it mainly focuses on governance and collaboration aspects. There is still limited attention on how cities can systematically select and compare climate actions in practice. This gap supports the need for more structured and analytical approaches.

2.3. The Covenant of Mayors and the Development of SECAPs as Urban Climate Strategies

As an example of the strategies and initiatives developed by cities to address climate challenges, the European Commission (EC) launched the Covenant of Mayors (CoM), which brings together local and regional authorities voluntarily committing to develop and implement a Sustainable Energy and Climate Action Plan (SECAP) (Vullo, 2022), in order to reduce their energy related Greenhouse Gas (GHG) emissions a voluntary agreement under which local governments commit to reduce CO_2 emissions by at least 20% within 2020 (Molteni, 2017), then they focused on the active role of local authorities and increased its targets by 2016, through the Sustainable Energy and Climate Action Plans (SECAPs) in terms of greenhouse gas reduction from 20% to 40% by 2030 (Scorza.F, 2021), and an ambitious project is set to achieve climate neutrality by 2050 (Manzan.M, 2022). The Covenant of Mayors will tackle three key issues: climate change mitigation, adaptation to the several effects of climate change and universal access to secure, clean and affordable energy (Santopietro.L, 2020). The initiative registered a very rapid growth from 241 signatories in 2008 in the EU 27 to more than 10 000 signatories covering more than 869 million inhabitants worldwide in March 2020 (Kona.A, 2021).

Figure 2: Map of the updated Covenant signatories (Covenant of mayors, 2025)

Central to the Covenant of Mayors' functioning is its online platform, which serves as both a reporting interface and a comprehensive repository of municipal climate data. As of recent years, the website hosts thousands of reports submitted by local and regional authorities. For instance, around 8077 reports are publicly accessible, representing municipalities of various scales and geographical contexts (Figure 2). Each of these submissions follows a standardized reporting procedure based on the Common Reporting Framework (CRF), which ensures that the information provided is consistent and comparable throughout cities. This structure has been pivotal in creating one of the most extensive open datasets on local climate action worldwide, encompassing urban territories that together represent hundreds of millions of inhabitants (Kona.A, 2021). The framework allows policymakers, researchers, and citizens to monitor cities' commitments, implementation progress, and actual GHG reduction outcomes.

The preparation of a SECAP begins with the establishment of a Baseline Emission Inventory (BEI), which quantifies the city's GHG emissions during a selected base year. This inventory is essential for identifying the primary emission sources, such as residential and tertiary buildings, transport, and waste management, and for determining where the most impactful actions can be taken. Following this step, each city defines its own emission reduction target, generally expressed as a percentage reduction compared to the baseline. The targets, initially set at a minimum of 20% reduction by 2020, have evolved in alignment with EU policy frameworks to 40% by 2030, with many cities now aspiring toward climate neutrality by 2050. These objectives are formalized within the SECAP and supported by a portfolio of mitigation and adaptation measures specifically tailored to local contexts (Montés, 2025).

Each report uploaded to the Covenant of Mayors platform must include a minimum set of standardized elements, ensuring transparency and accountability. Among the mandatory information are the city's population, total area, and geographic boundaries, as these factors determine the scale and feasibility of proposed actions. Furthermore, the plan must detail the baseline year, total GHG emissions in tonnes of $CO_{2eq.}$, and per capita emission indicators. The city must also provide a comprehensive description of the actions planned or implemented, organized by sectors such as energy production, building efficiency, transport, waste management, and land use. For each action, signatories are expected to report the expected energy savings, estimated GHG reductions, implementation timeline, responsible bodies, and financial mechanisms supporting the measure (Keya, 2019). This standardized documentation process enhances comparability between municipalities and facilitates the aggregation of data at regional and continental levels.

Beyond the mandatory elements, the SECAP template also recommends the inclusion of contextual and analytical information that provides a deeper understanding of local conditions. This includes socioeconomic indicators, such as gross domestic product (GDP), employment distribution, and urban density, as well as qualitative assessments of the city's vulnerability to climate impacts. For example, adaptation components often require cities to conduct vulnerability and risk assessments to identify potential threats such as heatwaves, flooding, or drought. The combination of quantitative inventories and qualitative risk analyses ensures that the SECAP framework remains both rigorous and flexible, allowing cities of differing capacities and resource levels to participate meaningfully in the Covenant of Mayors initiative (Rivas, 2022).

The CoM reporting platform serves not only as a compliance tool but as a dynamic knowledge infrastructure. By consolidating thousands of reports, it enables large scale comparative analyses and the identification of common patterns, such as which types of actions yield the highest emission reductions or which governance models are most effective. According to the dataset compiled by Kona et al. (2021), the Covenant's database includes detailed records on over 6200 cities within Europe and neighbouring regions, with each entry containing metadata such as the signatory ID, country, population size, area, baseline year, emission inventory, reduction target, and progress achieved. These data enable the European Commission and researchers to evaluate collective progress toward EU climate goals and to identify where additional policy support may be needed.

However, the robustness of this framework also presents certain challenges. Studies have shown that while the number of signatories has grown rapidly, not all cities submit complete or updated monitoring reports. The transition from the initial SEAPs to the more complex SECAPs has required higher technical capacity, broader stakeholder involvement, and improved data management, which some municipalities still struggle to achieve. Rivas et al. (2021) note that a significant share of local authorities failed to deliver Monitoring Emission Inventories (MEIs) on time, limiting the ability to evaluate progress toward emission targets. The quality of data also varies, particularly in smaller municipalities with limited staff and technical expertise. As such, capacity-building and financial support from national and European institutions remain essential to ensure consistency and long-term reliability of the reporting system.

Despite these challenges, the Covenant of Mayors continues to be recognized as a cornerstone of European multi-level climate governance. The initiative's strength lies in its ability to translate global and regional climate ambitions into local action while fostering a shared sense of responsibility and community among municipalities. The SECAP framework, by requiring the inclusion of population data, geographical boundaries, baseline emission inventories, detailed descriptions of actions, expected reductions, and regular monitoring, has become an effective tool for both planning and evaluation. Furthermore, the transparent publication of these reports on the Covenant's website allows for public scrutiny, peer learning, and replication of successful practices throughout different contexts (Colocci, 2025).

Ultimately, the Covenant of Mayors demonstrates that city level action is not only a complement but an essential driver of broader climate policy. By institutionalizing reporting standards, encouraging measurable commitments, and fostering data transparency, it bridges the gap between high level policy frameworks and practical urban implementation. The presence of over 8000 accessible reports, each adhering to common methodological standards, represents an unprecedented resource for understanding how cities operationalize climate goals. This wealth of information enables the continuous refinement of local climate strategies and contributes to a growing body of knowledge on effective urban mitigation and adaptation. In this sense, the Covenant of Mayors and its SECAP platform are not only administrative mechanisms but active instruments of learning, collaboration, and transformation in the pursuit of urban climate resilience.

Despite the richness and scale of the Covenant of Mayors database, the existing literature has only partially explored its full potential. Most studies use this source for descriptive analysis or to evaluate specific indicators, but relatively few attempt to systematically analyse the large number of available reports to extract general patterns or support decision-making. In addition, the data are often treated at an aggregated level, limiting the ability to compare individual climate actions across cities. This highlights a clear gap in the literature, where this extensive and standardized dataset remains underused as a basis for developing analytical and data-driven tools. The present research addresses this limitation by using the Covenant of Mayors reports as a structured dataset to categorize climate actions and develop decision-support approaches.

2.4. Systematic and Computational Approaches to the Analysis of Urban Climate Action Plans

The increasing number of SECAPs published under the Covenant of Mayors initiative has generated a significant corpus of textual data describing local climate strategies, targets, and implementation mechanisms. While these documents represent valuable sources of information, their volume and heterogeneity make manual comparative analysis both time consuming and methodologically inconsistent. Consequently, systematic analytical approaches are required to extract patterns, categorize actions, and identify recurring strategic orientations across cities.

Urban climate governance literature has traditionally relied on qualitative case studies or policy analysis to assess municipal strategies (Heidrich, 2016) (Leichenko, 2011). Although these approaches provide an understanding of the governance dynamics, they often lack systematic comparability when large samples of cities are considered. However, quantitative assessments frequently focus on emission inventories or technical performance indicators (Molteni, 2017), with limited attention to the textual and strategic content of action plans themselves. This gap highlights the need for analytical approaches capable of bridging large scale document analysis with governance-oriented inquiry. Such an approach is directly aligned with the objectives of Sustainable Development Goals 11 and 13. SDG 11 emphasizes sustainable and resilient urban systems, while SDG 13 calls for the integration of climate action into policies, strategies, and planning processes (Nations, 2022). Systematically analysing municipal climate plans contributes to evaluating how cities operationalize these global objectives within local contexts. In this sense, the study of SECAP documents is not only descriptive, but it also constitutes an assessment of how global sustainability frameworks are translated into urban policy instruments. Although recent studies recognize the potential of systematic and computational approaches, their application to urban climate action plans remains limited. Most existing work still relies on either qualitative analysis or isolated quantitative indicators, without fully exploiting the potential of large-scale textual datasets. This shows a clear need for approaches that combine systematic data analysis with practical decision-support tools.

2.4.1. Text mining as a method for reports analysis

Text mining has emerged as an interdisciplinary field combining information retrieval, machine learning, natural language processing, and statistical modelling to extract structured knowledge from unstructured textual data (Hotho, 2005) (Talib, 2016). Unlike traditional data mining, which operates primarily on structured numerical datasets, text mining transforms qualitative documents into analysable representations, enabling systematic comparison across large datasets.

Theoretical foundations of text mining rest on the representation of documents as structured vectors of terms (Bag of Words or Vector Space models), followed by feature selection, clustering, categorization, and pattern detection (Rajamani, 2017). Techniques such as information extraction, summarization, and matrix-based modelling allow researchers to reduce complexity while preserving semantic meaning (Dang, 2014).

In the context of climate governance research, text mining offers three theoretical advantages. First, it enhances transparency and replicability in policy analysis by formalizing classification procedures. Second, it allows the identification of latent structures within strategic documents, such as recurring intervention types or consistent co-benefit narratives. Third, it enables scaling from exploratory case studies to larger comparative datasets. The relevance of computational text analysis in environmental governance research has increased in recent years, particularly for analysing climate pledges, sustainability reports, and municipal strategies (Antons, 2020). These methods allow researchers to move beyond anecdotal comparison and toward systematic knowledge discovery across policy datasets. While text mining offers a structured approach for analysing large sets of documents, other machine learning methods such as neural networks, topic modelling techniques (e.g., Latent Dirichlet Allocation), and deep learning approaches are also used for text analysis. These methods can provide more complex representations of textual data but often require larger datasets and are less interpretable. In this research, text mining was preferred because it provides a transparent and interpretable framework that is well suited for identifying patterns and categorizing climate actions in a way that can be directly used for comparison and decision-making. Despite this potential, text mining has rarely been applied to convert the heterogeneous content of urban climate action plans into a consistent, comparable set of action categories; this research uses it for precisely that purpose, providing the structured input required by the subsequent decision-support model.

2.5. The Role of Data Science Tools in Evidence-Based Climate Action Planning

The increasing complexity of climate governance at the urban scale has created an urgent need for structured, data-driven decision-support tools (Betsill M. M., 2005). Cities operate at the intersection of environmental, social, spatial, and economic systems, making climate action planning a multidimensional challenge (Meerow, 2016). Traditional planning approaches, often reliant on qualitative assessments and sector-specific strategies, may fail to fully capture the interdependencies between urban characteristics and climate interventions (Kitchin, 2014). As a result, there is growing recognition that computational and data science tools can significantly enhance the transparency and replicability of climate action planning (Janssen, 2018).

Thousands of climate action plans have been published worldwide, particularly within transnational municipal networks such as the Covenant of Mayors for Climate and Energy. While these reports provide valuable documentation of mitigation and adaptation strategies, they are rarely transformed into structured knowledge systems capable of informing future decision making. The transition from descriptive reporting to predictive and prescriptive tools represents a methodological advancement in climate governance research. Data science enables the systematic extraction, categorization, and modelling of large volumes of policy data. By analysing patterns across hundreds of published climate actions, it becomes possible to identify recurring strategic logics and contextual determinants. Such approaches align with the broader movement toward evidence-based policymaking, which emphasizes the integration of empirical data into governance processes (Head, 2016). In climate planning specifically, evidence-based approaches enhance accountability, reduce trial and error implementation, and support more efficient allocation of limited financial resources (Reckien, 2018).

Developing decision-support tools from published action plans contributes to the knowledge transfer between cities, the identification of best practices, the standardization of planning logic, the reduction of planning uncertainty and an increased strategic coherence in urban contexts. This transformation reflects a shift from static documentation toward dynamic analytical frameworks capable of guiding future interventions (Andersson-Sköld, 2016). Despite the growing use of data science tools in urban studies, their application to climate action planning remains limited. Most existing approaches focus on data analysis but do not provide practical decision-support tools that can directly guide the selection of climate actions. This highlights the need for methods that move from analysis to application, which is addressed through the development of a data-driven decision-support model.

2.5.1. Decision Trees

Among machine learning approaches, decision trees are particularly suitable for policy applications due to their interpretability and logical structure (James G. W., 2013). Unlike ‘black box’ algorithms, decision trees provide clear branching logic that mirrors human reasoning processes. This characteristic is especially important in public policy contexts, where transparency is essential for stakeholder trust and institutional legitimacy. Decision trees operate by recursively partitioning data based on feature thresholds, identifying the most informative variables that explain variations in categorical outcomes. In urban climate planning, such outcomes may include the prioritization of specific action categories like building renovation, renewable energy transition and transport optimization. By integrating urban features such as demographic indicators, spatial distribution characteristics, energy profiles, and financial capacity, the decision tree framework allows for context-sensitive recommendations. The value of decision trees in environmental and urban research has been widely acknowledged. They have been applied in risk assessment, land-use classification, sustainability performance evaluation, and energy system modelling (Olden, 2008). Their strength lies not only in predictive capacity but in their ability to reveal underlying structural relationships between variables. In the context of climate action planning, a decision tree model derived from empirical analysis of hundreds of published actions represents a form of collective policy intelligence. Rather than prescribing universal solutions, it identifies probabilistic pathways based on contextual similarities. This contributes to adaptive planning and supports municipalities in selecting actions that are consistent with their socio-spatial characteristics. However, although decision trees have been widely applied to environmental and urban problems, their use as a transparent decision-support tool for selecting and prioritising urban climate actions from large, multi-city datasets remains largely unexplored. This gap is directly addressed by a decision tree model trained on hundreds of published action plans to guide context-sensitive climate action selection.

2.5.2. The Importance of API supported data integration

A critical advancement in contemporary urban analytics is the integration of Application Programming Interfaces (APIs) as mechanisms for real-time and large-scale data collection. APIs enable automated access to structured datasets from external platforms, facilitating reproducibility and scalability in urban research (Jacobson, 2012). In climate related modelling, APIs play a vital role in collecting spatial distribution data like land use and infrastructure networks, climatic variables, energy consumption statistics and geodemographic dynamics. For example, open-source spatial platforms such as OpenStreetMap (OSM) allow researchers to bring back standardized geospatial information for cities worldwide. The use of APIs ensures methodological consistency, reduces manual data errors, and enhances the comparability of urban case studies. Nevertheless, while APIs are increasingly used for isolated data tasks, their systematic integration to enrich multi-city climate action datasets with consistent geodemographic and spatial features has received little attention. The present research closes this gap by using API-based data integration to build the unified database that underpins the proposed decision-support model.

The incorporation of API supported data collection strengthens the analytical framework in three main ways:

- Scalability
- Objectivity
- Dynamic updating

From a governance perspective, API integration aligns with the concept of ‘data-driven urbanism’, where digital infrastructures support smarter, more adaptive city management (Kitchin, 2014).

By structuring heterogeneous climate action reports into a coherent predictive model, data science tools enhance the strategic alignment of urban interventions with resilience objectives, improve mitigation and adaptation targeting, facilitate monitoring and evaluation, and Support long-term sustainability transitions. In this sense, computational decision-support models do not replace policy judgment but augment it, enabling more informed and context-sensitive climate governance.

2.6. Research assumptions

By revisiting the research questions established in Section 1.5 and conducting a critical review of the findings and connections with the already available and above mentioned literature, it becomes possible to formulate the corresponding research assumptions. The three research assumptions are as follows.

RA1: Applying systematic analytical approaches to published urban climate action plans allow the identification and categorization of recurring climate action patterns across municipalities.

RA2: Increasing public awareness through a higher number of climate actions targeting citizens, together with improvements in education levels, contributes to better environmental outcomes by supporting emission reduction and improving air quality in urban areas.

RA3: Urban climate action planning can be improved by using decision-support tools based on the analysis of existing climate action plans, as these tools allow cities to identify more appropriate and evidence-based climate actions.

RA4: The environmental performance of climate action projects is strongly influenced by the type and amount of construction materials used, and a material-based evaluation at the project level allows a more consistent comparison between different types of interventions.

3. Data and Methods

This section presents the methodological approaches used to investigate the research assumptions of this thesis. The chapter is organized into four parts, each corresponding to one of the research assumptions and the associated analytical study. For each part, the methodological workflow and supporting flowcharts are presented together with a description of the data and data sources used in the analysis. The explanation of methods and data collection is therefore integrated within each subsection in order to clearly illustrate the analytical procedures followed in the different studies.

3.1. Exploratory Analysis of 99 SECAP Reports

Building on the text mining general principles and methodological considerations mentioned in section 2.4.1, an exploratory analysis was conducted during the initial phase of this doctoral research, focusing on a sample of 99 SECAP documents published by European municipalities under the Covenant of Mayors framework (Figure 3). The selection of these 99 reports was carried out from a larger pool of available documents, with the aim of ensuring diversity in terms of geographic location, city size, and types of climate actions included in the plans.

Particular attention was given to selecting reports that contain a wide range of actions across different sectors in order to facilitate the development of the categorization process and the application of text mining techniques. This sample was therefore not intended to be exhaustive, but rather representative and suitable for testing the methodological approach. Therefore, this analysis served as a pilot study designed to test the applicability of text mining techniques for structured comparison of urban climate strategies. The dataset will be expanded in subsequent stages of the research.

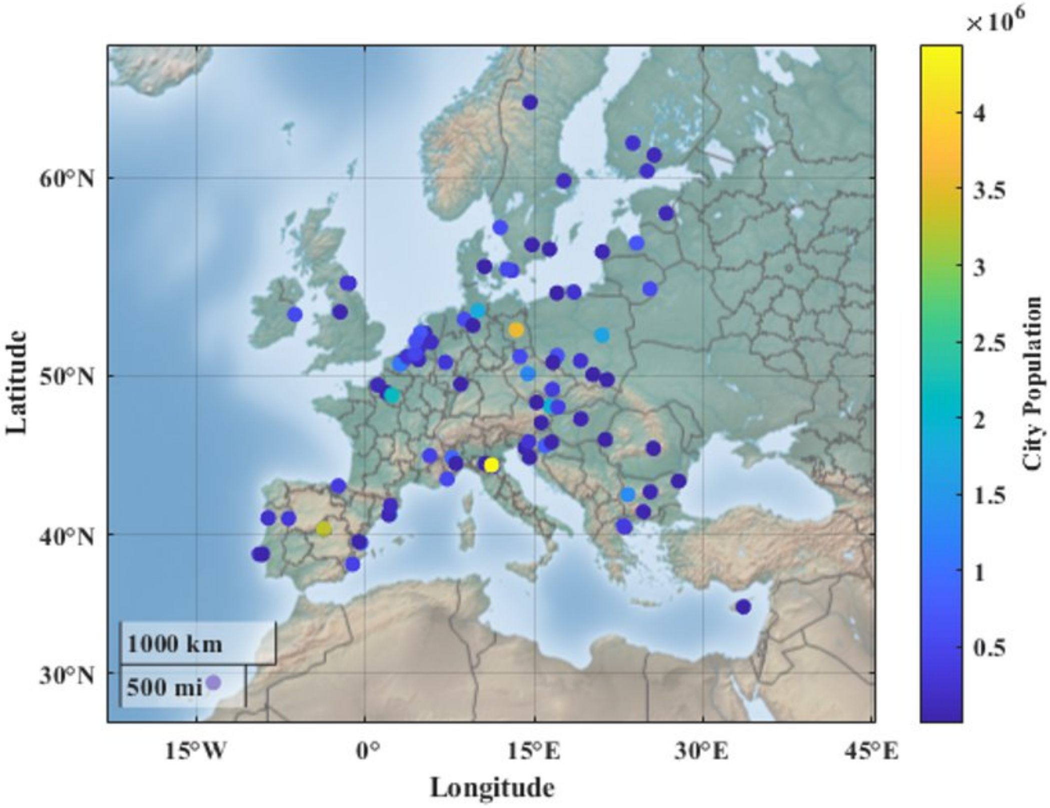


Figure 3: Geographic localisation of the different action plans added to the covenant of mayors website.

The analytical process consisted of several steps consistent with established text mining procedures (Figure 6):

- Data gathering

SECAP documents were collected from the Covenant of Mayors repository. These reports detail mitigation targets, adaptation measures, sectoral interventions, and implementation mechanisms.

- Structured Information Extraction

Key attributes were systematically extracted and organized into a detailed classification table. These included city characteristics (population, area), year of accession, action plan type, declared impacts, co-benefits, and budget allocation.

- Categorization of climate actions

Through iterative thematic grouping, ten major categories of climate action were identified (Figure 4), including:

- Building renovation and insulation
- Heat system improvement
- Community engagement
- Transportation optimization
- Renewable energy transition
- Green infrastructure development
- Flood prevention
- Data analysis strategies
- Financial mechanisms

Categorization reduces semantic variability and supports cross-city comparability (Rajamani, 2017).

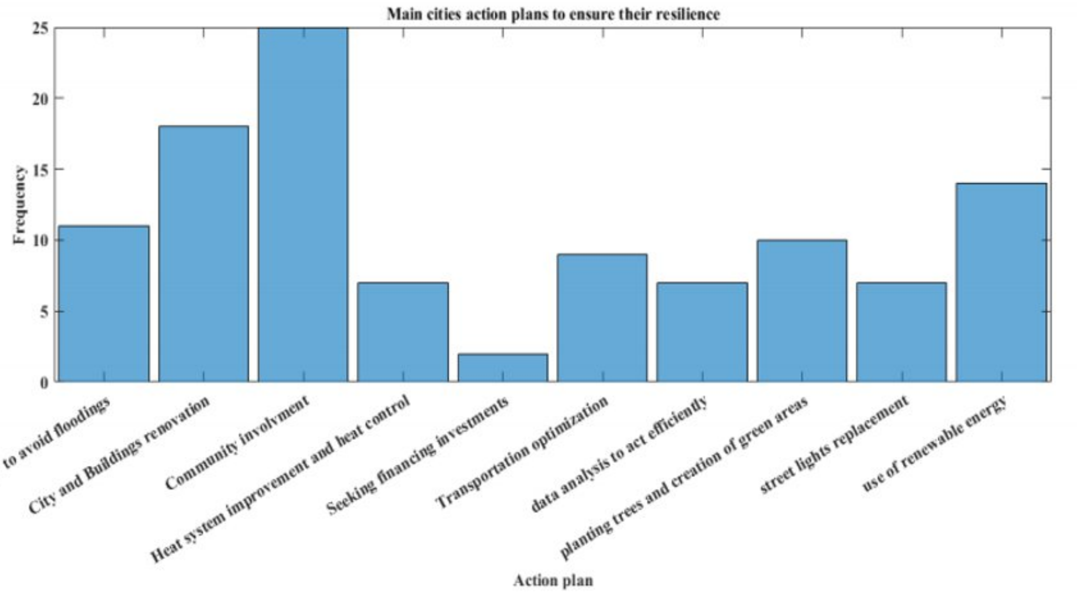


Figure 4: Occurrence of the action plan categories in the cities publications.

- Co-benefits extraction and classification

In parallel, nine categories of co-benefits were identified, including awareness raising, biodiversity protection, economic savings, traffic reduction, and citizen safety (Figure 5). The identification of co-benefits is consistent with climate policy literature emphasizing that mitigation strategies produce multiple socio-economic and environmental gains beyond emission reduction (Urge-Vorsatz, 2014).

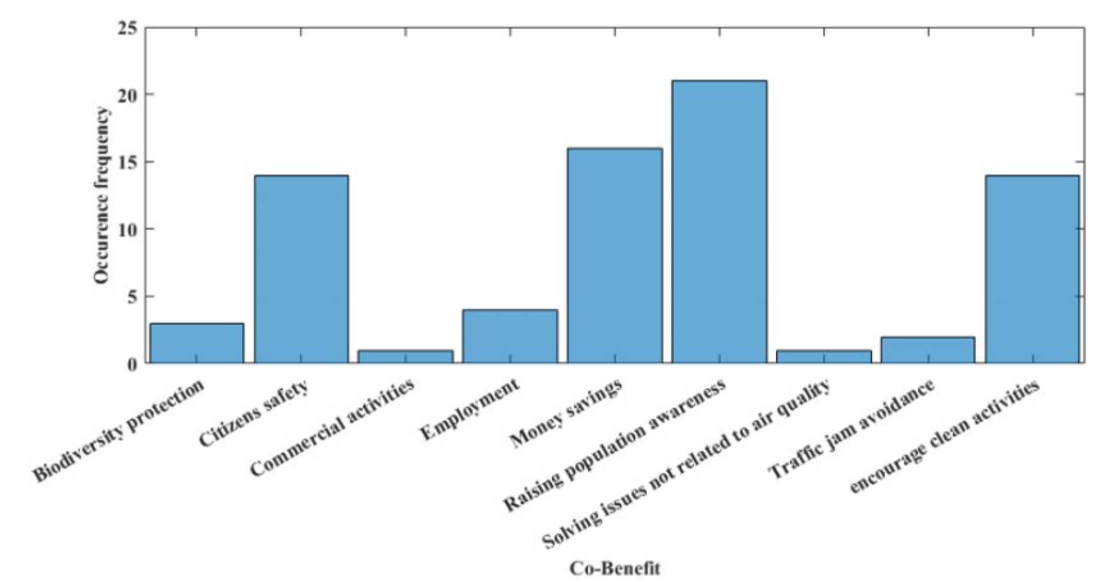


Figure 5: Co-benefit occurrence in the cities publications.

- Summarization and matrix extraction

To enhance analytical clarity, a simplified classification table was developed, followed by the creation of two binary matrices inspired by Q-matrix modelling approaches (Barnes, 2005). The first matrix mapped the occurrence of action plan categories across cities. The second linked action categories to co-benefit categories, allowing identification of structured relationships between intervention types and declared benefits.

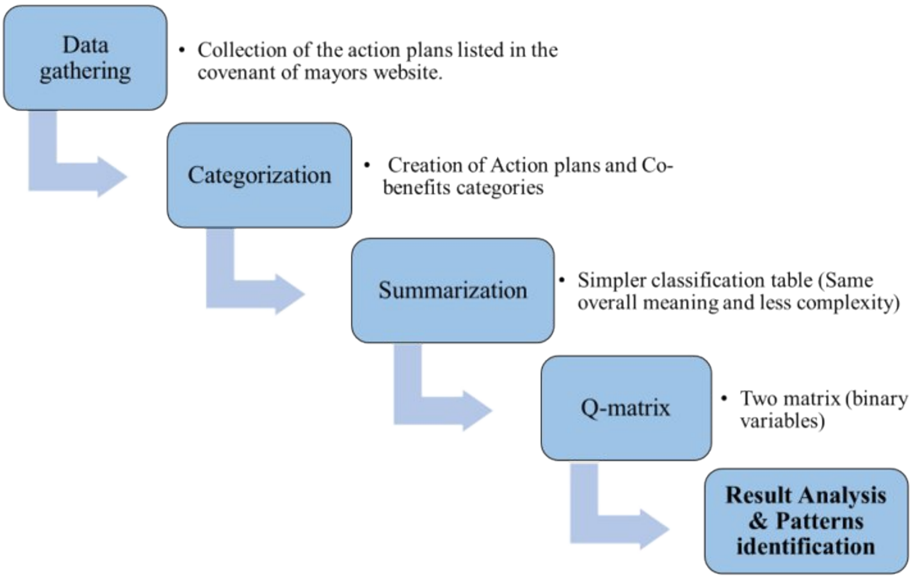


Figure 6: Application of a text mining concept on the case study.

The exploratory results showed several recurring patterns: Community engagement measures have become increasingly prominent in recent SECAP publications, suggesting growing attention to participatory governance, which is a key principle of SDG 11. Building renovation measures were particularly prevalent in Central and Eastern European cities, reflecting infrastructural modernization needs. Renewable energy transitions and transportation optimization appeared consistently throughout the different municipal contexts. The analysis demonstrated systematic relationships between intervention types and specific co-benefits (Figure 7). For example, transportation measures were frequently associated with traffic reduction and air quality improvement, while green infrastructure projects were linked to biodiversity protection and public health benefits. These findings indicate that urban climate strategies exhibit patterned internal structures rather than isolated interventions.

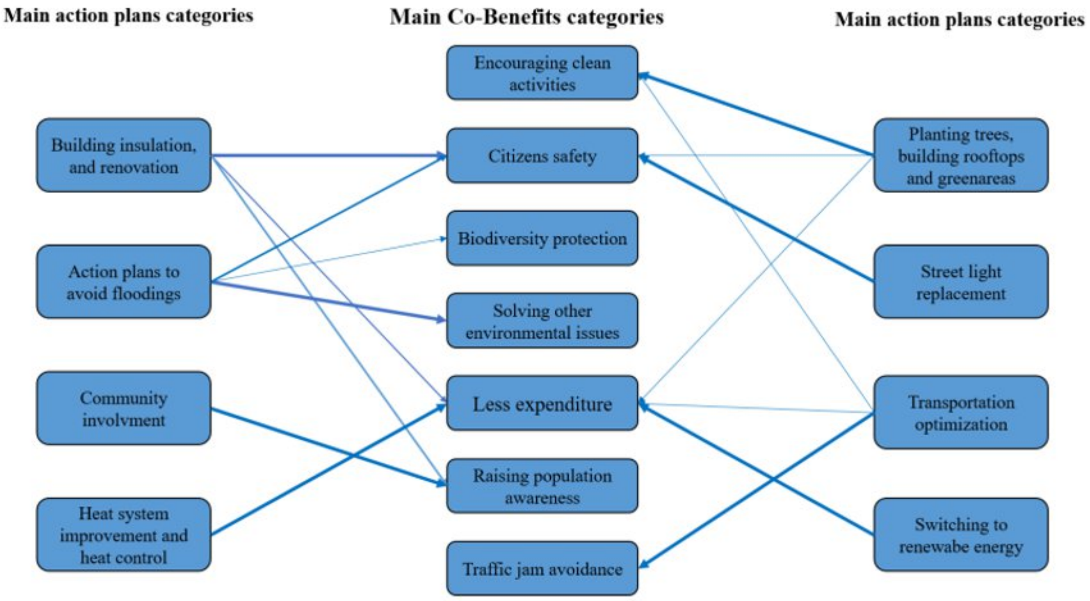


Figure 7: Relation action plans - Co benefit categories.

This initial sample-based investigation serves as a methodological foundation for the broader research framework developed in this thesis. The dataset will be expanded and complemented with additional analytical layers, including spatial distribution analysis and life cycle assessment of material related impacts. In doing so, the research advances toward a more comprehensive framework for assessing how cities operationalize SDG 11 and SDG 13 through structured and context sensitive climate action strategies.

This analysis served as a preparatory pilot study that validated the text-mining approach and produced the initial categorisation scheme, but its sample of 99 reports was too small to train a reliable model, which is what motivated the expansion to the 454-report database used in the main study.

3.2. Conceptual Framework for Assessing the Role of Public Awareness in Urban Climate Resilience

This part of the work is an exploratory, country-level analysis intended to motivate the inclusion of public awareness as a factor in the urban-scale study that follows. The comparison among three contrasting countries (Germany, Brazil, and Kenya) is therefore presented as an associational observation rather than a causal claim, since three cases are too few to isolate causal effects among awareness, education, air quality, and emissions; the country scale was chosen because reliable, comparable education and awareness indicators are not consistently available at the city level. As shown in Figure 8, awareness indicators are extracted for each case and linked to the emissions situation, with the findings to be read in this scoped sense.

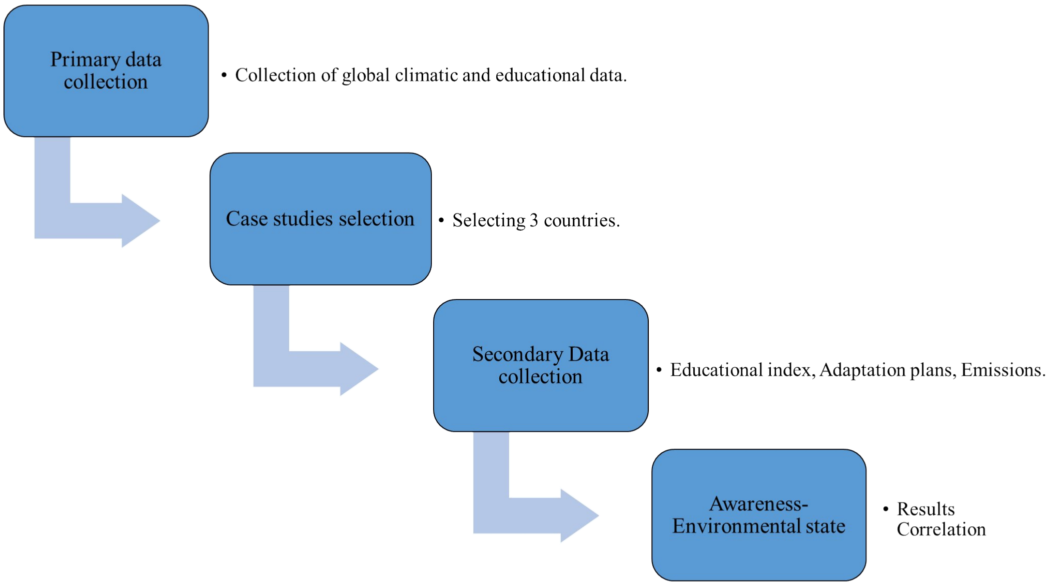


Figure 8: Work methodology to analyse the role of raising awareness in ensuring cities resilience.

3.2.1. Case study selection

The three countries (Germany, Brazil, and Kenya) were selected to maximise contrast in climatic, educational, and awareness conditions, so that any relationship between awareness and environmental outcomes would be visible across very different settings.

Germany is part of the temperate, rainy climate zone of the mid-latitudes (Kaspar, 2013). The annual mean temperature between Sylt (an island in northern Germany) and the Zugspitze (Germany's highest peak) from 1961 to 1990 was 8.2°C. Germany has a very strong educational system, ranked the third among the countries with the best educational systems, and fourth among the countries with the most educated population (Table 1).

Brazil experiences equatorial, tropical as well as subtropical climates (Alvares, 2013). The annual average temperature in the region is 22 to 26 °C, with not much variation between the warmest and the coldest months. The education system in Brazil is ranked 36 in the educational ranking of 2023 (Table 1).

Kenya has three types of climates: temperate subtropical climate in the west and southwest highlands (where Nairobi is located), hot and humid along the coast, and hot and dry in the north and east (Griffiths, 1962). The education system in Kenya is ranked 68 in the educational ranking of 2023 (Table 1).

Table 1: Main climatic and educational characteristics of Germany, Brazil and Kenya.

	Population (2023)	Climatic zone	Educational ranking (2023)
Germany	83 294 633	Temperate, rainy	3
Brazil	216 422 446	Equatorial	36
Kenya	55 100 586	Hot, temperate subtropical	68

3.2.2. Secondary data collection

The indicators used in this analysis are summarised in Table 2, together with their data source, reference year, and measurement unit. Education and awareness are characterised by the adult literacy rate, average years of schooling, completion rates at primary, upper-secondary, and tertiary level, and public spending on education as a share of GDP, all drawn from Our World in Data. Climate-related awareness is described by the Lenzholzer et al. (2020) international overview, which reports the share of citizens and policymakers aware of selected adaptation strategies. Environmental performance is measured by annual CO_2 emissions, the country contribution to the global temperature rise, and pollution-related mortality (deaths per 100 000 inhabitants), drawn from Our World in Data; the adaptation-plan information used to identify whether the countries include social actions in their strategies is taken from the CDP and the Covenant of mayors reports.

Table 2: Indicators used in the public-awareness analysis, with sources, reference years, and units.

Indicator	Unit	Reference year	Source
Adult literacy rate	%	2021	Our World in Data
Average years of schooling	years	2021	Our World in Data
Completion rate (primary / upper-secondary / tertiary)	%	2021	Our World in Data
Public spending on education	% of GDP	2018	Our World in Data
Climate-adaptation awareness (citizens, policymakers)	%	2020	Lenzholzer et al. (2020)
Annual CO_2 emissions	million tonnes	1990–2021	Our World in Data
Pollution-related mortality	deaths per 100 000	2017–2019	Our World in Data
Climate adaptation plans	count / categorical	2017	CDP, CoM reports

Two comparability limits apply. First, the reference year is not identical across all indicators (Table 2). The differences mainly affect static indicators such as public spending (2018) used alongside multi-year trends like emissions (1990–2021), and the results should therefore be read as an indicative association rather than a strictly synchronised snapshot. Second, the indicators are measured at the national level, which matches the availability of comparable education and awareness data but is coarser than the urban focus of the rest of the dissertation.

The implicit assumption followed in this analysis, justified by the gradual nature of educational attainment, is treating education and awareness as relatively stable, slowly changing structural characteristics of a population, and links them to multi-year trends in emissions rather than to single-year values.

3.2.3. Public awareness-Air quality

In this step, the awareness indicators are linked to the emissions situation in each case. Because the three countries differ simultaneously in climate and in educational level, the comparison is interpreted as an associational observation rather than evidence of a causal effect of awareness on air quality or resilience.

3.3. Development of a Decision-Support Model for Climate Action Planning Based on Published Urban Action Plans

Following the analysis of the role of public awareness in enhancing urban climate resilience, the next step focuses on supporting the planning process of climate actions through a data-driven approach. Whereas the public-awareness analysis was carried out at the national scale, as an exploratory step constrained by the availability of comparable data, the decision-support model operates at the city level and draws on a large dataset of individual European cities. This shift from a few contrasting countries to hundreds of cities allows the broad association observed earlier to be examined with the granularity and empirical basis required for practical, city-specific planning.

This part of the study presents the methodological approach used to develop a data-driven decision-support model for urban climate action planning. This model is built around a machine-learning technique, the decision tree, which forms its analytical core. Among the various techniques available in data science and machine learning, the decision tree method was selected because it allows complex decision-making processes to be represented in a clear and structured way, making it particularly suitable for planning contexts where several environmental, social, and spatial factors must be considered simultaneously. Its transparent and easily interpretable results are a further advantage, since the aim is not only to classify cities but to turn this analysis into a decision-support model that planners and decision-makers can understand and use. In practice, the decision tree identifies the relationships between city characteristics and the types of climate actions implemented, while the decision-support model is the broader tool that translates these patterns, extracted from previously published experiences, into structured guidance for selecting appropriate actions. The model was developed using data extracted from climate action plans published by European cities. Europe was selected as the study area due to the large availability of publicly accessible climate action reports and the diversity of climatic, geographical, and socio-economic conditions across the continent. European cities face a wide range of climate-related challenges, including heat waves, flooding, air pollution, and changing precipitation patterns, which makes the region a suitable context for examining different approaches to climate action planning. Furthermore, the presence of several international initiatives encouraging cities to publish their climate strategies has resulted in the creation of extensive databases of urban climate actions. One of the most important platforms in this regard is the Covenant of Mayors initiative, which collects and publishes climate action plans developed by local authorities.

The database was constructed through the analysis of 454 adaptation strategy reports from 443 distinct European cities located in 32 different countries. These reports were selected from a total of 8077 publications listed on the Covenant of Mayors website, which represents one of the largest publicly available repositories of municipal climate action plans. By analysing this large set of documented actions, it becomes possible to identify common strategies, extract relevant planning parameters, and use these insights to build a structured decision-support model for future climate action planning.

Figure 9 showcases the diverse climate classes and population distributions across target cities. The definition of the climate class codes added in the figure can be found in the abbreviation list. The readily apparent variations in both population and climate class across the map underscore the importance of selecting cities with distinct characteristics. Homogenizing their selection according to criteria such as population range, climate class, and climate hazards could negatively impact the predictive accuracy of the final results. By incorporating a wider range of data points and ensuring diversity, the capabilities of the model are enhanced in terms of capturing the complexities of real-world scenarios and delivering reliable predictions.

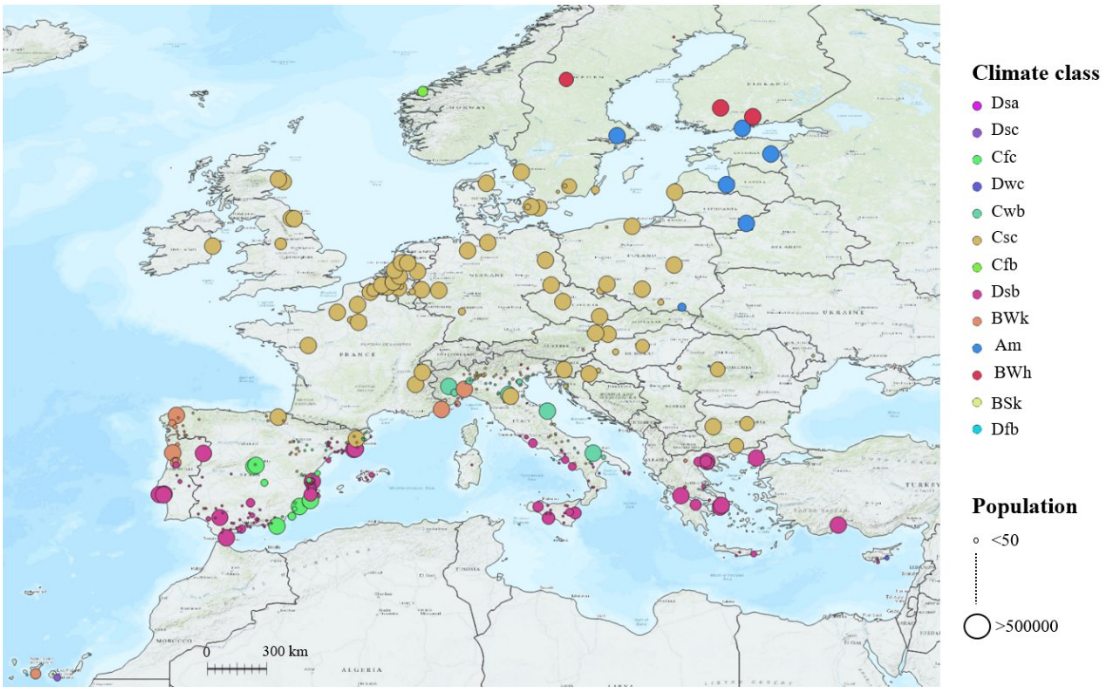


Figure 9: The population and climate class distribution of the analysed European cities.

The steps of the process, followed to create a decision tree model are presented in Figure 10. Firstly, the modelling variables and existing climate actions necessary to create the database are collected. Characteristics of the cities are then integrated through external data sources by Application Programming Interfaces (APIs), before the decision tree model drawn up. The structure of the model is optimized both beforehand and afterwards, as a result of which the selection of the potential and most promising climate change actions in the future can be realized. This methodology provides a groundbreaking way to enhance climate change planning.

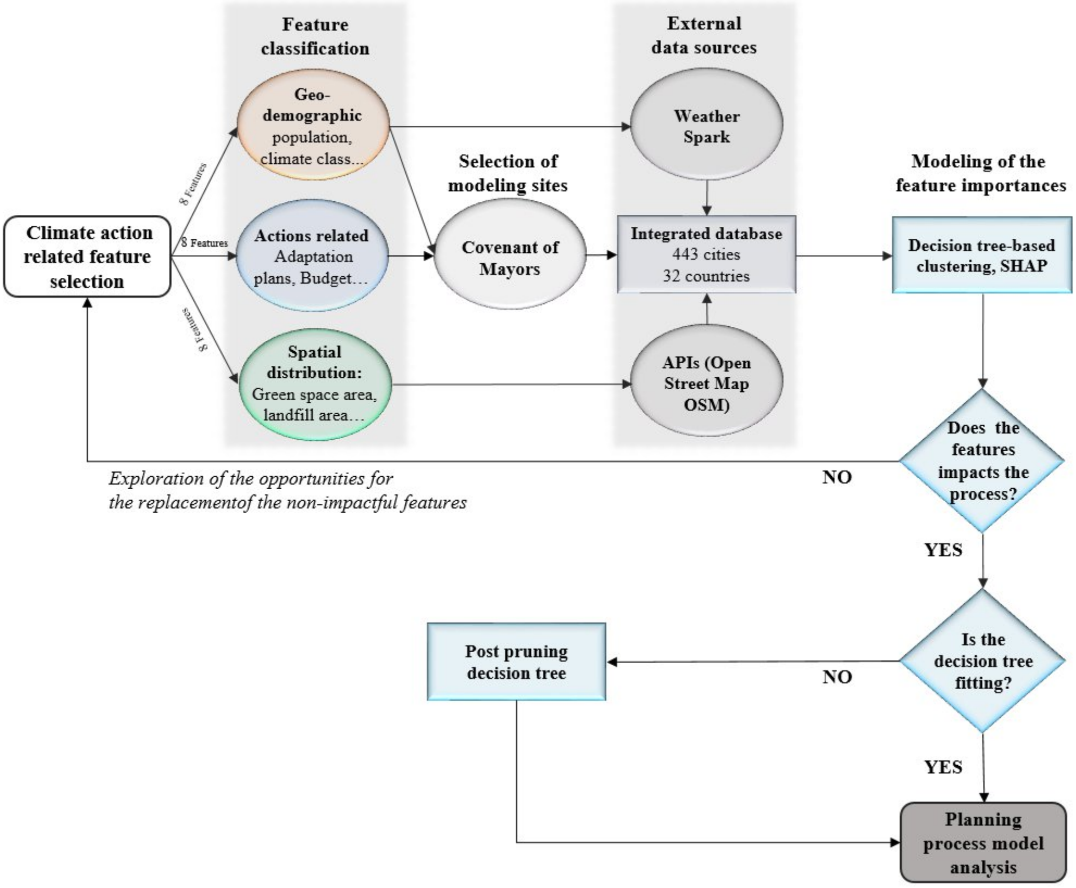


Figure 10: Workflow for the climate action plan selection algorithm.

3.3.1. Feature selection

The initial phase of the climate action planning process involves choosing the parameters that must be taken into account to gather the most details about the conditions and situations of each city. Feature Selection is one of the most important and frequently used techniques in data preprocessing for data mining. Selecting the maximum number of impactful features is a key condition to obtain an accurate decision tree (Esmaeili, 2011).

Planning for climate change involves consideration of a wide range of parameters, including fundamental environmental data such as greenhouse gas emissions and pollutant levels. Additionally, socio-economic factors like job creation, the budget for climate action, and land use considerations, e.g the extent of green spaces and deforestation rates, are also critical. However, incorporating such a huge number of parameters into a final model is challenging due to data availability and the complexity of the results: Collecting all the necessary data for 443 cities is difficult, and including every parameter could make the decision tree too complex, thereby reducing its accuracy. Therefore, a focused search was conducted to identify the most crucial features. These key parameters were selected to ensure that accurate and reliable results would be achieved by adding them to the database. 24 features were selected in this climate action framework (Seto, 2016), which can be classified into three categories: Geodemographic features, spatial distribution features and action plan-related features (as highlighted in Figure 10).

Eight features from all the parameters considered are classified as geodemographic:

- Population (1) and population density (2): Population plays a crucial role in shaping the category of an effective action plan when considering the combined population of the target cities, by serving as a valuable metric to assess the distribution of the impact of adaptation plans among sub-populations within each city (Levy, 2002). Every city incorporated population data in the reports published on the Covenant of Mayors website. Population density directly influences air pollution, with a higher population density correlating to an elevated level of air pollution (Chen, 2020).
- Temperature (°C) (3) and precipitation (mm) (4): The direct impact of local climate effects, influences vulnerability and adaptation needs for specific regions. By incorporating those factors, a decision tree can tailor climate action plans to address those specific challenges (Cisse, 2022). Data for these two features were primarily gathered from the Weather Spark website.
- Climate classes (5) and hazards (6): Incorporating climate classes (Köppen climate classification) and the climate hazards of each city into a decision tree for climate action planning is essential to provide a framework for understanding the regional climate patterns, tailor mitigation and adaptation strategies accordingly, identify vulnerable areas, prioritize risk reduction measures, and build resilient infrastructure (Wannous, 2017). In order to avoid any issues during the simulation of the decision tree, the climate hazards added to the database were categorized into 11 categories: Floods, droughts, heatwaves, coastal erosion and sea level rise, extremely cold temperatures, coastal flooding, heavy rainfall, snowstorms, strong winds, wildfires and storm surges.

- Human Development Index (HDI) (7): Considering this feature is crucial to ensure the equitable distribution of resources, prioritize vulnerable communities, as well as empower individuals and communities to adapt to climate change (Telleria, 2023).
- Geographic location (Coastal/Landlocked) (8): This is strongly related to determining the exposure of the target cities to specific climate hazards which influences the choice of mitigation and adaptation strategies (Leal Filho, 2019).

The second group of parameters added to the database are classified as spatial distribution features. The inclusion of these features aims to visually represent the allocation of space for each sector in targeted cities. Collecting the spatial distribution features of a city is crucial with regard to climate action planning because it helps identify areas most vulnerable to climate impacts, optimize resource allocation, as well as design targeted interventions that enhance urban resilience and sustainability. These data were mainly collected through the Open Street Map (Figure 10):

- Total city area (1): This influences the urban heat effect, and the scale of infrastructure requirements, impacting mitigation and adaptation strategies (Makunda, 2020).
- Landfill (2) and industrial (3) areas: the industrial sector is a significant source of greenhouse gas emissions and contributes to environmental degradation. Analysing and addressing these areas is crucial to develop effective climate action plans (Johnson, 2023).
- Agricultural (4) as well as lake, and water body (5) areas: play crucial roles in carbon sequestration, water management, and biodiversity conservation, making their consideration essential for developing comprehensive climate action plans (Alberti, 2022).
- Green areas (6): A key feature when assessing the effectiveness of nature-based solutions (Kabisch, 2016).
- Cumulative building area (7) and the total length of roads (8): Both are important when evaluating the impact of urbanization on energy consumption and transportation emissions, as well as developing strategies for sustainable urban development (Grimmond, 2014).

The final group of features is comprised of action-related parameters, which are the most important because collecting data related to the climate actions themselves is essential (Figure 10). Eight more preliminary selected features are tailored to the published action plans, which is why the primary source of data for these parameters is the reports released by the various targeted cities published on the Covenant of Mayors website:

- Adaptation plans (1): A basic feature, as the analysis of published action plans serves as the primary source of inspiration when identifying actions that will be regarded as final outputs. The process commenced by extracting details from each action plan, followed by categorizing them into 10 distinct categories. A code was assigned to each category to streamline the simulation step as well as improve the visualization and analysis of the decision tree (Table 3, first column).
- Public awareness actions (2): By analysing the published awareness actions, it was revealed that nearly all the cities intend to implement social actions in order to raise awareness of climate challenges. This observation prompted the inclusion of this feature. The identical process of transforming detailed adaptation plans into codes was applied to the public awareness actions feature (Table 3, second column).
- GHG emissions per capita (3) and emission reduction targets in 2030(4) and 2050(5): It is necessary to quantify the emissions and be aware of the short and long-term emissions reduction targets of each city, in order to align the mitigation strategies with the overall climate goals and assess the effectiveness of implemented measures.
- Energy supply (6) and renewable energy ratio (7): The aim of adding such features is to evaluate the effectiveness of energy transition strategies in each city, in order to prioritize investments in renewable energy infrastructure (Asmelash, 2021).
- Budget of adaptation plans (8): This is essential to prioritize feasible and implementable climate action strategies, ensure financial viability, and allocate resources effectively.

Table 3: Codes attributed to the adaptation plans and public awareness actions

Action plan category	Code	Public awareness action category	Code
Buildings retrofit and renovations	Br	Campaigns and projects to involve citizens	CA
Heat control and improvement of heating systems	Hi	Training and education	TR
Seeking financial investments, and joining projects	Fi	Lessons on eco-driving	DR
Involving the community in decision making phase	Ci	Creation of websites, information points and surveys	WEB
Optimizing transportation	To	Public events (ex: running)	EV
Street light replacement	Str	Adding Policies and regulation promoting the reduction of emissions	PO
Transition to renewable energy	Re		
Adding green areas, parks and planting trees	Tp		
Enhance monitoring systems and data analysis	Da		

3.3.2. Boundary conditions to identify the decision tree model

The previously constructed database will serve as the input table when incorporating the relevant Python script to identify the decision tree model. The initial task in this step is to decide whether or not to employ a regression or classification decision tree. A regression tree is used to predict a continuous target when the predicted outcome is a real number, while a classification tree is used to predict a categorical target variable and the class to which the data belongs. Based on these definitions, the most suitable decision tree in our case is a classification tree, as our objective is to obtain the adaptation class that aligns with the conditions of as the final output. It should be noted that cities typically implement several climate actions simultaneously. The dependent variable was therefore defined as the single, primary action category that a city should prioritise given its specific characteristics, rather than the only action it should undertake. For this reason, the problem was treated as a single-label classification task, in which the predicted class represents the dominant or most strongly recommended category. This definition is consistent with the analysis of the published reports, where, although most cities adopt multiple actions concurrently, a primary strategy could be identified for each city. The model thus guides the prioritisation of actions and remains fully compatible with the parallel implementation of complementary measures. Next two important boundary conditions must be evaluated:

- Modelling Feature Importance: The goal of this step is to enhance the accuracy of the final model by identifying and removing features that have a minimal impact on the results. Non-influential features will be excluded from the input table since they do not alter the final results and can have a detrimental effect on the visualization of the decision tree.
- Selection of Optimal Depth Size: This step entails choosing the most suitable depth size for the decision tree. Choosing the optimal number of levels in the decision tree is crucial to achieve the most accurate model accuracy. A tree that is too small may overlook important data, reducing accuracy, while a tree that is too large becomes complex and difficult to interpret.

To accomplish this task, the proposed approach involves creating decision trees with various sets of features and depth, subsequently calculating the training and testing accuracy of each. The decision tree that is ultimately selected will be the most accurate one. The training and testing accuracy use the same formula and differ only in the set of samples evaluated. The training set for the training accuracy and the test set for the testing accuracy, as follows (Patil, 2010):

$$\text{Accuracy} = \frac{Number\ of\ correct\ predictions}{Total\ number\ of\ samples} \qquad \text{Equation 1}$$

Since the decision tree used is a classification one, it was identified based on the calculation of the Gini index which quantifies the impurity or probability of misclassifying data points in node of a decision tree, guiding the splitting process to improve the classification accuracy (James G. W., 2013). The goal is to minimize the

Gini-impurity when choosing splits. The Gini-impurity is given by the following formula (Yuan, 2021):

$$\text{Gini impurity} = 1-\sum_{i=1}^{C} p_i^2 \qquad \text{Equation 2}$$

where C denotes the number of node types in the model, and p_i stands for the proportion of samples of class i in the node. By calculating the accuracy and adhering to the Gini index, the most suitable decision tree classifier is derived, which is crucial for clarifying the optimal path when selecting the appropriate class of action plan class and conducting a meaningful analysis of the various nodes and branches of the decision tree.

3.3.3. Modelling of the feature importance and interconnectedness

Following the final decision tree simulation, feature analysis facilitates the crucial understanding of individual contributions, leading to the detection of other features with negligible impact or redundancy, potentially thereby streamlining the process. Evaluating the feature importance is achieved by a SHAP analysis, while the connections between variables are visualized using a cluster map, offering a holistic understanding of the interplay between features within the proposed decision tree model.

SHAP (SHapley Additive exPlanations) aims to identify important features, help reduce model complexity and improve interpretability (Belle, 2021). By analysing SHAP values for unexpected predictions, potential sources of bias or errors in the model can be uncovered (Biecek, 2020). SHAP assigns each feature a "Shapley value", representing its marginal contribution to the model’s prediction compared to all possible feature subsets (Lundberg S. L., 2017). These values are calculated using the following equation (Sundararajan, 2020):

$$\text{SHAP}\ (x_i, f) = \mathbb{E}\ [f\ (x'_i \cup \{x_i\}) - f\ (x'_i) \mid x'_i \sim P\ (x')] \qquad \text{Equation 3}$$

Where: x_i denotes the feature of interest, f stands for the model prediction function, x'_i refers to a subset of features excluding x_i and $P\ (x')$ represents the background distribution of all possible sets of features. Clustermaps are invaluable for uncovering hidden patterns and relationships between variables or features within complex datasets. The specific equation used for calculating similarity depends on the chosen metric. In this study, the Pearson Correlation is used, which is commonly used for gene expression data, measuring the linear relationship between two variables, ranging from -1 (perfect negative correlation) to 1 (perfect positive correlation). Applications in diverse fields are uncovered by cluster maps, ranging from image analysis to customer segmentation. They efficiently identify latent structures, detect outliers, and visualize trends. Clustermaps also serve as springboards for further analysis, guiding hypothesis generation and targeted experimentation.

3.3.4. Post pruning of the decision tree

Inspite of their simplicity and interpretability, decision trees are susceptible to overfitting due to their propensity to learn complex details of the training data. If the decision tree lacks clarity or readability, post-pruning will be employed. This step identifies and removes over fitted branches that memorize specific training data, preventing the tree from generalizing well to unseen examples. Ultimately, post-pruning simplifies the tree and enhances its interpretability. The aim of post-pruning, also known as "pruning after tree construction", is to reduce overfitting by removing branches that do not significantly improve the performance of the tree. Cost-complexity pruning assesses the trade-off between the loss in training accuracy and the reduction in model complexity associated with removing a branch. The cost-complexity criterion for a subtree T_t rooted at node t is given by the following equation:

$$R_\alpha (T_t) = (T_t) + \alpha|T_t| \qquad \text{Equation 4}$$

where $R_\alpha (T_t)$ denotes the cost-complexity measure of subtree T_t with penalty parameter α, $H(T_t)$ stands for the impurity measure of subtree T_t, $|T_t|$ refers to the number of samples in subtree T_t, and α represents the penalty parameter controlling the trade-off between complexity and fit. To compute the cost-complexity measure for the entire tree, we sum the total of the cost-complexity measures of all subtrees is calculated:

$$(T) = \sum_{t \in T} R_\alpha(T_t) \qquad \text{Equation 5}$$

By iteratively removing the branch that minimizes this cost-complexity, a balance between accuracy and generalization is achieved. Post-pruning plays a vital role in mitigating overfitting as well as enhancing the performance and interpretability of decision trees. This step is optional but becomes essential if the final decision tree model includes overfitted branches that reduce its readability.

3.4. Methodological Framework for the Environmental Assessment of Construction Materials in Climate Action Projects

While the previous section focused on the development of a data-driven decision-support tool for selecting appropriate climate actions, it is equally important to evaluate the environmental performance of these actions once implemented. In particular, many climate interventions rely heavily on construction materials, whose environmental impacts can significantly influence the overall sustainability of the projects. Therefore, the following section introduces a methodological framework based on life cycle assessment to analyse and compare the material-related environmental impacts of selected climate action projects.

The diversity of climate actions requires an environmental impact assessment method suitable for identifying and comparing the impacts of fundamentally different processes. The proposed workflow introduces a climate action specific, material centred analytical framework based on Life Cycle Assessment principles. It is important to clarify that this framework does not constitute a complete, ISO 14040/14044 compliant life cycle assessment, but a material centred analysis that adapts LCA principles to the specific needs of comparing climate action projects. Within this scope, the goal is to compare the material related environmental impacts of heterogeneous climate interventions on a common basis. The system boundary is restricted to the production and delivery stages of construction materials (a cradle to gate perspective), excluding the use, maintenance, and end of life phases. The inventory data on project materials are drawn from the official project reports available in the Covenant of Mayors library; the functional units are defined per climate action category, as detailed in Table 4, and the impact assessment relies on three characterization indicators, namely Global Warming Potential, Ozone Depletion Potential, and Human Toxicity, whose per kilogram characterization factors were obtained from the GaBi life cycle assessment database and are reported in Table 6. The assumptions applied where material or dimensional data were incomplete are stated explicitly in the relevant sections. Its applicability is demonstrated through selected projects from European cities, illustrating how established LCA methods can help to assess the material related impacts of several climate action interventions. The process of the proposed methodological framework is presented in detail in Figure 11.

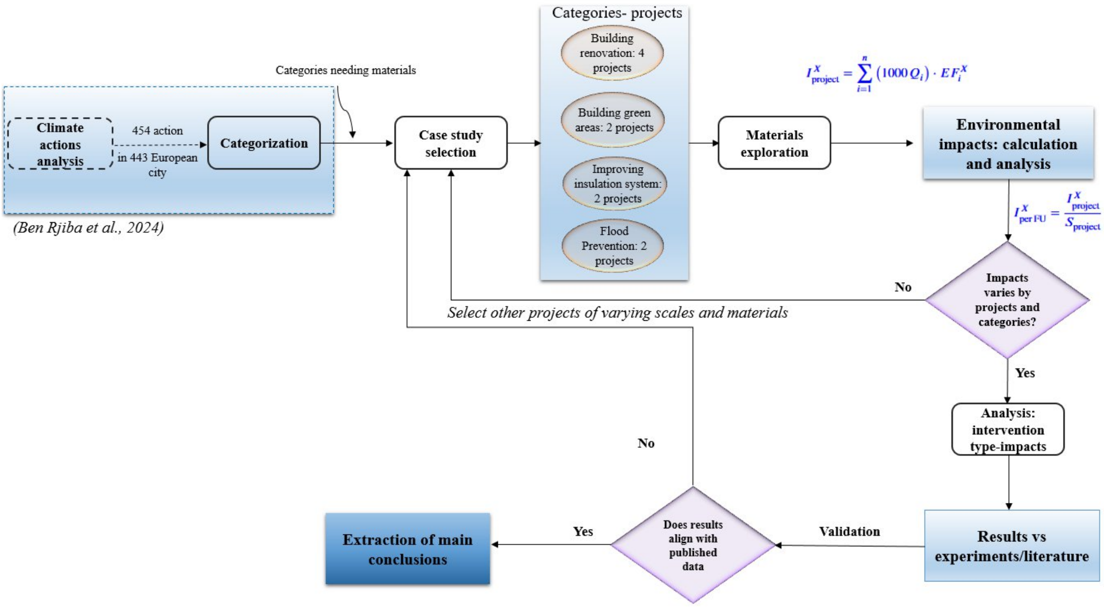


Figure 11: Workflow of the life cycle impact assessment methodology for climate action projects

Figure 11 illustrates the process and key steps involved in assessing the environmental impacts of commonly used construction materials in climate action projects. The climate actions are grouped by analysing and studying 443 already implemented action plans, which is the input climate action pool for the development of the material centred life cycle based analytical framework. From the different categories identified previously, the analysis focuses on climate action initiatives that require significant quantities of construction materials, as these are expected to have more significant environmental impacts. These categories have been prioritized to ensure that the analysis remains centred on projects where construction materials play an important role. In addition, it helps identify the specific areas where construction materials play an important role, providing a foundation for deeper investigation of their environmental impacts. Within the categories selected, multiple case studies of climate action projects will be chosen to ensure a diverse and representative sample. In order to widely demonstrate the applicability of the proposed framework, case studies will be selected to include a range of project scales, from small to large, as well as a variety of construction materials used. This approach aims to provide an understanding of the usage of materials in different project contexts, highlighting variations in environmental impacts based on the scale and type of materials used. After selecting the case studies, the next phase focuses on quantifying the quantities of construction materials used in each project. This quantification process will be conducted with great precision, ensuring that the material data is accurately recorded to serve as a reliable foundation for further analysis. Once the material quantities have been documented, the data will undergo a detailed life cycle-based analysis (Figure 11). This methodological approach will assess the environmental impacts associated with each project, increasing awareness of the sustainability and ecological implications of materials used in varying project contexts. This analytical approach provides a comprehensive framework for measuring and analysing the environmental impacts of each project (Menoufi, 2011). This study will employ three critical indices to evaluate these impacts: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), described as follows:

- GWP will be the primary environmental indicator, estimating the potential contribution of each project to global warming over the next 100 years. This metric shows the long-term climate implications of the materials and processes used in the projects (Neubauer.C, 2015).
- ODP will measure the extent to which each project may contribute to the depletion of the ozone layer, an essential factor in evaluating its effects on atmospheric protection and stability (Lane, 2015).
- HT will focus on evaluating the potential risks to human health posed by materials and processes used throughout the project life cycle, highlighting the broader implications of construction choices (Fantke, 2018).

Several environmental indicators are available within life cycle impact assessment frameworks. However, the selection of indicators was guided by their relevance to material production processes, data consistency, and their direct link to the objectives of climate action projects. The Global Warming Potential was selected as the primary indicator because greenhouse gas emissions from construction material production are a dominant contributor to climate change and represent the main target of mitigation-oriented climate actions. Ozone Depletion Potential was included to account for the possible influence of specific substances related to materials on stratospheric ozone, particularly in industrial production chains, where ozone depleting emissions, although reduced, remain relevant. Human Toxicity was selected to capture the potential risks to human health associated with material extraction and manufacturing, which are increasingly considered in sustainability-oriented infrastructure planning. Other impact categories, such as acidification and eutrophication, were not included because their effects are highly location dependent and primarily driven by site specific emissions and environmental conditions that cannot be assessed within the defined system boundary and data availability. In addition, these categories are less directly influenced by material production alone and are more strongly associated with operational or local scale environmental processes. Focusing on GWP, ODP, and HT, therefore, enables a scientifically consistent and comparable assessment of material-related impacts while avoiding uncertainties associated with indicators that require spatially explicit modelling beyond the scope.

Together, these indices provide a detailed understanding of the environmental and human health impacts associated with the selected case studies. To perform these evaluations, the total potential influence of each project will be calculated for each environmental impact. This analysis includes the aggregation and comparison of data, allowing to identify trends and patterns in the environmental performance of various construction materials and types of projects. By comparing these impacts, the analysis provides valuable results showing how different materials and construction practices influence environmental outcomes, offering a deeper understanding of their ecological implications and sustainability profiles. This process requires drawing conclusions about the most suitable construction materials by evaluating a combination of key factors, such as construction quality, project lifespan, and environmental sustainability. Through this integrated approach, the analysis aims to identify materials that provide an optimal balance between durability and environmental impacts, offering an actionable vision to advance future climate action initiatives and promoting sustainable construction practices. This methodology ensures an evaluation of construction materials in the context of climate action, thereby supporting more informed and strategic decision-making in the pursuit of sustainable urban development.

3.4.1. Selection of material-intensive climate actions

A total of 454 climate actions, implemented and planned by 443 European cities, were identified and subjected to an in-depth analysis. This evaluation aimed to classify the range of climate initiatives into different categories based on their objectives and implementation strategies. As a result, the actions were grouped into ten primary categories, of which the categories with significant construction material needs and used to demonstrate the applicability of the proposed framework are underlined:

- <u>Buildings retrofit and renovations (Br).</u>
- <u>Heat control and improvement of heating systems (Hi).</u>
- Seeking financial investments and joining projects (Fi).
- Involving the community in decision-making phase (Ci).
- Optimizing transportation (To).
- Street light replacement (Str).
- Transition to renewable energy (Re).
- <u>Adding green areas, parks and planting trees (Tp).</u>
- <u>Flood avoidance (Fa).</u>
- Enhance monitoring systems and data analysis (Da).

These categories, due to their dependence on various construction materials, were considered most relevant for further study. The categorization process not only provided a clear framework for understanding the various approaches taken by cities in their efforts to combat climate change but also served as an important foundation for the next phase of the study. This phase involves selecting specific climate action projects from the identified categories to allow a focused analysis of the environmental impacts associated with the construction materials used. This structured method guaranties a focused assessment that enables the extraction of valuable discoveries and trends.

3.4.2. Case studies selection

Ten climate action projects were selected from the initiatives listed on the Covenant of Mayors website. These projects were carefully chosen to represent a wide range of categories and objectives (Figure 12). Four of the selected projects focus on building renovation and retrofitting, which is the highest number of projects selected, as this category involves the largest variety and quantities of construction materials. These projects are the following:

- The renovation of Fondazione Prada in Milan, Italy.
- The retrofit of the Stedelijk Museum in Amsterdam, Netherlands.
- The restoration of Fondaco dei Tedeschi in Venice, Italy.
- The Restoration of the Vieux Lyon Renaissance Houses in Lyon, France.

Two projects fall under the category of ‘Expanding green spaces and parks’, emphasizing the creation and enhancement of urban green areas. The associated projects are:

- Parque Madrid Rio in Madrid, Spain.
- Superkilen Park in Copenhagen, Denmark.

Another two projects belong to the category of "Enhancing heat control," highlighting efforts to improve heating systems in residential settings. These initiatives are as follows:

- Improvement of heat systems in a multi-family residential building in Feldkirch, Austria.
- Improvement of heat systems in a multi-family residential building in Frankfurt, Germany.

Lastly, two projects address "Flood prevention," focusing on safeguarding urban areas from flooding risks:

- The ‘Room for the River’ project in Nijmegen, Netherlands.
- The Thames Estuary 2100 (TE2100) Plan in London, United Kingdom.

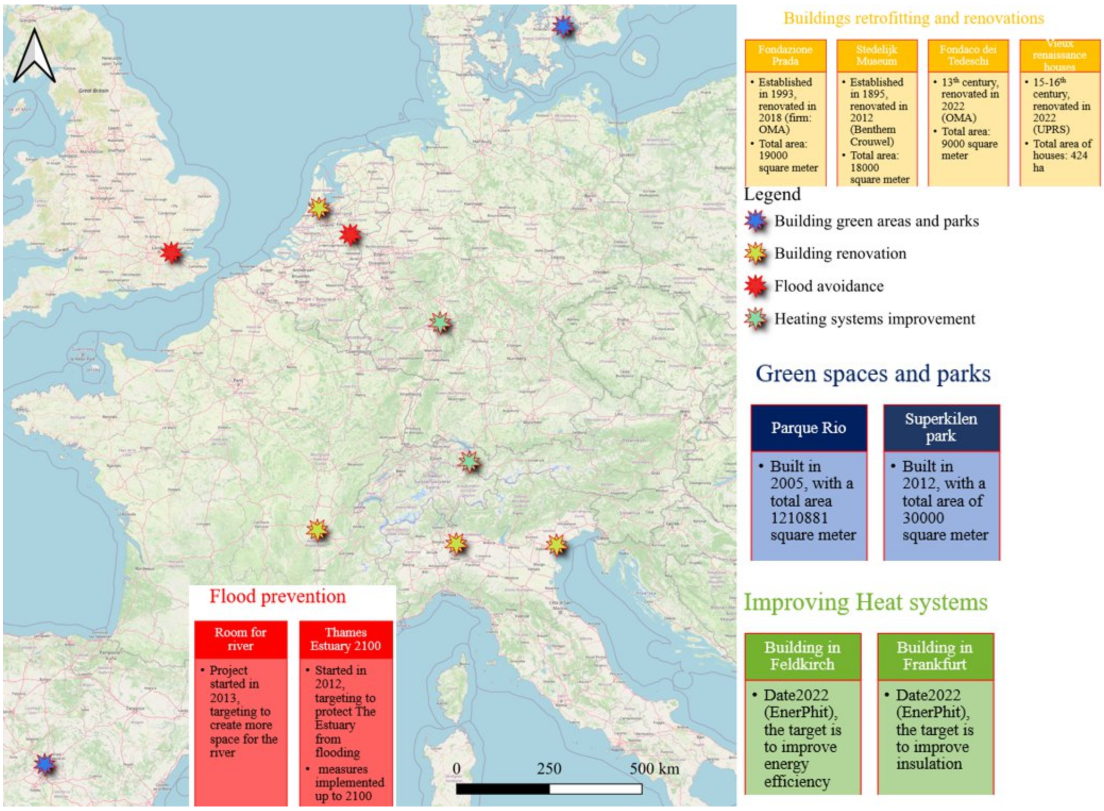


Figure 12: Map of the case studies location and their basic properties.

This selection of projects provides a well-rounded representation of climate actions, enabling a detailed study of the environmental impacts associated with the construction materials used in various contexts.

Figure 12 highlights the geographic distribution of the 10 selected climate projects in various European regions and countries. These projects were deliberately chosen from different locations to reflect the wide range of climatic, economic, and social conditions that exist throughout Europe. It provides also an overview of the general information for each selected project. Notably, the starting dates of projects within the same category are relatively close to each other. This alignment was intentionally designed to ensure that all the cases reflect the same period’s availability and advancements in commonly used construction materials.

By selecting projects initiated within a similar time frame, analysis can focus on comparing materials under consistent market and technological conditions. Furthermore, the projects within each climate action category were chosen to be of comparable scale. This alignment was purposefully created to ensure that each case represents the availability and developments of widely used building materials throughout the same time period. By reporting both total impacts and normalized material intensities, the framework distinguishes infrastructure scale from design efficiency. This allows engineering performance to be interpreted in terms of material strategy rather than project size alone.

3.4.3. Construction materials quantification

Once the projects selected for the study have been finalized, the next step involves collecting detailed data on the types and quantities of construction materials utilized in each project. This data collection process is essential for understanding the composition of the material and the scale of resource usage in the chosen initiatives. The projects analysed are available in the Covenant of Mayors library as official reports, which provided the necessary information to identify the main materials used in each case. The quantities of these materials were estimated primarily based on the dimensions of the buildings associated with each climate action project. In this study, functional units were defined in a category-specific manner to ensure meaningful comparison of material-related environmental impacts across heterogeneous climate action projects. Rather than applying a single functional unit to all interventions, the analysis adopts reference metrics that reflect the primary function and scale of each climate action category. For building renovation and heating or insulation improvement projects, the functional unit is defined as one square meter of treated floor area, representing the service provided by the intervention. For urban green space projects, impacts are normalized per square meter of park or green area developed, while for flood prevention measures, the functional unit is defined per kilometer of flood defence or riverfront intervention. These functional units were selected to align with established practices in infrastructure and building assessment and to enable comparison within each category while preserving physical relevance. Material quantities for each project were normalized using the corresponding reference metric, based on available project documentation and dimensional characteristics, with explicit assumptions applied where detailed information was unavailable. The environmental assessment focuses on the production and delivery stages of construction materials. This functional unit framework allows consistent evaluation of material-related impacts within each climate action category while avoiding inappropriate cross-category aggregation based on a single, non-representative unit.

Table 4:Project metadata and functional unit definition.

Project & Action category	Functional unit type	Ref metric value	Ref metric unit	Quantity unit
Fondazione Prada (Br)	floor area (m^2)	19000	m^2	tonnes\m^2
Stedelijk Museum (Br)	floor area (m^2)	8000	m^2	tonnes\m^2
Fondaco dei Tedeschi (Br)	floor area (m^2)	9000	m^2	tonnes\m^2
Vieux Lyon Renaissance Houses (Br)	floor area (m^2)	600	m^2	tonnes\m^2
Parque Madrid Rio (Tp)	park area (m^2)	1210881	m^2	tonnes\m^2
Superkilen Park (Tp)	park area (m^2)	30000	m^2	tonnes\m^2
Multi-family residential building in Feldkirch (Hi)	floor area (m^2)	1800	m^2	tonnes\m^2
Multi-family residential building in Frankfurt (Hi)	floor area (m^2)	1500	m^2	tonnes\m^2
‘Room for the river’ Nimejen (Fa)	flood defence length (km)	0.8	km	tonnes\km
Thames Estuary plan (Fa)	flood defence length (km)	330	km	tonnes\km

In addition to defining functional units, Table 4 further documents the reference metric values and quantity units used to normalize material quantities for each project. The reference metric value specifies the physical scale of the intervention and serves as the basis for converting absolute material quantities into comparable intensities, while the quantity unit indicates whether normalization is expressed per square meter or per kilometer. For projects where material data or dimensional information were incomplete, explicit assumptions were applied, which may introduce a degree of uncertainty in the estimated values. In the Fondazione Prada renovation, wood quantities initially reported in square meters were converted to mass using an assumed thickness of 2 cm and a density of 500 kg/m^3, corresponding to 0.01 tonnes per m^2. For the multi-family residential building in Feldkirch and the Vieux Lyon Renaissance Houses, reference floor areas of 1800 m^2 and 600 m^2, respectively, were assumed based on typical scales of comparable residential and historic renovation projects. These specifications ensure dimensional consistency and transparency in the normalization of material flows across projects.

Table 5: Construction materials distribution normalized per category functional unit (tonnes/m^2 for Br, Tp, Hi; tonnes/km for Fa).(Br: Building renovation, Tp: Extending green areas and parks, Hi: Improvement of the heating and insulation system, Fa: Flood prevention)

Project & Action category	**Concrete**	**Brick**	**Steel**	**Terrazzo/gypsum**	**Stones**	**Bamboo/Timber/liners**	**Glass/Aluminum**	**Wool**	**Foam**	**Wood/Hardwood**
Fondazione Prada (Br)	1.01053	0	0.05263	0	0	0	0.00105	0	0	0.03158
Stedelijk Museum (Br)	4.5	0	0	0.03125	0	0.025	0.00656	0	0	0
Fondaco dei Tedeschi (Br)	0	0.00972	0.00111	0.00444	0.01333	0	0.0005	0	0	0.00042
Vieux Lyon Renaissance Houses (Br)	0	0.05	0.00833	0.03333	0.25	0	0.00383	0	0	0.005
Parque Madrid Rio (Tp)	0	0	0.00002	0	0	0.00002	0	0	0	0.00017
Superkilen Park (Tp)	0.00667	0	0	0	0.005	0	0	0	0	0.014
Multi-family residential building in Feldkirch (Hi)	0	0	0	0	0	0.00333	0.08333	0.0125	0.00161	0
Multi-family residential building in Frankfurt (Hi)	0	0	0	0	0	0	0	0.006	0	0.002
Room for the River Nijmegen (Fa)	90000	0	6250	0	650000	0	0	0	0	0
Thames Estuary Plan (Fa)	0	0	0	0	0	14.54545	0	3.0303	0	0

Following the definition of reference metrics and normalization assumptions, Table 5 presents the distribution of construction materials normalized per category-specific functional unit, allowing comparison of material intensities across climate action projects. Within the building renovation category, significant variability in material use per square meter is observed, reflecting differences in the function of the building, the structural requirements and the scope of the renovation. Large cultural buildings such as the Stedelijk Museum exhibit high concrete intensities, indicating the structural reinforcement demands associated with large-scale renovations, while historic renovation projects, such as the Fondaco dei Tedeschi and the Vieux Lyon Renaissance Houses, show lower concrete use but higher relative contributions from masonry-related materials and stones, consistent with preservation-oriented interventions. Urban green space projects show markedly lower material intensities per square meter compared to building-related actions. Parque Madrid Río and Superkilen Park are characterized by very small and normalized quantities of steel, liners and wood-related materials, reflecting the spatially extensive but materially light nature of landscape and surface-level interventions. Despite their low per-unit material intensity, the large surface areas involved imply that these projects may still generate considerable absolute material demands, highlighting the importance of normalization when comparing across categories. Heating and insulation improvement projects demonstrate a distinct material profile, dominated by insulation materials such as wool and foam, along with glass-related components. The Feldkirch residential building shows higher normalized values for glass and insulation materials, consistent with envelope-focused retrofitting strategies, while the Frankfurt case exhibits a more limited material palette, reflecting differences in intervention depth and building typology. Flood prevention projects stand out due to their exceptionally high material intensities per kilometer, particularly for concrete and stones. The ‘Room for the River’ project demonstrates the dominance of heavy mineral materials required for large-scale hydraulic and earthwork interventions, while the Thames Estuary Plan highlights the use of linear structural elements and protective layers over long distances. These results underline the fundamentally different material demands of flood prevention infrastructure compared to building and area-based climate actions, reinforcing the need for category-specific normalization when assessing material-related environmental impacts.

3.4.4. Environmental impacts of the construction materials used in the climate action projects

Table 6 presents the environmental impacts of 1 kg of the different construction materials selected for the various projects, assessed using three key indices: GWP (Global Warming Potential), ODP (Ozone Depletion Potential), and HT (Human Toxicity). Each construction material listed in the table includes several types depending on its intended use. For example, wool can appear as natural sheep wool, glass wool, or rock wool, each with distinct environmental characteristics. However, in this study, and considering that the differences in environmental impact between types of the same material are relatively minor, the average environmental impact for each material type was used.

Table 6: Environmental impacts per 1 kg of construction materials across projects

Material	GWP ($kgCO_{2eq.}$\1kg)	ODP ($kgR_{11eq.}$\1kg)	HT (CTUh\1kg)
Concrete	0.1	0.00002	0.000065
Brick	0.5	0.000035	0.000045
Steel	2	0.000003	0.00015
Terrazzo	0.7	0.00002	0.00065
Gypsum	0.2	0.00002	0.00025
Stones	0.3	0.00003	0.00013
Bamboo	0.2	0.00002	0.00012
Timber	0.2	0.000022	0.00025
Liners	0	0.00003	0.003
Glass	1.5	0.00002	0.00055
Aluminium	8.8	0.000025	0.002
Wool	3	0.00003	0.00075
Foam	4.4	0.00002	0.0024
Wood	0	0.000015	0.0002
Hardwood	0	0.00001	0.00025

Table 6 summarizes the environmental impact factors used to evaluate material-related contributions in climate action projects. Clear differences are observed among construction materials, particularly in terms of GWP, reflecting the energy intensity and emission profiles of their respective production processes. Aluminium exhibits the highest GWP value at 8.8 $kgCO_{2eq}. /kg$, highlighting the carbon-intensive nature of primary aluminium production. Similarly, foam and steel display relatively high GWP values, consistent with their reliance on energy-intensive and chemically driven manufacturing processes. In contrast, materials such as concrete, gypsum, bamboo, and stones show lower GWP values, indicating comparatively lower climate impacts per unit mass. Originally, negative GWP values were associated with certain bio-based materials, including wood, hardwood, and liners, reflecting temporary biogenic carbon storage assumptions embedded in some life cycle databases. However, these negative values were conservatively set to zero. This adjustment was made to avoid overstating climate benefits that depend on long-term carbon storage assumptions, end of life scenarios, and temporal system boundaries that are not explicitly modelled within the defined cradle-to-gate scope. By assigning a neutral GWP value, the analysis ensures consistency with the selected system boundary and avoids introducing methodological bias when comparing material-related impacts across heterogeneous climate action projects. The values of Ozone Depletion Potential remain uniformly low in all materials, generally within the range of 10^{-5} to 10^{-6} $kgR_{11eq.}/kg$, indicating a limited influence on stratospheric ozone depletion. Brick shows a comparatively higher ODP value, likely linked to emissions associated with high-temperature kiln processes. Other materials, such as concrete, gypsum, glass, bamboo, and stones, present similar magnitudes of ODP, suggesting that ozone depletion is a secondary concern relative to other impact categories for material production. Human Toxicity indicators show pronounced variability among materials. Steel, foam, aluminium, and liners exhibit higher toxicity values, reflecting the presence of heavy metals, solvents, and chemical additives in their production chains. However, mineral- and bio-based materials, such as stones, bamboo, gypsum, and timber, demonstrate lower HT values, suggesting comparatively lower risks to human health per unit mass. Materials such as concrete and terrazzo occupy an intermediate position, with moderate impacts across all three indicators.

The table underscores the need for strategic material selection in climate action projects. While high-performance materials like aluminium or foam offer structural or thermal benefits, their elevated environmental burdens (especially in GWP and HT) require careful assessment. In contrast, renewable or natural materials such as wood, bamboo, and stones demonstrate a more favourable environmental profile.

All of these findings suggest that the type of material has a significant influence on the environmental impacts. However, it is worth highlighting that there are significant efforts to reduce these impacts in the development of different construction materials. For example, in the case of concrete, the majority of carbon dioxide emissions come from the manufacturing process of Portland cement, as direct emissions (Griffiths B. K., 2023). The greatest potential for reducing emissions lies in the substitution of Portland cement clinker with suitable supplementary cementitious materials. But there is also considerable promise in the use of waste concrete, available worldwide, as recycled aggregates, supplementary cementitious materials, filler, and feedstocks for clinker production (Villagrán-Zaccardi, 2022). It is also important to note that the global construction sector is a major producer of waste, using only half of the waste materials. The principles of the circular economy are therefore increasingly important here, as the reuse of materials minimizes waste and avoids the extraction and production of new raw materials, reducing the environmental footprint (Devos, 2024). This is also true for ceramic bricks, where reuse can lead to an environmental improvement of around 85% compared to new bricks.

Building on the material-specific impact factors discussed previously, the next step consists of quantifying the total environmental impacts associated with the construction materials used in each climate action project. For each project, material quantities were first harmonized in mass units to ensure consistency with the characterization factors, which are expressed per kilogram of material. Quantities originally reported in tonnes were therefore converted to kilograms prior to calculation. The total impact for each environmental indicator was then obtained by multiplying the mass of each material by its corresponding characterization factor and summing the contributions of all materials included in the project inventory. This calculation was performed separately for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), using the impact factors reported in Table 6 and within the defined system boundary covering material production and delivery stages.

$$I^{X}_{project} = \sum_{i=1}^{n} (1000\ Q_i) \cdot EF_i^{X} \qquad \text{Equation 6}$$

In this expression, $I^{X}_{project}$ represents the total impact of a given project for impact category X (GWP, ODP, or HT), Q_i is the quantity of material i expressed in tonnes, EF_i^{X} is the corresponding characterization factor per kilogram of material and n denotes the number of material types considered in the project. This approach ensures dimensional consistency between material quantities and impact factors and provides an absolute measure of the environmental burden associated with each project. In addition to total project impacts, environmental indicators were also normalized using category-specific functional units to allow comparison among projects of different sizes within the same climate action category. Normalization was performed by dividing the total project impact by the reference metric value associated with each project, such as the treated floor area, developed park area, or flood defence length, depending on the intervention type. This step yields an intensity-based indicator that expresses environmental impacts per unit of delivered service, rather than per project.

$$I_{per\ FU}^{X} = \frac{I_{project}^{X}}{S_{project}} \qquad \text{Equation 7}$$

$I_{per\ FU}^{X}$ denotes the normalized impact per category functional unit, and $S_{project}$ corresponds to the reference size of the project expressed in square meters or kilometers, as defined in Table 3. This normalization enables consistent comparison of material-related impact intensities across projects within the same climate action category, independent of overall project scale. Reporting both total and normalized indicators provides complementary information. Total impacts reflect the absolute environmental burden associated with material use and are relevant for understanding the contribution of individual projects to city- or program-level emissions and impacts. Normalized impacts, in contrast, reveal the environmental intensity of material use per unit of intervention and support comparative evaluation across projects with differing dimensions. Together, these indicators offer a more complete basis for interpreting material-related environmental performance in climate action projects.

4. Results and discussion

This section presents and discusses the results obtained from the application of the methodological approaches described in the previous chapter. Following the same structure, the section is organized into three parts, each corresponding to one of the research assumptions and its associated analysis. In each subsection, the results and their interpretation are presented together in order to provide a clearer understanding of the findings. The analysis covers the role of public awareness, the development of the data-driven decision-support model, and the assessment of construction materials. The results are supported by tables and figures and are discussed in relation to the objectives of the study.

4.1. Impact of Public Awareness on Urban Climate Resilience and Air Quality

As mentioned in Table 1, Germany has the best educational ranking among the case studies (third), then Brazil (36) and the last position for Kenya. The extraction and analysis of other educational index (Table 7) confirm this ranking.

Table 7: Global educational index of Germany, Brazil and Kenya (Roser, 2016)

Country	Adult literacy rate (2021)	Average years of schooling (2021)	Public spending on education as a share of GDP (2018)
Germany	>99%	17.01	4.99%
Brazil	93.23%	15.6	6.09%
Kenya	81.53%	10.7	5.08%

In 2021, only 81.53% of adults aged 15 and older can both read and write. This rate is higher in Brazil (93.23%) but it still low comparing to Germany, where the adult literacy rate is 100% approximately. Germany has the highest average years of schooling among the 3 countries and the lowest is Kenya with 10.7 years. A low years of schooling will cause a non-completed training for the students, and this can affect their awareness about several topics related to climate change and environmental challenges in general.

The completion of the primary school is over 99% in the three countries. However, only 3.4% complete their tertiary education in Kenya, 20.10% in Brazil and 31.3% in Germany. Cities resilience, climate change impacts and different ways to improve the air quality, are all topics that can be mentioned, mainly in the upper secondary and tertiary education. Having a low percentage of students who completed these levels will cause lack of knowledge toward these topics (Table 8).

Table 8: Completion rate of the different educational level in Germany, Brazil and Kenya (Roser, 2016)

Country	Tertiary education	Upper secondary education	Primary school
Germany	31.30%	54.90%	99.02%
Brazil	20.10%	36.90%	99%
Kenya	3.40%	21.15%	99.68%

4.1.1. Adaptation plans and public awareness

Adaptation plans play a crucial role in ensuring the resilience of communities and ecosystems in the face of climate change and other environmental challenges. By anticipating and planning for the potential impacts of climate change, such as sea level rise, extreme weather events, and changes in temperature and precipitation patterns, adaptation plans can help to reduce vulnerabilities and increase the capacity of communities and ecosystems to adapt. Adaptation plans can also help to identify and prioritize actions that can be taken to mitigate the impacts of climate change, such as reducing greenhouse gas emissions, conserving natural resources, and improving infrastructure and land use practices. Furthermore, adaptation planning can be an important tool for promoting equity and social justice, by ensuring that vulnerable and marginalized communities have a voice in decision-making and are included in the planning process. Ultimately, adaptation planning is essential for building more sustainable and resilient communities and ecosystems that can withstand the impacts of climate change and other environmental challenges.

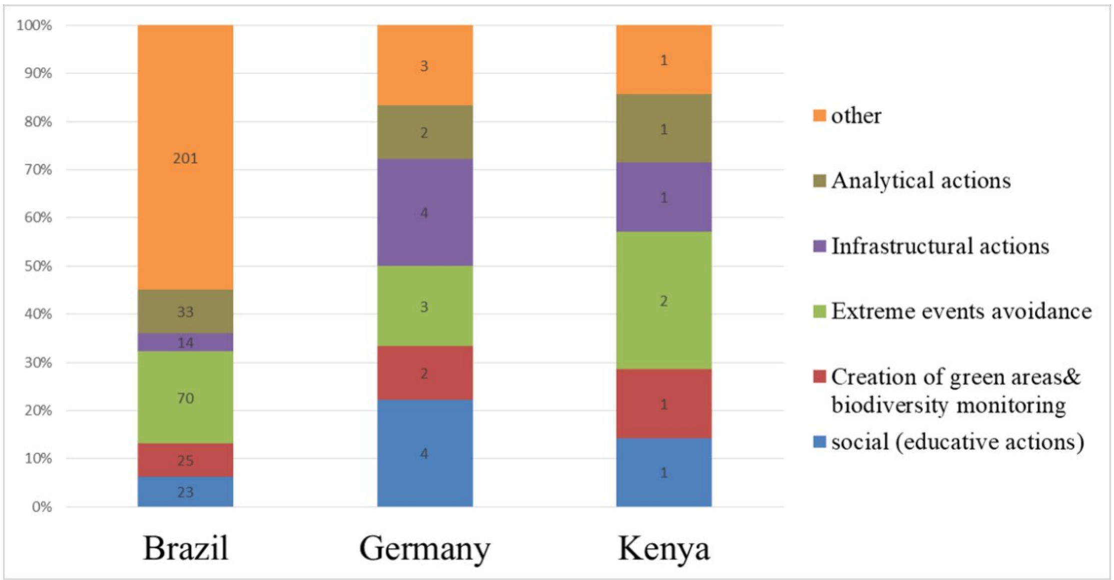


Figure 13: Adaptation plans classification 2017

In 2017, 366 action plans were announced by different Brazilian cities. Only 6.3% of these actions are targeting to include the society in the adaptation strategies through raising their awareness (Figure 13). Only one social adaptation plan was published in Kenya (14.28% of the total number of adaptation plans). Despite the low number of action plans announced by the German cities at the same year, 22.22% of these actions have social and educative targets, to encourage the citizens to act in tackling climate change impacts. Two sub-categories of social adaptation strategies are applied as action plans in the three countries: Educative actions aiming to improve the citizens knowledge regarding the future challenges and the cities targets, and another type of social actions targeting a public engagement in the decision making through surveys and websites.

A survey conducted in 2020 (Lenzholzer, 2020) aiming to evaluate the awareness level related to specific environmental in several countries. The results of the survey show that the citizens and politicians in Kenya are, totally, not aware of the influence of city layout on the urban climate. 9.09% of the German citizens know this influence, and 36.36% of the politicians are aware of the topic. 45.45% of the citizens and 40% of the politicians in Kenya are aware of the influence of vegetation on the urban climate. 36.36% of the citizens and 90.9% of the politicians in Germany are aware or very aware of this influence. This particular survey did not include Brazil, the cross-country comparison therefore rests primarily on the education and awareness indicators from

Our World in Data, which are available consistently for all three countries, and the survey is used only as complementary context for the two countries it covers.

4.1.2. Greenhouse gas and climate hazards emissions

Data presented in the 'Brazil's Initial National Communication' document indicated that the country is one of the top world greenhouse gases (GHG) emitters. A large majority of Brazil's GHG emissions come from deforestation mainly of the Amazon biome for agriculture and livestock land uses. Sub-Saharan African countries, such Kenya, are facing growing problems of poor air quality in its cities due to the high urbanization rates. The annual CO_2 emissions decreased in Germany from 1 billion tonnes in 1990 to 674 million tonnes in 2021. However, it increased from 218 million tonnes in 1990 to 488 million tonnes in 2021 in Brazil, and from 5 million tonnes in 1990 to 20 million tonnes in Kenya (Roser, 2016)(Figure 14).

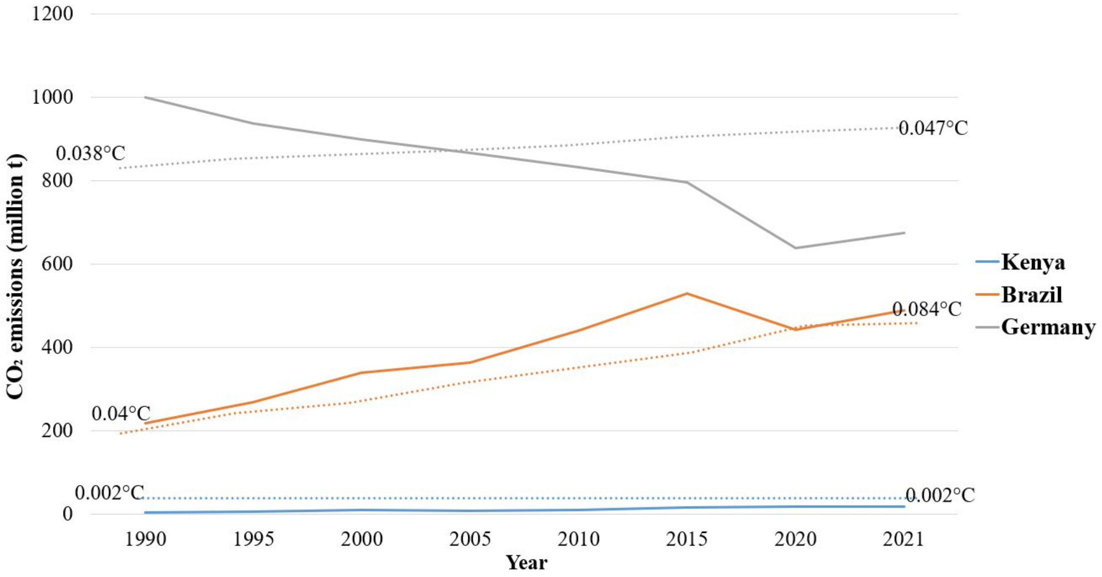


Figure 14: Annual CO_2 emissions and contribution in the worldwide temperature rise of Germany, Brazil and Kenya.

The air index is in a good level in the three countries: The highest is in Germany 25, then Brazil 24 and the lowest is Kenya 10. The death rate because of air pollution is high in Kenya. It reached 124 deaths per 100 000 people comparing to 27 in Brazil and 14 in Germany per the same number of people. 24% of this death rate (29 deaths per 100 000 people) is caused by particulate matter in Kenya, which is the main pollutant in the country, compared to 70% in Brazil and 86% in Germany. 43% of the climate hazards emitted mainly by the Kenyan citizens are extremely serious and harmful. 86%

of the climate hazards emitted by the Brazilian citizens are either serious or extremely serious. There are no extremely serious hazards emitted in Germany, however 80% of the emissions are classified as serious (Figure 15).

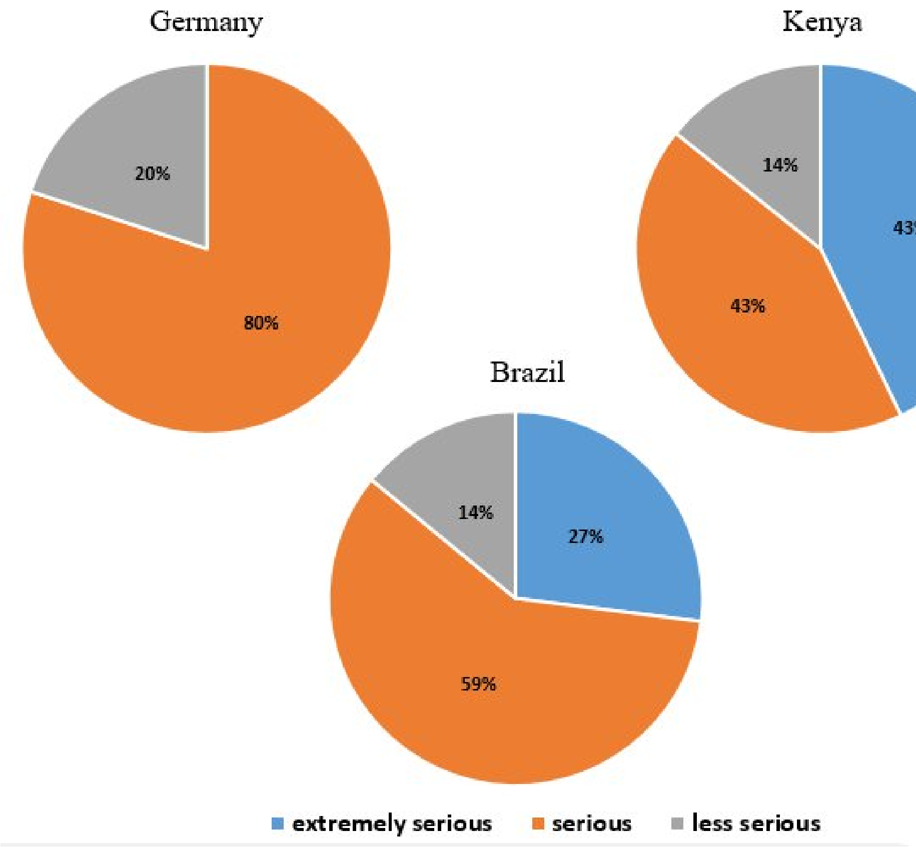


Figure 15: Climate hazards classification in Germany, Brazil and Kenya

4.1.3. Awareness level-GHG emissions

As shown in Figure 13, 22.22% of the adaptation plans planned in Germany published in 2017 are targeting to involve the community, which is the highest percentage compared to Brazil (despite the high quantity of actions), and Kenya. A calculation made, aiming to link this factor to the air quality index through a multidimensional scale figure confirm a correlation between the two parameters (Figure 16). Despite the high quantity of adaptation plans applied in several Brazilian cities, the CO_2 emissions are increasing from 2017 to 2021 (Roser, 2016)(Figure 14). In fact, applying various categories of actions depending on the cities situation and issues can have better impacts than focusing on the quantity of actions. The low percentage of the social actions applied in the Brazilian cities from 2017 to 2021 could be a reason of the ascendant trend of the emissions in the country.

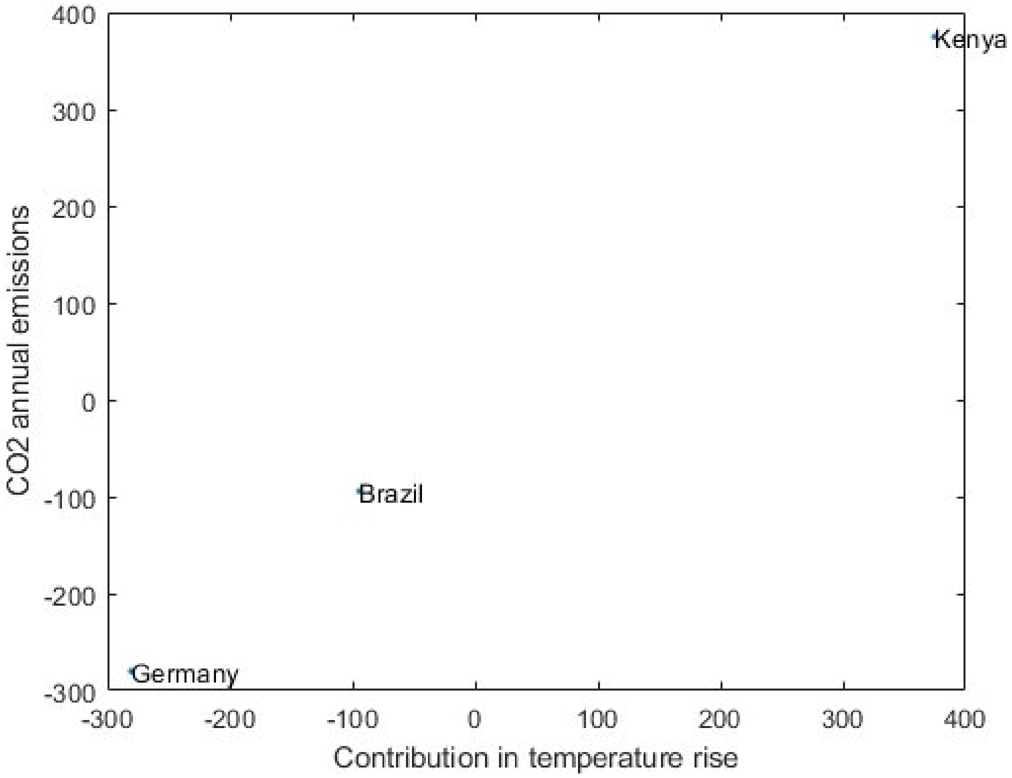
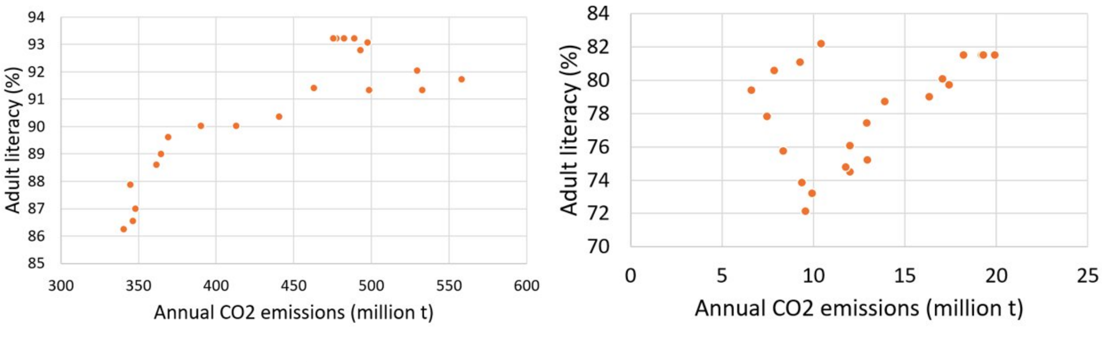


Figure 16: Multidimensional scaling (MDS) linking air index and social adaptation plans percentage in Germany, Brazil and Kenya.

Adult literacy rate and average years of schooling are two of several educational index that can have direct impact on the public awareness level. A regression calculation was conducted, aiming to find a correlation between the adult literacy and the annual CO_2 emissions, this calculation was applied only in Brazil and Kenya because the adult literacy is stable at almost 100% in Germany the last decade. The results show a high correlation between these two parameters in both cases: Low adult literacy can cause higher emissions (Figure 17).



Brazil

Kenya

Figure 17: Correlation Adult literacy-CO2 emission in Brazil and Kenya

The adult literacy rate and the years of schooling are higher in Germany than Brazil and Kenya, these results are correlating with the nature of climate hazards emitted in each country: Kenyan population, which have low literacy rate, are emitting a high percentage of extreme serious hazards, and this can be explained by their lack of knowledge of emitting such components, which is not the case in Germany. Completion of advanced studies is low in Brazil and Kenya. This made the main social actors (politicians, citizens) not aware of several topics related to urban climate. This lack of awareness could lead to breaches in the decision-making procedure and increase in the GHG emissions.

4.2. Results of the Decision-Support Model for Climate Action Planning

After examining the impact of public awareness, the focus now shifts to the core contribution of this thesis, presenting the results of the data-driven climate action planning model.

The distribution of the action plans adopted by the 443 European cities studied is illustrated in Figure 18. The analysed reports revealed that a significant majority of these cities implemented various categories of action plans concurrently. The analysis allowed for the identification of the primary and most extensively described action within each report. The most applied category focused on community engagement through different methods, including initiating awareness campaigns, organizing training sessions, as well as establishing dedicated websites and information points. While nearly all the studied cities utilized this category, 85 of them explicitly identified it as their main strategy for environmental improvement.

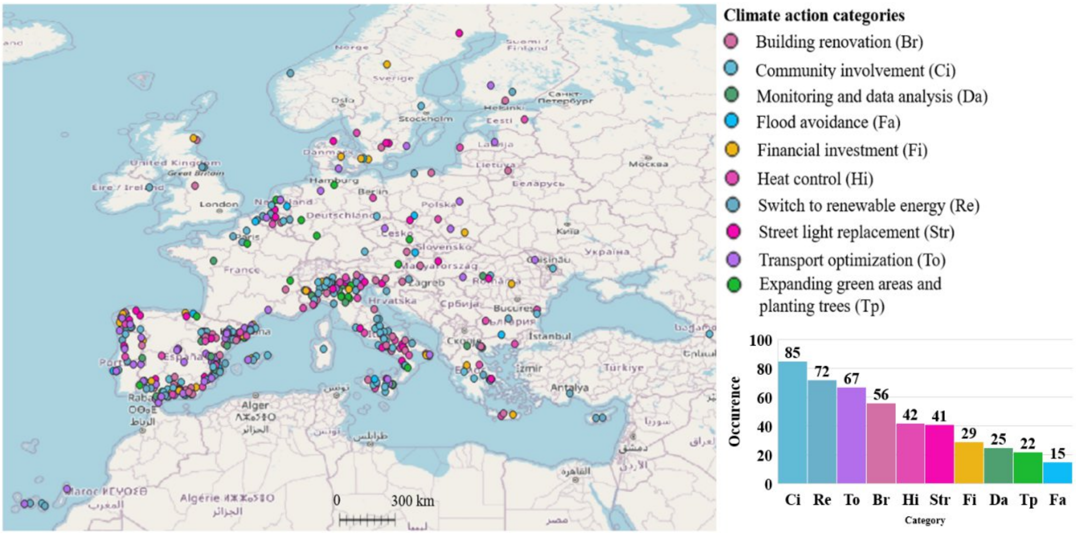


Figure 18: Distribution of observed climate action plans in the analysed cities.

The data analysis shows that transitioning away from fossil fuels towards renewable energy sources constitutes the second most commonly implemented climate action plan among the European cities investigated. Notably, this strategic approach stands as the core initiative for 72 of the studied municipalities, and is particularly prevalent within smaller, less populous cities. Classifying ‘switching to renewable energy’ as a category originates from the observation that many cities aim to increase their renewable energy ratio by transitioning energy sources in sectors like heating and education. The database includes a parameter for the renewable ratio, highlighting the significance of this climate action category. This preference can be attributed to the generally simplified logistics of integrating renewable energy sources into less extensive energy grids. Consequently, several northern and northeastern European cities with lower population densities, e.g. Gothenburg and Östersund, boast impressive renewable energy ratios exceeding 60%. Moreover, these municipalities continue to actively pursue additional strategies aimed at achieving complete reliance on renewable energy sources, demonstrating their unwavering commitment to environmental sustainability.

The transportation sector emerges as a significant contributor to greenhouse gas (GHG) emissions within densely populated cities, primarily due to the prevalence of traffic congestion. Consequently, many cities dealing with this challenge prioritize the enhancement of their transportation systems as a key strategic response. Among the municipalities studied, 67 identify a reduction in transportation emissions as their primary strategy. Notably, a striking 74.6% of these cities possess population densities in excess of 100 individuals per square kilometer, with a further 72% boasting densities surpassing 1000 individuals per square kilometer. To achieve their goals and improve the transportation sector, these cities primarily implement a repertoire of methods, including the modernization of public transportation infrastructure through the acquisition of new, low-emission fleets, the promotion of car and bike sharing programs to stimulate a shift away from individual car ownership, as well as the adoption of electric buses to minimize emissions stemming from public transportation services (Figure 18).

4.2.1. Selection of the impactful features

Selecting the appropriate features for the database is essential to achieving an accurate decision tree model. A successful selection process must include all factors that influence the model while excluding non-impactful features, which could otherwise reduce the quality of the model. The initial analysis revealed that the data extracted from the different reports relied on only 8 common features. Unfortunately, this limited feature is insufficient to achieve an accurate and nuanced classification. To address this challenge, an additional 16 features were selected and integrated into the database. The principle behind this feature selection process was two-fold, that is, to maximize the inclusion of pertinent parameters and ensure data variability across different cities. This approach aimed to encompass the broadest possible spectrum of scenarios and enhance the ability of the model to generalize to unseen circumstances. While the initial feature selection sought comprehensiveness, concerns emerged regarding the potential inaccuracies and impact of certain features on the outcome of the model. Therefore, another crucial step was introduced to eliminate "non-impactful" features.

While the 24 selected features undoubtedly influence air quality and are crucial for decision-making, in this particular case, it is more accurate to exclude features that do not have a significant impact on the final results. Identifying and removing these less impactful features from the database improves the model by focusing only on the parameters that affect the outcomes. This reduction will enhance the accuracy, clarity, and readability of the decision tree model, making it easier to analyze and interpret. One challenge encountered was incomplete data collection regarding specific features across all cities. When data points were missing, the process employed the mean value from geographically proximate cities to impute the missing data. However, for features like "landfill area," where over 50% of data was absent, imputation was deemed unreliable and could significantly compromise accuracy. As a result, the "landfill area" feature was excluded from the dataset. To identify and remove other non-impactful features, a systematic approach was devised. Each feature was removed individually, and the resulting impact on testing accuracy measured (stepwise feature selection). Features whose removal led to an increase in accuracy were deemed redundant and subsequently eliminated. This analysis resulted in the removal of 3 features: "landfill area", "reduction target in 2030", and "reduction target in 2050". The GHG reduction target set by a city will not have a remarkable impact on deciding the most appropriate climate actions. In addition, redundant patterns offer an additional opportunity for model development to develop a model, as shown in Figure 19.

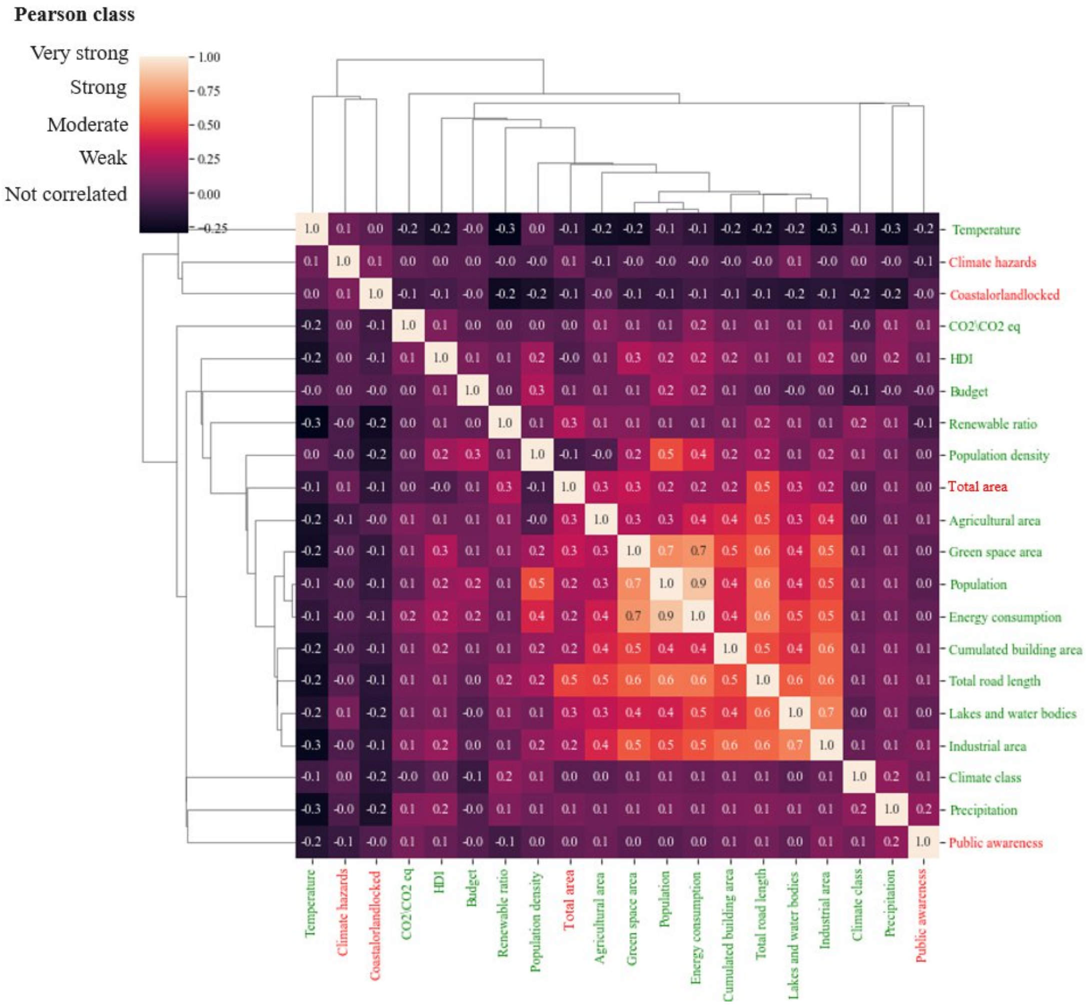


Figure 19: The interconnectedness of the features. Features marked in green are used in the final DT model, while those in red do not contribute to improving model performance.

The relationships between the involved climate-related features of the analysed cities are shown in Figure 19, painting a picture of a complex ecosystem where features interact with and influence each other. Recognizing these connections is crucial for building robust and insightful decision trees. The Pearson classification used in this figure facilitates the analysis and visualization of the interconnections between parameters. Correlations above 0.75 are considered to be very strong, between 0.75 and 0.5 as strong, between 0.5 and 0.25 as moderate, while below 0.25 as weak but positive. If the correlation is negative, no relationship is observed.

The first remark extracted from the analysis of the clustermap is the very strong and near-perfect correlation between the population and energy consumption (0.9), highlighting their direct dependency. This reinforces the notion that population is a vital input, despite its seemingly low overall impact. Further exploration shows a web of interconnected features centred on the population. The population density, as well as spatial distribution elements like the industrial area (0.5), surface area of lakes and standing water bodies of water (0.4), total road length (0.6), cumulative building area (0.4), and green space area (0.7) all exhibit strong links. This interconnectedness underscores the importance of including the population, even if its direct impact appears modest. By capturing these cascading influences, the accuracy of we ensure the model's accuracy the model and its ability to reflect real-world dynamics are ensured.

While some spatial distribution grouped features like 'Cumulative building area', 'Green space area', and 'Industrial area' appeared to have a minimal individual impact individually on the final decision tree, the analysis paints a different story. It shows a strong degree of interconnectedness within this group, with dependencies ranging from 0.3 to 0.7, suggesting that their influence is not isolated, but rather manifests through their combined effect on other variables. While the individual impact of each parameter might be subtle, their combined effect through these connections could be significant. This underscores the importance of retaining these parameters together in the database. By capturing their intricate interplay, the model does not miss hidden patterns and accurately reflects the real-world complexities where variables rarely act in isolation, drawing This draws attention to the fact that a significant emphasis must be placed on feature engineering when identifying evidence-based decision-support climate action planning models.

4.2.2. Depth Selection

Finding the right balance in terms of decision tree complexity is essential to achieve optimal accuracy. Insufficient levels can block the ability of the model to identify underlying patterns, whereas excessive levels can lead to a model that is overly adjusted to the training data and performs poorly on new data. Evaluating the sweet spot between accuracy and overfitting is necessary to achieve the aim of this step, by calculating both training and testing accuracy at different depths of the decision tree. This analysis determines the ideal number of levels, striking a balance between capturing nuances of the data and avoiding over-complication. The results of the proposed complex approach, revealing the optimal tree depth, are further explored in Figure 20.

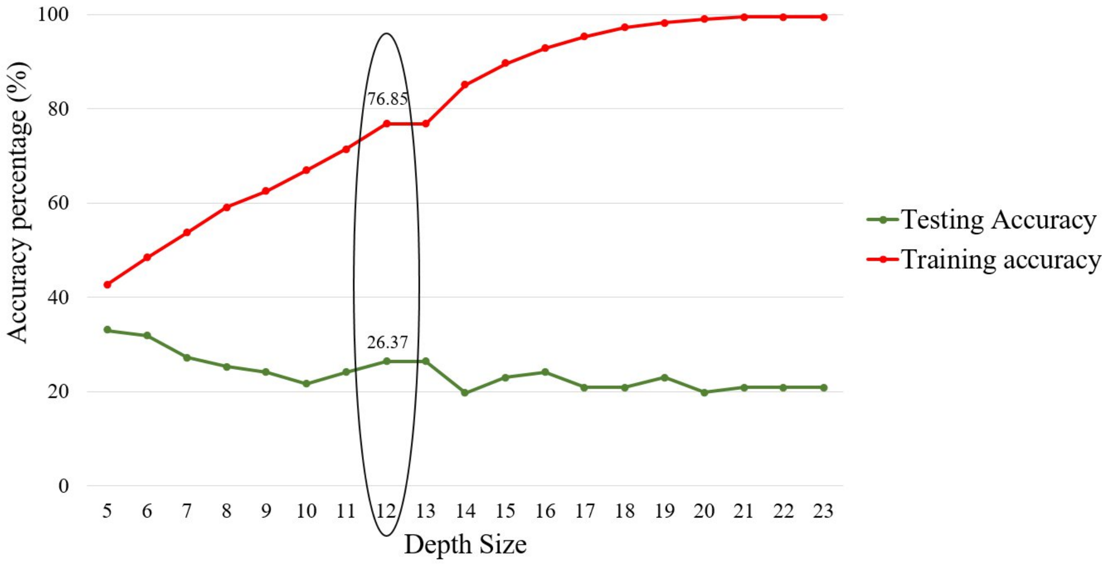


Figure 20: Test and train accuracy by stepwise feature engineering for optimal decision tree depth size selection.

As can be seen in Figure 20, a depth of 21 offers the highest training accuracy (99.44%), however its low testing accuracy (20.87%) is indicative of overfitting and hinders interpretability. Conversely, the highest testing accuracy of 32.96% at depth 5 comes at the cost of a low training accuracy (42.69%). Therefore, the middle ground has to be found ensuring both an acceptable level of accuracy and a readable structure of the decision tree. The second-highest testing accuracy of 26.37% appears at depths 12 and 13, paired with a respectable training accuracy of 76.85%. Ultimately, a depth of 12 is opted for, prioritizing a slightly clearer degree of visualization over a marginally higher testing accuracy at depth 13. This choice ensures a balance between performance and interpretability, making the resulting decision tree more valuable for analysis and real-world application.

4.2.3. Decision tree simulation and feature contribution analysis

Having culled out features with negligible influence (Landfill area, Reduction targets) and pinpointed the ideal tree depth (12), all the necessary elements to generate the decision tree are available, culminating in a streamlined model poised for insightful analysis. But before diving into visualization, evaluating the impact of individual features and their interconnectedness is crucial to gaining a deeper understanding and refining the model further, which draws attention to the importance of integrating expert knowledge into model identification. This analysis will inform the pruning process, and ensure valuable insights are retained while eliminating noise and enhancing visualization.

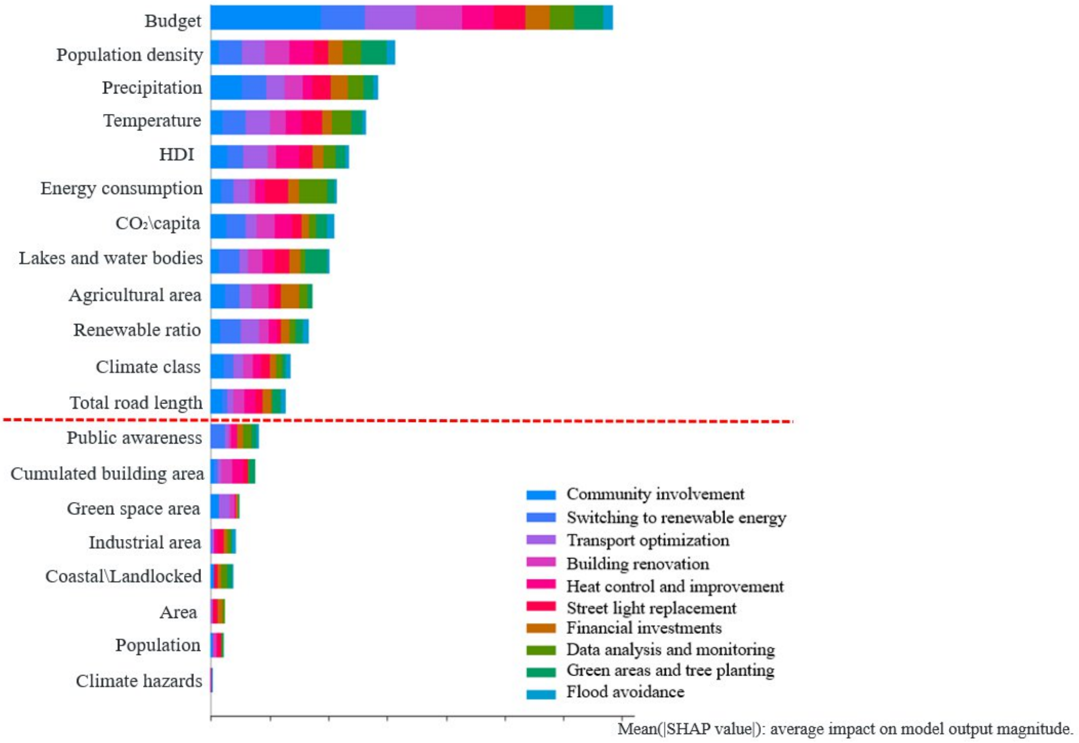


Figure 21: The Shapley value contribution of the features for climate action planning. The neglect threshold of the features is indicated by the red dashed line.

The Shapley values as the influence of the model outcome of the involved features are shown in Figure 21. Budgeting reigns supreme, as its impact is evident across all categories, particularly those demanding hefty investments like the creation of green spaces and building renovations. This aligns with expectations, as budgets invariably steers strategic choices. Population density follows closely behind, mirroring the observed variation in action plans between densely populated cities and sparsely populated villages. Notably, the individual impacts of the features ’Public awareness’, ’Cumulative building area’, ’Green space area’, ’Industrial area’, ’Coastal/Landlocked’, ’Area’, ’Population’ and ’Climate hazards’ are minimal (less than 0.15 when combining their impacts in all the categories of action plans), suggesting their influence might be better understood through their interaction with other factors.

4.2.4. Post-pruned decision tree

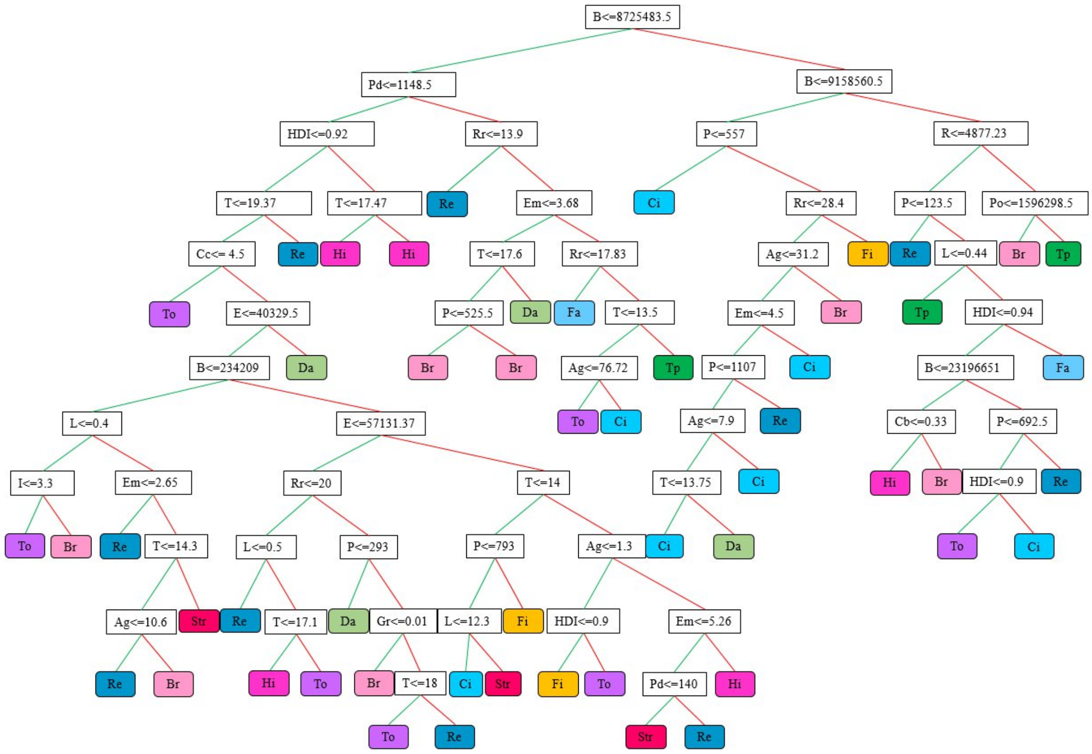


Figure 22: Post-pruned decision tree drawn up. Features: Ag: Agricultural area (km^2) B: Budget (Euro) Cb: Cumulated building area (km^2) Cc: Climate class E: Energy consumption (MWh) Em: $CO_2/CO_{2eq.}$ emissions (t) Gr: Green space area (km^2) HDI: Human Development Index (-) I: Industrial area (km^2) L: Surface area of lakes and standing water bodies (km^2) P: Precipitation (mm) Po: Population Pd: Population density (capita/ km^2) R: Total road length (km) Rr: Renewable ratio (%) T: Temperature (°C).

The post-pruned decision tree is showcased in Figure 22, crafted from the original Python plot to enhance visual clarity and usability. This transformation not only yielded a more interpretable representation, but also delivered a significant improvement in testing accuracy, jumping from 26.37% to 32.9%, and demonstrating the effectiveness of post-pruning in optimizing both clarity and prediction predictive power. This level of accuracy is consistent with values reported for comparable multi-class classification tasks on heterogeneous policy and urban datasets, where ten-or-more-category problems commonly yield test accuracies well below 50%

Further analysis reveals the absence of four features in the post-pruned tree, namely ‘Public awareness’, ‘Total area’, ‘Climate hazards’, and ‘Coastal/Landlocked’, which aligns with the findings from the previous section, where both Figure 19 and Figure 21 indicated the minimal impact and weak connections for these variables. Their exclusion in the pruned tree, therefore, comes as a validation of the result analysis validates the analysis of the results, reinforcing the notion that the interpretability and accuracy of the model can be harmoniously achieved through strategic pruning, ultimately leading to an impactful decision-making tool. Consequently, within this dataset, features such as geographic location (coastal or landlocked), the specific climate threats a city faces, and its total area did not significantly improve the prediction of the broad climate-action category. This does not imply that geographic conditions are unimportant, they remain among the most critical determinants of climate risk and strongly shape the detailed design of interventions. Rather, it indicates that, at the level of the broad action category, cities with otherwise similar characteristics tend to adopt comparable categories regardless of these features. This information therefore remains highly valuable for refining and tailoring the selected actions to local conditions.

4.2.5. Results validation

Validating the final results started with comparing the distribution of action plans across three groups:

- Applied action plans: The plans actually implemented by the studied cities, serving as our real-world benchmark.
- Pre-pruned decision tree suggestions: The initial recommendations before post-pruning.
- Post-pruned decision tree suggestions: The refined recommendations after pruning

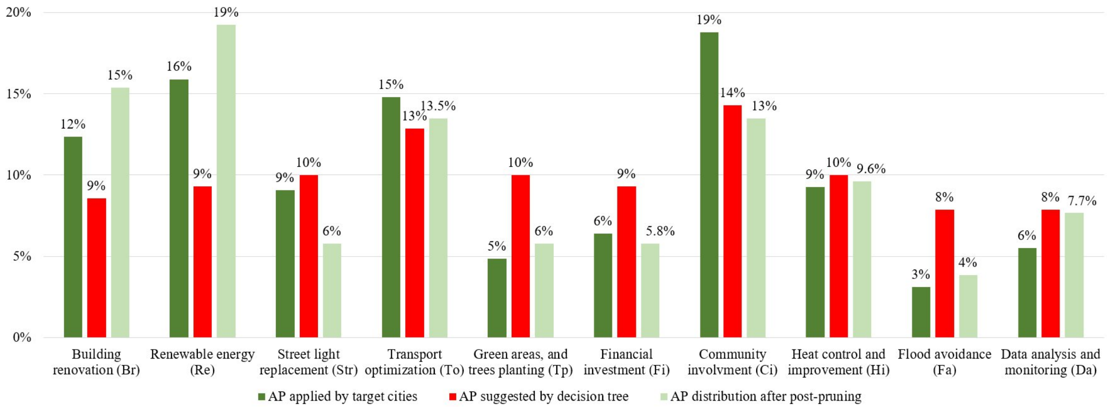


Figure 23: Comparison of the distribution of action plans in the studied action plans with their distribution in pre- and post-pruned decision trees.

Figure 23 is a visual presentation of the forementioned comparison as a global validation of the proposed framework. Revealing a significantly closer match between the distribution of applied action plans and the post-pruned decision tree compared to the pre-pruned version. This strong correlation underscores the effectiveness of post-pruning in this case, leading to an optimal alignment between the predictions of the model and real-world actions.

Beyond the distribution match described above, the model was evaluated using standard classification metrics on the held-out test set, together with 5-fold stratified cross-validation. Results are summarised in Table 9 (overall) and Table 10 (per category).

Table 9: Overall performance of the decision tree model: held-out test metrics, 5-fold cross-validation, and baseline comparisons.

Metric	**Value**
Test macro precision	0.311
Test macro recall	0.262
Test macro F1	0.248
Test weighted F1	0.302
5-fold CV accuracy (mean ± std)	0.280 ± 0.035
5-fold CV macro-F1 (mean ± std)	0.184 ± 0.026
Majority-class baseline (test)	0.154
Random uniform baseline (test)	0.033

Table 10: Per-category precision, recall, and F1 of the decision tree model on the test set.

Category	Precision	Recall	F1
Ci	0.611	0.786	0.688
Tp	1	0.25	0.4
Str	0.235	0.5	0.32
Re	0.316	0.316	0.316
To	0.25	0.417	0.312
Fi	0.2	0.167	0.182
Hi	0.333	0.091	0.143
Br	0.167	0.091	0.118
Da	0.000	0.000	0.000
Fa	0.000	0.000	0.000

The model achieves a test accuracy of 33.0%, more than double the majority-class baseline (15.4%) and an order of magnitude above a uniform random baseline (3.3%) over ten imbalanced categories. The dominant category, involving the community (Ci), is recovered with high reliability (F1 = 0.69), and several further categories, adding green areas (Tp), street-light replacement (Str), renewable energy transition (Re), and transport optimisation (To), are predicted at F1 ≥ 0.31. The lower per-category F1 values are concentrated in the rarest categories (Da, Fa) for which the test fold contains only three reports each, so the corresponding metric values reflect small-sample instability rather than model failure. The 5-fold cross-validation results (accuracy 0.28 ± 0.04; macro-F1 0.18 ± 0.03) are consistent with the held-out test, indicating that the single-split performance is not the result of a favourable partition. The confusion matrix (Appendix) shows that misclassifications are not random: the model tends to confuse functionally related categories (for example, Re with To and Hi with Str), which is consistent with the conceptual overlap between these climate-action categories rather than with a failure of discrimination.

4.2.6. Policy implications

The decision tree model developed for climate action planning has led to policy insights by showing the need for appropriate strategies based on local specific factors, such as budgets and, population density, amongst the other environmental conditions. Policymakers can use this tool to prioritize high-impact, cost-effective actions that align with specific characteristics of cities:

- Densely populated areas with limited green space might focus on tree planting and public awareness campaigns.
- Regions with high levels of industrial activity could prioritize the adoption of renewable energy.
- Cities with high energy consumption could focus on building renovation to improve energy efficiency and reduce overall demand.
- Areas subjected to frequent flooding might prioritize the replacement of streetlights with flood-resistant infrastructure and flood prevention measures.
- Regions with high levels of precipitation should consider tree planting to enhance storm water management and reduce runoff.
- Cities with abundant green spaces should invest in transport optimization to connect these areas and reduce traffic-related emissions.
- Localities with limited budgets may focus on data analysis to identify cost-effective climate actions and simplify resource allocation.
- Communities with low HDIs could place an emphasis on raising community awareness to ensure equitable participation in climate actions.
- By exploiting these insights, policymakers can develop comprehensive, context-specific climate action plans that enhance resilience, optimize resource allocation, and ensure long-term sustainability.

4.2.7. Analysis of feature importance and interconnectedness

This study confirms that a variety of factors must be considered when planning climate actions due to their significant impact on the implementation of an action plan. Among these factors, the budget is the most influential in decision-making for cities, as can be seen in Figure 21, which is consistent with previous studies of municipal climate action planning, which identify budget and urban density among the principal determinants of the type and ambition of adopted actions (Reckien, 2018). However, the post-pruned decision tree also shows that factors such as building retrofitting and renovation are essential actions in response to climate change, even in the event of a lower or higher budget as presented in Figure 22.

Analysing the distribution of categories of action plans in the decision tree, in the light of with published reports, reveals the interconnectedness of these categories, as they are similarly influenced by various features. Therefore, implementing policies and regulations to manage the factors identified can effectively address all these categories simultaneously.

The interconnectedness of the analysed climate action categories is illustrated in Figure 24, emphasizing how each category influences and supports the others. For example, community involvement drives building renovation, which in turn encourages the integration of green spaces that help mitigate flood risks. This effect continues through the network, showing how improvements in one area, such as the adoption of renewable energy, can lead to advancements in others, like the replacement of streetlights and transport optimization. The flow of relationships highlights the importance of this approach, where strategic investments and data analysis support effective climate action across all categories. By understanding these connections, policymakers can create more integrated and impactful climate strategies.

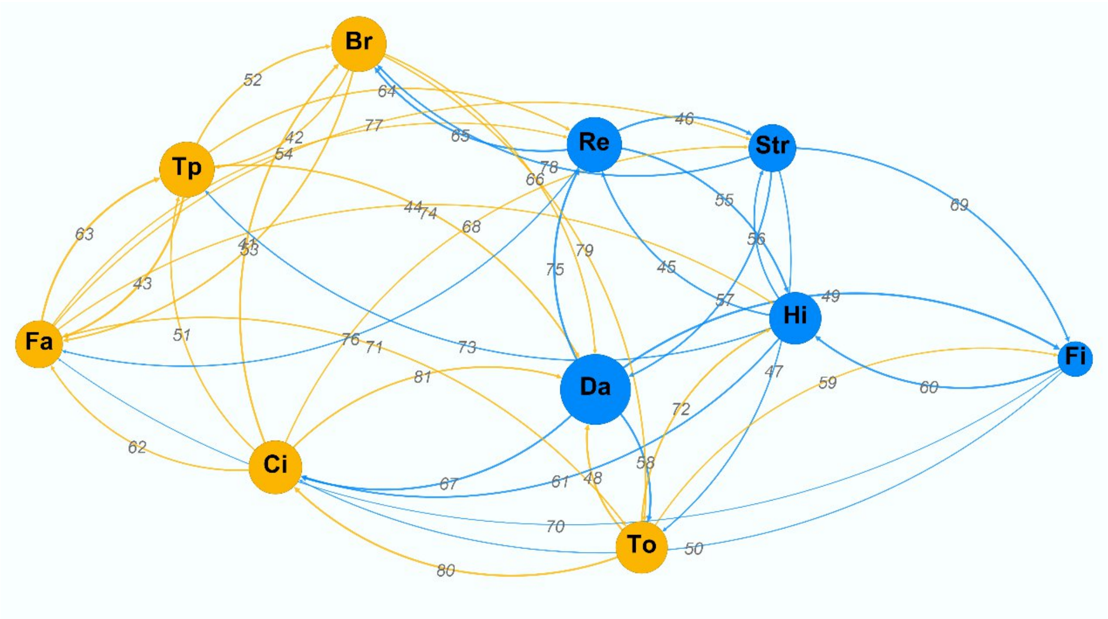


Figure 24: Network representation of the interconnectedness of the climate action plan categories.

The nodes represent the 10 analysed categories, the sizes of which are proportional to their weighted degrees. As is shown in Figure 24, the data analysis "Da" category the most edges (33), followed by the categories Planting trees and the creation of green areas "Tp" and switching to renewable energy "Re" with 23 and nodes each. The colours of the nodes denote the results of the community detection algorithm, according to which two main communities can be identified (as highlighted in Figure 24 in orange and blue). Based on the analysis of the climate action categories, data analysis plays the most decisive role, but this is also the most affected action plan category, followed by building renovation. This fact also highlights the extent to which the fight against climate change requires digitization. The authors are convinced that the set goals cannot be met without digital management and data science, therefore, it is necessary to support the harmonization and integration of further data-based climate action planning studies.

4.3. Comparative Environmental Assessment of Construction Materials in Climate Action Projects

After presenting the results of the decision-support model for climate action planning, the focus shifts to the environmental assessment of construction materials and their influence on the overall sustainability of climate actions.

Table 11: Project-level impact results and normalized impacts per category functional unit (FU). Total impacts are reported for the full project, while normalized impacts divide totals by the category reference metric (m^2 for Br/Tp/Hi; km for Fa).

Project & Action category	Total GWP	Total ODP	Total HT	GWP\FU	ODP\FU	HT\FU
Fondazione Prada (Br)	4096000	396.5	1558	215.5789474	0.02087	0.082
Stedelijk Museum (Br)	3768750	730.05	2455.375	471.09375	0.09126	0.30692
Fondaco dei Tedeschi (Br)	134500	7.6395	50.2725	14.94444	0.00085	0.00558
Vieux Lyon Renaissance Houses (Br)	87450	6.056	36.465	145.75	0.01009	0.06078
Parque Madrid Rio (Tp)	60000	4.068	129.3	0.04955	0.000003	0.00011
Superkilen Park (Tp)	65000	12.7	137.5	2.16667	0.00042	0.00458
Multi-family residential building in Feldkirch (Hi)	305260	3.913	124.335	169.58889	0.00217	0.06908

Project & Action category	Total GWP	Total ODP	Total HT	GWP\FU	ODP\FU	HT\FU
Multi-family residential building in Frankfurt (Hi)	27000	0.315	7.35	18	0.00021	0.0049
‘Room for the river’ Nimejen (Fa)	173200000	17055	73030	216500000	21318.75	91287.5
Thames Estuary plan (Fa)	3960000	135.6	1950	12000	0.41091	5.90909

Table 11 synthesizes the results of the life cycle based analytical framework by reporting both absolute project impacts and impacts normalized per category functional unit (FU). Across all projects, the results show pronounced variability in GWP, ODP and HT, driven by two main factors: (i) the total quantity and type of materials used, which determine the absolute impacts, and (ii) the material intensity per unit of intervention, which is captured by the FU-normalized indicators. This dual reporting is essential for interpreting climate action projects because the interventions differ significantly in scale and physical configuration; therefore, absolute impacts alone would primarily reflect project size, whereas normalized results show the environmental intensity of delivering a unit of service within each climate action category. Flood prevention interventions exhibit the highest absolute impacts, dominated by the ‘Room for the River’ project, which reaches 173.2 million $kg\ CO_{2eq.}$ and 73030 $CTUh$, reflecting the heavy reliance on concrete and stones required for large-scale earthworks and hydraulic protection. Normalization by the category FU (km of flood defence) further highlights the exceptional material intensity of this intervention, yielding 216.5 million $kg\ CO_{2eq.}/km$ and 91287.5 $CTUh/km$. In contrast, the Thames Estuary Plan shows lower total impacts than ‘Room for the River’, but the FU-normalized values remain substantial (12000 $kg\ CO_{2eq.}/km$ and 5.91 $CTUh/km$), illustrating that flood-prevention measures can differ strongly in environmental intensity depending on design approach, scale of structural works and protective layers. These findings emphasize that flood prevention climate actions constitute a distinct class of material intensive infrastructure compared to building and area-based interventions. Within the building renovation category, large cultural buildings exhibit the highest absolute impacts, with the Fondazione Prada and Stedelijk Museum projects reaching 4.10 million and 3.77 million $kg\ CO_{2eq.}$, respectively. However, the FU normalized results show that the Stedelijk Museum has a markedly higher GWP intensity (471.09 $kg\ CO_{2eq.}\ /m^2$) than Fondazione Prada (215.58 $kg\ CO2_{eq.}\ /m^2$), indicating that the environmental burden per unit renovated area is more strongly influenced by the material mix and intervention depth than by total project scale alone. The relatively low normalized values for the Fondaco dei Tedeschi (14.94 $kg\ CO_{2eq.}\ /m^2$) suggest a lower material intensity per unit area, whereas the Vieux Lyon Renaissance Houses show intermediate intensities (145.75 $kg\ CO_{2eq.}/m^2$), consistent with renovation strategies where stone and finishing materials contribute more strongly relative to structural concrete. Similar patterns are observed across ODP and HT, where the Stedelijk Museum also presents the highest intensities (0.0913 $kg\ R_{11eq.}\ /m^2$ and 0.3069 $CT\ U\ h/m^2$), pointing to both higher material demand per m^2 and the use of materials with higher characterization factors. Heating and insulation improvement projects present lower absolute impacts than major renovations, yet FU normalized results indicate that these interventions can still be environmentally intensive per treated area, depending on the retrofit package. Feldkirch exhibits 169.59 $kg\ CO_{2eq.}/m^2$ and 0.0691 $CT\ U\ h/m^2$, while Frankfurt shows much lower intensities (18 $kg\ CO_{2eq.}/m^2$ and 0.0049 $CT\ U\ h/m^2$). This contrast reflects differences in material composition, particularly the relative contribution of insulation and envelope related materials and demonstrates the value of FU normalized indicators for distinguishing between shallow and deep retrofit strategies when evaluating climate action measures that target operational energy savings but require additional embodied impacts. Green space projects show comparatively small absolute impacts (60000-65000 $kg\ CO_{2eq.}$), and their FU normalized intensities are also low, especially for Parque Madrid Rio (0.0496 $kg\ CO_{2eq.}/m^2$). Superkilen Park presents a higher normalized intensity (2.17 $kg\ CO_{2eq.}\ /m^2$), indicating a more material intensive landscape design relative to its area. Although these values are lower than those of building and flood prevention interventions, their interpretation is important because green space climate actions can cover very large areas. Therefore, small per unit intensities may still translate into significant absolute material demands at the city scale. Overall, the FU normalized results provide category consistent intensity metrics that make it possible to compare projects within the same climate action category on an equal basis and to identify projects where material choices or intervention depth drive disproportionately high impacts per unit of delivered service. This category-based normalization is particularly relevant for climate action portfolios, where decision makers must prioritize among heterogeneous interventions (buildings, green infrastructure, and flood prevention) that cannot be compared meaningfully using a single universal functional unit. By linking material inventories and impact indicators to climate action typologies through category specific functional units, the results support a more interpretable and action-oriented assessment of material-related environmental performance than reporting total impacts alone.

4.3.1. Environmental impact comparison of project categories

As demonstrated in the previous section, comparing all selected projects provides a general comparison depending on their scale. To make this comparison more specific, it should be assessed across project categories, because the materials used vary significantly between projects, depending on their respective climate action categories. Therefore, this section focuses on comparing the environmental impact indices of projects within the same climate action category.

4.3.1.1. Building renovation projects

The comparison between the Fondazione Prada and Stedelijk Museum projects illustrates how differences in material composition translate directly into both absolute and normalized environmental impacts.

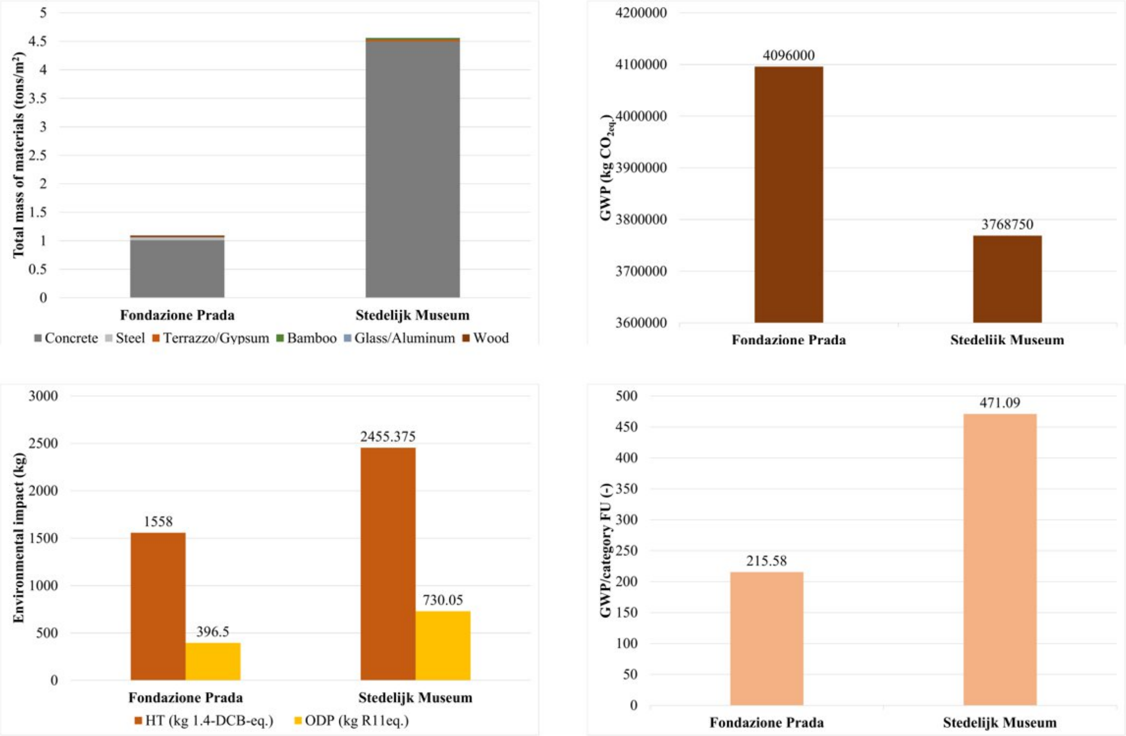


Figure 25: Comparison of GWP, ODP, HT, and material distribution between Fondazione Prada and Stedelijk Museum projects.

The plot of the intensity of the stacked material shows that the Stedelijk Museum requires more concrete and steel per square meter than the Fondazione Prada renovation, resulting in a total intensity of the material more than four times higher (Figure 25). Because concrete dominates the mass profile of both projects, even moderate increases in concrete use produce large differences in total embodied impacts. This relationship is reflected in the total GWP results, where Fondazione Prada reaches 4.10 million $kg\ CO_{2eq.}$ while the Stedelijk Museum records 3.77 million $kg\ CO_{2eq.}$, despite the latter having a smaller reference floor area. When normalized by functional unit, the contrast becomes more pronounced: the Stedelijk Museum exhibits a GWP intensity of 471 $kg\ CO_{2eq.}/m^2$ compared to 216 $kg\ CO_{2eq.}\ /m^2$ for Fondazione Prada. This indicates that the environmental burden per renovated square meter is driven more by structural reinforcement and material choice than by project size alone. The toxicity and ozone depletion indicators follow a similar pattern. The Stedelijk Museum shows higher HT and ODP values, consistent with its greater reliance on steel and processed materials that carry higher characterization factors. Importantly, the normalized indicators show that the difference between projects is not simply a scale effect but reflects a fundamentally different material strategy. While both projects fall within the same climate action category (building renovation), the figure demonstrates that renovation depth, structural intervention, and finishing materials can shift the environmental profile significantly. This result highlights the analytical value of combining absolute impacts with functional unit normalization: total values capture city scale burden, whereas normalized metrics expose material efficiency. Together, they provide a more varied understanding of how design decisions influence the environmental performance of climate action projects.

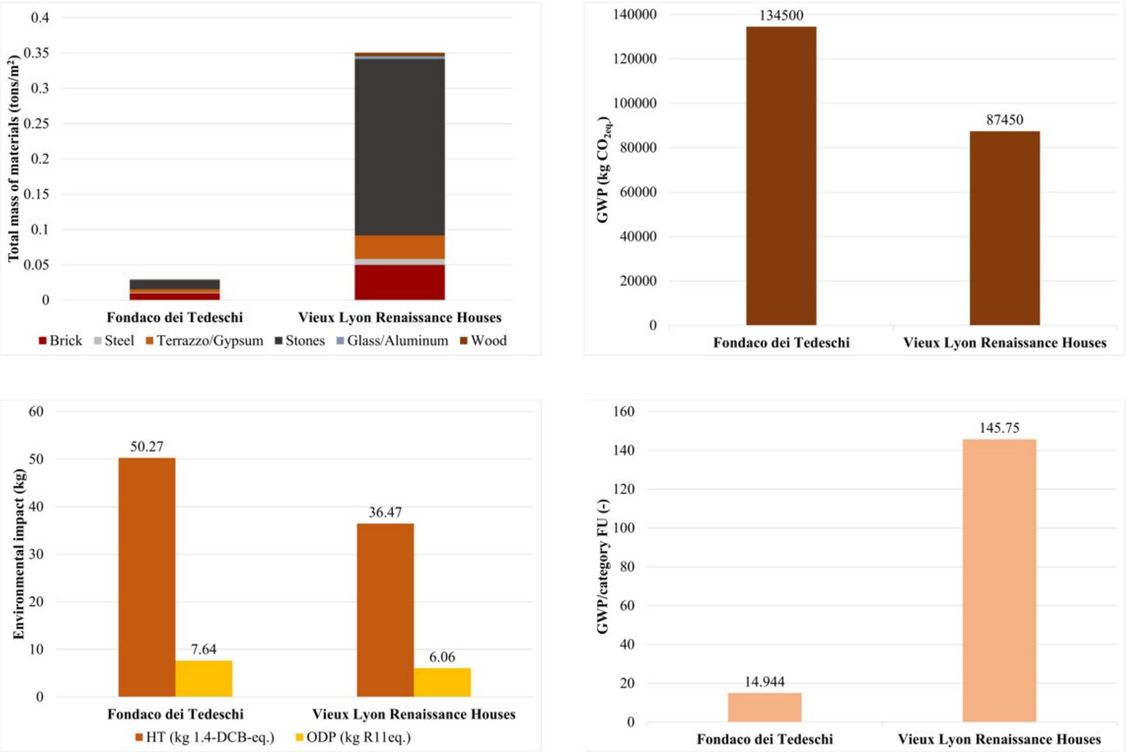


Figure 26: Comparison of GWP, ODP, HT, and material distribution between Fondaco dei Tedeschi and Vieux Lyon Renaissance Houses projects.

The comparison between the Fondaco dei Tedeschi and the Vieux Lyon Renaissance Houses shows how historic renovation strategies can produce markedly different material and environmental profiles. The stacked material plot indicates that the Vieux Lyon project relies more heavily on mineral materials, particularly stones and terrazzo-related components, resulting in higher material intensity per square meter. In contrast, Fondaco dei Tedeschi uses a lighter material palette, leading to lower normalized material demand (Figure 26). These differences are reflected in the impact results. Although Fondaco dei Tedeschi records a higher total GWP (134500 $kg\ CO_{2eq.}$) than Vieux Lyon (87450 $kg\ CO_{2eq.}$), normalization reverses the interpretation: Vieux Lyon reaches 145.75 $kg\ CO_{2eq.}/m^2$ compared to 14.94 $kg\ CO_{2eq.}/m^2$ for Fondaco. Similar trends are observed for ODP and HT. This demonstrates that environmental performance is governed more by material intensity and intervention depth than by absolute project scale. Reporting both total and normalized indicators, therefore, shows differences in renovation efficiency that would not be visible from project totals alone.

4.3.1.2. Park and Green Space Development Projects

The two projects selected for this category involve the creation of two parks: Parque Río in Madrid and Superkilen Park in Copenhagen. This category of climate actions does not rely on a large variety or quantity of construction materials but instead focuses on the extensive use of trees and grass.

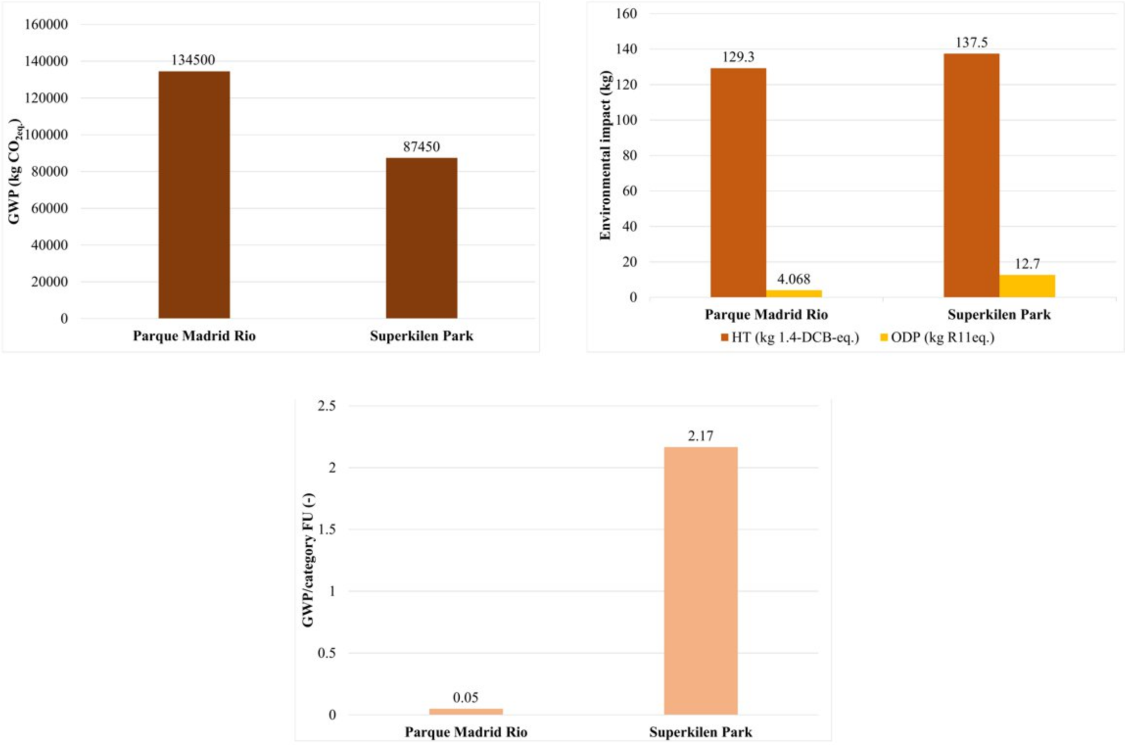


Figure 27: Comparison of GWP, ODP and HT between Parque Rio and Superkilen Park projects

The comparison between Parque Madrid Río and Superkilen Park highlights how urban green space projects can differ in environmental performance despite belonging to the same climate action category. In absolute terms, Parque Madrid Río exhibits the higher total GWP (134500 $kg\ CO_{2eq.}$) compared to Superkilen Park (87450 $kg\ CO_{2eq.}$), reflecting its larger spatial extent and total material demand. However, normalization per functional unit shows the opposite trend. Superkilen Park reaches a GWP intensity of 2.17 $kg\ CO_{2eq.}/m^2$, whereas Parque Madrid Río records only 0.0496 $kg\ CO_{2eq.}/m^2$. This indicates that Superkilen relies on a more material intensive design relative to its developed area (Figure 27). A similar pattern is observed for ODP and HT, where Parque Madrid Río shows higher absolute values due to scale, but Superkilen presents greater environmental intensity per square meter. These results demonstrate that, for green infrastructure projects, absolute impacts are primarily driven by total area, while normalized indicators capture differences in design strategy and material density. The figure therefore emphasizes the importance of functional unit normalization in distinguishing between large area, low intensity landscape interventions and smaller but more material intensive urban park developments.

4.3.1.3. Improving Building Insulation and Heating Efficiency

The two projects selected for this category are small-scale initiatives aimed at enhancing the insulation of two multi-family residential buildings, one located in Feldkirch and the other in Frankfurt. This type of actions does not require a wide variety of materials.

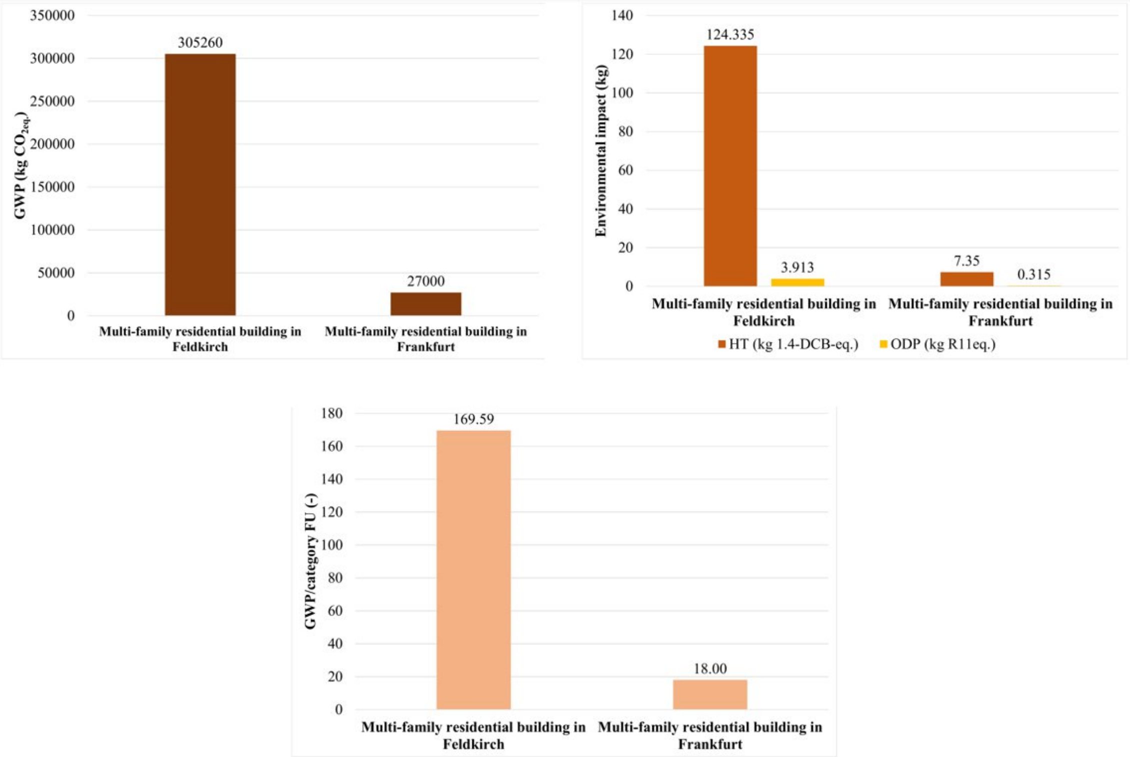


Figure 28: Comparison of GWP, ODP and HT between the insulation of the multi-family residential buildings in Feldkirch and Frankfurt.

The comparison between the residential buildings in Feldkirch and Frankfurt illustrates how differences in insulation strategies and façade systems translate into large variations in environmental performance. In absolute terms, the Feldkirch building shows higher total GWP (305260 $kg\ CO_{2eq.}$) than the Frankfurt case (27000 $kg\ CO_{2eq.}$), reflecting a greater reliance on glass, aluminium, and insulation materials. These material choices also drive the higher ODP and HT values observed for Feldkirch, particularly in relation to synthetic insulation components. Normalization per functional unit confirms that the difference is not only a matter of project size. Feldkirch reaches a GWP intensity of 169.59 $kg\ CO_{2eq.}/m^2$, compared to 18 $kg\ CO_{2eq.}/m^2$ for Frankfurt. Similar proportional gaps are visible for ODP and HT, indicating that the environmental burden per unit of floor area is consistently higher in Feldkirch. The figure therefore demonstrates that heating and insulation interventions can vary widely in material efficiency, and that high performance envelope solutions may introduce significant embodied impacts. Evaluating results per functional unit is essential to visualize these trade-offs and to support balanced design decisions in building energy retrofits (Figure 28).

4.3.1.4. Implementing Flood prevention measures

The two projects selected for this climate action category are ’Room for the River’ in Nijmegen (Netherlands), and the Thames Estuary 2100 (TE2100) Plan in London, the capital of the United Kingdom.

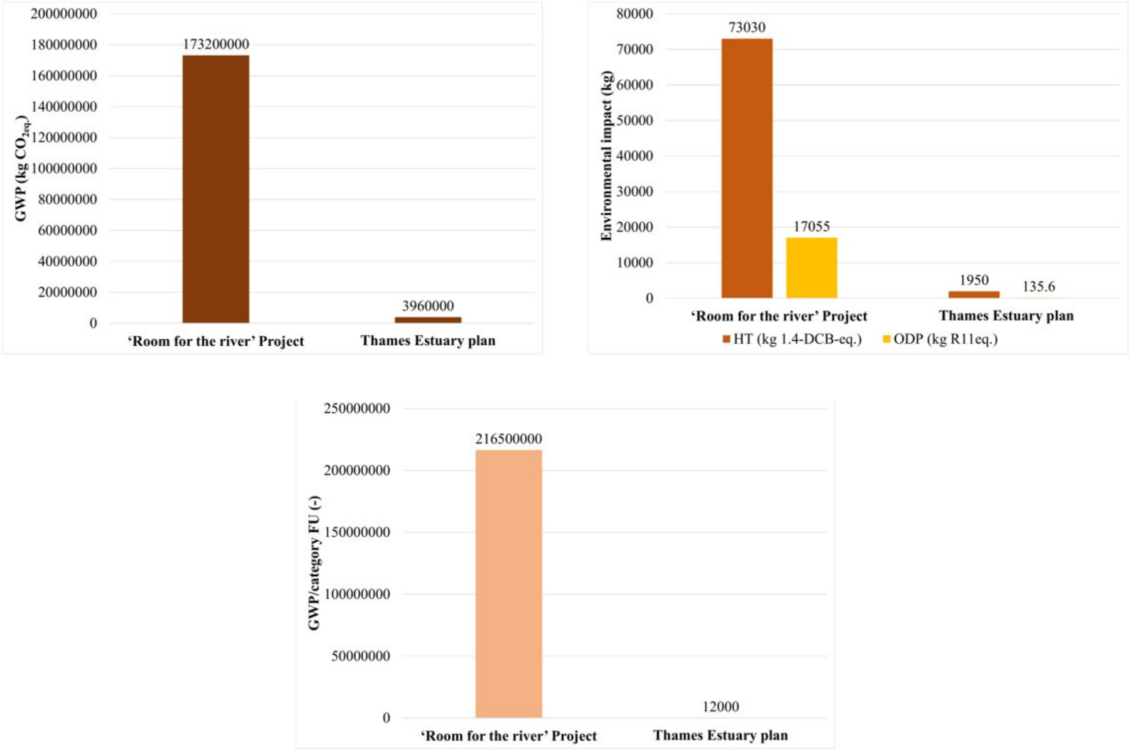


Figure 29: Comparison of GWP, ODP and HT between the 'Room for the River' and the TE2100 projects.

The comparison between the 'Room for the River' project and the Thames Estuary plan illustrates the extreme scale sensitivity of flood prevention infrastructure. In absolute terms, the Room for the River intervention exhibits a total GWP of 173.2 million $kg\ CO_{2eq.}$, far exceeding the 3.96 million $kg\ CO_{2eq.}$ associated with the Thames Estuary plan. This difference reflects the massive quantities of concrete and stone required for large hydraulic earthworks. The same trend is observed for ODP and HT, where the Room for the River project records higher totals due to the material intensity of structural flood defences. Normalization per functional unit reinforces this contrast. The Room for the River project reaches 21.65 million $kg\ CO_{2eq.}/km$, compared to 12000 $kg\ CO_{2eq.}/km$ for the Thames Estuary plan. Such a disparity indicates that the environmental burden is not only driven by project length but by the construction approach itself, particularly the reliance on heavy mineral materials. The figure demonstrates that flood prevention strategies can differ by several orders of magnitude in embodied impacts. Reporting normalized indicators is therefore essential to distinguish between infrastructural efficiency and total system scale, providing a clearer basis for evaluating alternative hydraulic engineering solutions (Figure 29).

4.3.2. Results discussion: modelled results vs experiments

In order to contextualize and validate the calculated material impacts, the modelled life cycle results were compared qualitatively and quantitatively with experimentally derived LCA data reported in the literature. The validation exercise focuses on GWP because greenhouse gas emissions are the dominant driver of embodied environmental impact in construction materials and represent the most consistently measured and experimentally reported indicator in industrial LCA datasets.

Table 12: Comparison of modelled material GWP factors with experimentally reported values.

Material	**Modelled GWP**	**Experimental /literature GWP**	**Reference**
	$(kgCO_{2eq.}/kg)$	$(kgCO_{2eq.}/kg)$	
Concrete	0.09 – 0.13	0.08 – 0.15	(Ugural, 2024); (Eštoková, 2023)
Glass	0.85 – 1.10	0.80 – 1.20	(Eštoková, 2023)
Steel	1.80 – 2.20	1.70 – 2.30	(Ugural, 2024)
Mineral wool insulation	0.90 – 1.10	0.95 – 1.05	(Flury.F, 2012)
Polymer foam insulation	2.50 – 3.20	2.30 – 3.50	(Ugural, 2024)
Wood (production stage)	0.00 – 0.05	0.00 – 0.10	(Ugural, 2024)

Previous life cycle assessment studies provide measured emission intensities for construction materials that allow benchmarking of the calculated factors used. For example, published experimental LCA results report that the upstream and core production of rock wool insulation generates approximately 1.01 $kg\ CO_{2eq.}/kg$ of product, with manufacturing energy use dominating the impact. This value falls within the range typically observed in measured industrial LCA datasets and aligns with the magnitude of the insulation related emission factors applied in the present analysis. The agreement supports the plausibility of the modelled GWP intensities for mineral based insulation materials. Comparative experimental studies of construction materials consistently show that structural materials such as concrete and steel contribute the largest share of embodied impacts when normalized per kilogram of product, while insulation materials exhibit lower GWP intensities. This general hierarchy of impacts is reproduced in the calculated results of the current study, confirming that the modelling approach reflects experimentally observed material behaviour.

The remaining differences between the modelled and experimental values are small and fall within the variability of the reference data: the modelled ranges sit inside the experimental ranges but are slightly narrower, and the experimental upper bounds tend to be higher. These discrepancies are mainly attributable to the cradle-to-gate system boundary, which excludes downstream stages captured in some reference studies; to differences in the background datasets and regional energy mixes used to derive the emission factors; and, for bio-based materials such as wood, to the conservative decision to set biogenic-carbon credits to zero, which raises the modelled lower bound relative to studies that account for temporary carbon storage. The close but non-identical match therefore reflects methodological and data-source differences rather than inconsistencies in the modelling approach.

Beyond validating emission factors, the comparison provides an application-oriented interpretation of life cycle data. Whereas most LCA studies discuss experimental results at the level of individual materials, the present work interprets these benchmarks within distinct climate action categories, including building renovation, insulation improvement, urban green space development, and flood prevention infrastructure. This linkage enables material level impact data to be understood in terms of their influence on real project outcomes. As a result, experimentally observed material performance is translated into a project scale perspective, offering practical insight into how material choices shape the environmental profile of different climate interventions implemented by cities (Table 12).

4.3.3. Research implications and limitations

This part of study presents a material centred analytical framework based on life cycle assessment principles to evaluate construction materials used in climate action projects, offering a novel contribution to the field by linking the quantification of materials with their environmental impacts. In contrast to conventional LCA studies, which are often conducted at the product or building component level, this research applies the assessment at the project scale, enabling comparison between different types of climate actions rather than isolated materials. Unlike traditional studies, that focus on general construction practices, this research provides a more specific and targeted analysis of materials used in climate action initiatives. Many existing studies emphasize the structural performance and durability of materials without integrating environmental considerations in full. For example, studies such as those by Michael et al. (2018) and Lee et al. (2020) focus on optimizing material strength and cost in construction projects but lack an in-depth evaluation of the environmental implications involved ((Michael, 2018); (Lee, 2020)). Additionally, Kumar et al. (2020) examined material selection for infrastructure projects but focused primarily on economic feasibility rather than environmental impact (Kumar, 2020). Furthermore, most existing LCA studies do not provide normalized indicators that allow comparison between heterogeneous projects, which limits their use in strategic planning contexts.

In contrast, this analysis emphasizes the balance between the functional performance of materials and their environmental implications, introducing a dual lens for material evaluation. By quantifying construction materials and correlating their quantities with metrics such as Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), this thesis highlights the importance of choosing materials that perform well structurally while minimizing ecological harm. From a practical perspective, this approach provides decision-makers with a clearer basis for comparing alternative design strategies and selecting materials that reduce environmental impacts at the project level. For example, it underscores that while materials such as concrete offer durability, their high GWP necessitates careful consideration and potential substitution with lower impact alternatives such as bamboo or stones. This type of information can support early-stage planning decisions, where material choices have a strong influence on the overall environmental performance of climate action projects.

However, the analysis relies on available data, which may not fully capture regional variations in construction practices or reflect the latest advancements in material technologies. Additionally, the scope of this research is confined to a specific set of climate action projects, primarily focusing on construction materials used in building renovation, green space expansion, heat control, and flood prevention initiatives. While these categories are important for sustainable urban development, the other significant climate action areas mentioned in Section 3.3.1 remain unexplored. It is recommended to extend the proposed framework to additional action categories. In addition, the aim is to evaluate the environmental impacts associated with construction materials up to their production and delivery stages. Consequently, a deeper exploration into material science field, particularly by assessing environmental impacts beyond additional Life Cycle Assessment (LCA) phases such as deconstruction and material circularity, can enhance the accuracy and completeness of the analysis.

5. Conclusion

5.1. Research summary

The main objective of this thesis was to contribute to the understanding of how climate actions can be planned and evaluated in urban contexts. In response to the increasing complexity of climate-related challenges faced by cities, the research aimed to explore different approaches that support decision-making processes and improve the design of climate strategies. The work was structured around several complementary components, each addressing a specific aspect of climate action planning.

The first part of the research focused on the analysis of existing climate action plans and the development of a structured categorization of climate actions. This task involved reviewing a large number of published reports and identifying recurring types of interventions implemented by cities. The categorization process provided an organized framework that groups actions into coherent categories, allowing a clearer representation of the different strategies applied in practice. This step also served as a foundation for the subsequent analyses carried out in the thesis. The second part of the work examined the role of public awareness within climate action planning. This involved the collection and analysis of data related to awareness-related actions, education levels, and environmental indicators. The objective of this part was to explore how social dimensions are considered in climate strategies and how they can be linked to environmental outcomes. The analysis provided a structured approach to studying awareness as a component of urban resilience. The central part of the thesis was dedicated to the development of a data-driven decision support tool for climate action planning. This work was based on the analysis of a large dataset of published climate action plans and the extraction of relevant features describing city characteristics and implemented actions. These data were used to construct a decision tree model designed to support the selection of climate actions. The methodological process included data collection, feature selection, and model development, resulting in a structured tool that translates empirical information into a decision-making structure. The final part of the research addressed the environmental dimension of climate actions through the analysis of construction materials. This involved a comparative assessment based on life cycle methodology, focusing on the quantification of material-related environmental impacts.

The work aimed to integrate material considerations into the evaluation of climate actions and to provide a more complete view of their environmental implications.

This thesis combines different methodological approaches to address the complexity of urban climate action planning. By bringing together the analysis of existing practices, the consideration of social factors, the development of data-driven tools, and the assessment of environmental impacts, the research provides a structured and multi-dimensional perspective on climate action in cities.

5.2. Research Theses

According to the research questions defined in Section 1.5 and based on the results presented in sections 4.1, 4.2 and 4.3, the following research theses are formulated. These theses are derived from the analyses carried out in the associated studies and are supported by the results presented in the corresponding articles. Each thesis reflects a specific scientific contribution of this work.

RT1: I developed a structured categorization of urban climate actions, beginning with a preparatory analysis of 99 SECAP reports and subsequently enlarging the dataset to 454 reports published by 443 European cities across 32 countries on the Covenant of Mayors platform. Using text mining, actions were grouped into ten consistent categories on a functional equivalence basis, whereby distinct measures serving the same objective (for example, car sharing schemes and public bus upgrades were assigned to a single category such as transport optimization). The associated co-benefits were likewise extracted and categorized. Unlike existing classifications, which are largely top-down sector taxonomies, the proposed categorization is derived bottom-up from published municipal practice and structured to serve as input for comparative analysis, data-driven modelling, and environmental assessment.

RT2: Motivated by the high frequency of public awareness actions observed in the analysed plans, I examined, as an exploratory analysis, the role of public awareness and education in urban climate action. The comparison was conducted at the national level, in three contrasting countries (Germany, Brazil, and Kenya), because comparable education indicators are available primarily at the country scale rather than the city scale. I observed that higher awareness and education levels are associated with more favourable trends in air quality and greenhouse gas emissions. Because this finding rests on a limited number of national cases, it is presented as an associational and motivating observation rather than a causal claim. On this exploratory basis, the thesis shows that social and educational dimensions are a relevant supporting factor alongside technical actions.

RT3: I developed a data-driven decision support model for urban climate action planning based on a structured database of 454 climate action reports from 443 European cities in 32 countries, characterised by 24 features organised into three groups: geodemographic, spatial-distribution, and action-related variables. Using this database, I constructed an interpretable Gini-based classification tree of depth 12, refined through feature importance (SHAP) analysis and post-pruning, which increased the testing accuracy to 32.9% while improving readability. The analysis identified budget and population density as the most influential drivers of the selected category. The resulting model translates empirical patterns in published plans into a transparent, context-based tool that indicates the climate action category most consistent with the observed practice of cities sharing similar characteristics. This thesis demonstrates that combining large-scale empirical analysis with interpretable model development transforms past municipal experience into a practical decision-support tool for more consistent and evidence-based planning.

RT4: I developed a material based evaluation framework that assesses climate action projects at the project level through three elements: The quantification of construction materials used in each project, the comparison of their environmental impacts using Global Warming Potential, Ozone Depletion Potential, and Human Toxicity, and the use of normalized functional units to enable consistent comparison across heterogeneous interventions. I demonstrated that environmental performance is governed primarily by the type and intensity of materials used rather than by project category alone, so that projects in the same category can differ substantially in impact. This thesis demonstrates that material intensity, expressed through normalized functional units, is a decisive criterion for accurate environmental evaluation in climate action planning.

5.3. Implications

Following the presentation of the main findings, this section discusses the practical implications of the research for climate action planning and decision-making. The results of this thesis highlight the importance of combining social, analytical, and environmental perspectives when designing climate strategies.

The first part of the research emphasizes the role of public awareness as a supporting factor in improving environmental outcomes. From a practical perspective, this suggests that climate strategies should not focus only on technical interventions but also consider the social context in which these actions are implemented. Decision-makers should develop climate policies that combine raising awareness initiatives with efforts to improve education levels, as these elements can influence how populations respond to environmental challenges. In addition, integrating awareness actions into local climate plans can help strengthen citizen engagement and support the long-term success of implemented measures. Building on this, the second part of the research provides direct support for decision-making through the development of a data-driven tool for climate action planning. The decision tree model offers a structured and accessible way to guide the selection of climate actions based on specific city characteristics. This approach allows policymakers and urban planners to move beyond general recommendations and rely on empirical evidence derived from existing practices. By identifying key factors that influence the implementation of climate actions, the model also highlights areas where policy interventions can be most effective. Furthermore, the adaptability of the model makes it suitable for application in different contexts, and its expansion beyond the European case could support the development of more comprehensive decision-support systems at a global scale. The third part of the research addresses the environmental implications of construction material choices in climate action projects. The results underline the importance of considering material-related impacts during the design phase of climate interventions. From an engineering and planning perspective, the proposed approach provides a basis for comparing different projects using normalized environmental indicators, allowing decision-makers to identify more efficient material strategies. This is particularly relevant for large-scale infrastructure and renovation projects, where material intensity plays a major role in overall environmental performance. Integrating such indicators into project evaluation processes can support more balanced decisions that take into account both operational benefits and embodied environmental impacts. More broadly, this approach contributes to shifting environmental assessment from isolated evaluations toward a comparative tool that can inform cross-sector planning decisions.

Overall, the implications of this research highlight the value of combining data analysis, social considerations, and environmental evaluation in climate action planning. By providing both conceptual insights and practical tools, the thesis supports the development of more informed, transparent, and effective strategies for addressing climate challenges in urban areas. From a practical point of view, this research offers concrete support for urban decision-makers. The developed tools and approaches can help cities better select, compare, and prioritize climate actions based on their local context. In addition, the results can support more informed planning by linking technical solutions with social factors and environmental impacts.

5.4. Contribution to literature

This thesis contributes to the literature on urban climate action by combining different analytical approaches within a unified framework. It brings together the analysis of existing climate action plans, data-driven modelling, and environmental assessment to support more structured and informed climate planning.

First, the research provides a categorization of climate actions based on a large set of published plans, offering a clearer overview of the strategies implemented by cities and supporting comparison across different contexts. Second, it contributes to data-driven urban planning by developing a decision-support model that translates empirical evidence from existing actions into a practical tool for guiding climate action planning. Third, the study extends environmental assessment approaches by introducing a project-level, material-based framework that enables comparison between different types of climate interventions. Finally, it highlights the role of public awareness and education as important factors in supporting climate action outcomes, contributing to a more comprehensive understanding of urban climate strategies.

The thesis adds to the literature by linking social, technical, and environmental aspects of climate action planning within a coherent approach.

5.5. Limitations and future research

This research provides a structured and multi-dimensional approach to urban climate action planning. However, several limitations should be acknowledged, which also open opportunities for further research. One of the main limitations is related to the geographical scope of the study, as the analysis was primarily based on European cities. This choice was driven by the availability and consistency of data, particularly through the Covenant of Mayors platform. While this allowed for a reliable and comparable dataset, it may limit the generalization of the results to cities in other regions with different climatic, socio-economic, and governance conditions. Expanding the analysis to a global scale would allow the identification of additional influencing factors and improve the applicability of the developed approaches. This limitation may reduce the direct transferability of the results to cities with different institutional or environmental conditions and highlights the need for validation in other regions. Another limitation concerns the scope of climate action categories considered in the study. While the research focused on key areas such as public awareness and construction material-related actions, other important sectors, such as transportation systems, energy infrastructure, and urban mobility, were not explored in detail. Including these additional categories in future work would provide a more comprehensive understanding of urban climate strategies and strengthen the applicability of the proposed frameworks. In addition, the environmental assessment of construction materials was limited to specific life cycle stages, mainly focusing on production and early phases of the project. This partial scope may affect the completeness of the environmental evaluation and should be considered when interpreting the results. Extending the analysis to include use-phase performance, maintenance, and end-of-life scenarios would provide a more complete evaluation of environmental impacts and support more accurate decision-making.

Building on these limitations, several directions for future research can be identified. First, the expansion of the data-driven decision-support model to a global context represents a key opportunity. Incorporating data from cities outside Europe would enhance the robustness of the model and allow the identification of new features relevant to different urban environments, ultimately improving its predictive capacity and practical applicability. Second, future research could further develop the integration between environmental assessment and digital tools such as Building Information Modelling (BIM). Finally, future research could explore the integration of multiple analytical approaches developed in this thesis into a unified framework. Combining data-driven decision-support tools with environmental impact assessment and social factors such as public awareness would provide a more comprehensive tool for climate action planning. Such an approach would support cities in designing strategies that are not only technically effective but also socially accepted and environmentally efficient.

While this thesis focuses on specific aspects of urban climate action, it provides a foundation for future research aimed at developing more comprehensive, scalable, and integrated approaches to support sustainable urban development.

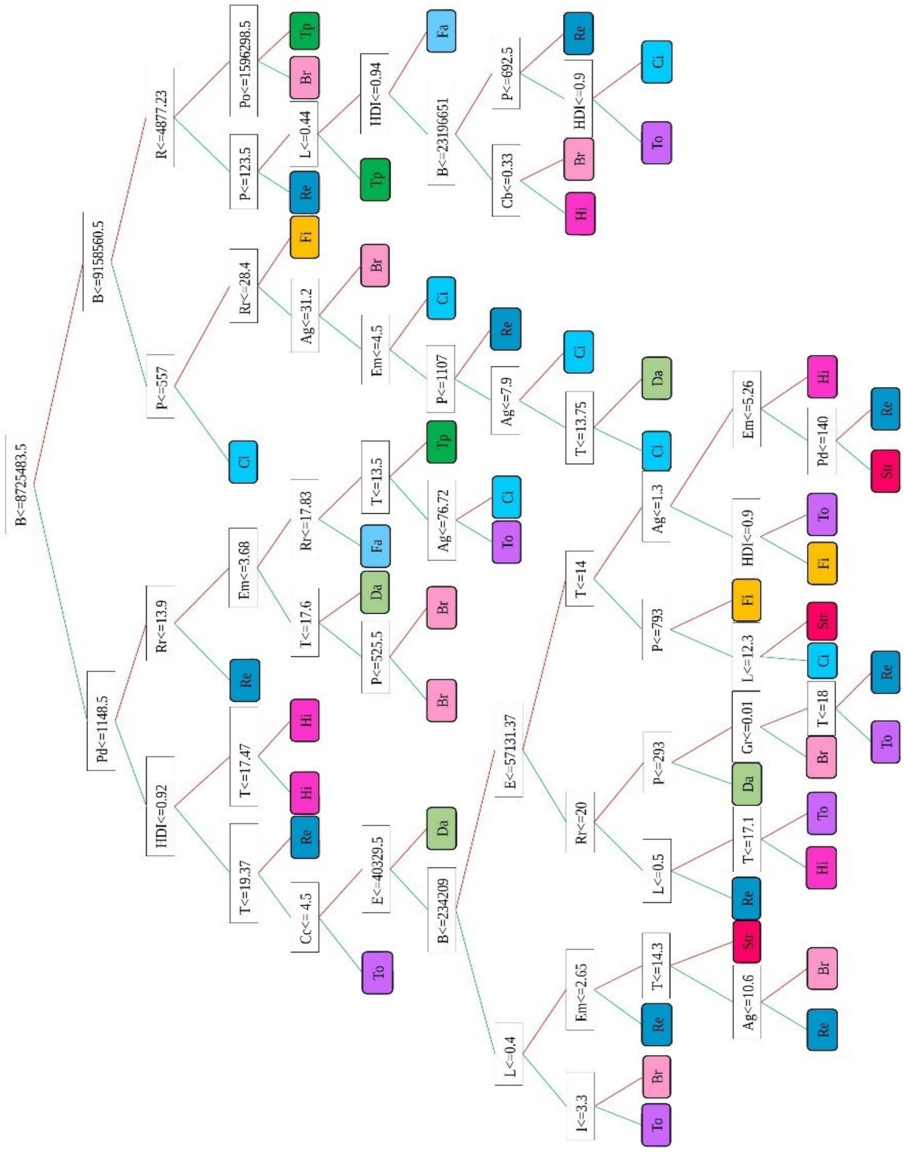
Table 13: Summary table for Research Questions, Assumptions and Theses.

Item	Statement
RQ1	To what extent can systematic analytical approaches be used to identify and categorize recurring climate action patterns from published urban climate action plans?
RA1	Applying systematic analytical approaches to published urban climate action plans allow the identification and categorization of recurring climate action patterns across municipalities.
RT1	I developed a structured categorization of urban climate actions, beginning with a preparatory analysis of 99 SECAP reports and subsequently enlarging the dataset to 454 reports published by 443 European cities across 32 countries on the Covenant of Mayors platform. Using text mining, actions were grouped into ten consistent categories on a functional equivalence basis, whereby distinct measures serving the same objective (for example, car sharing schemes and public bus upgrades were assigned to a single category such as transport optimization). The associated co-benefits were likewise extracted and categorized. Unlike existing classifications, which are largely top-down sector taxonomies, the proposed categorization is derived bottom-up from published municipal practice and structured to serve as input for comparative analysis, data-driven modelling, and environmental assessment.
RQ2	How does increasing public awareness through climate actions targeting the population, together with higher education levels, influence air quality and emission reduction outcomes in urban areas?
RA2	Increasing public awareness through a higher number of climate actions targeting citizens, together with improvements in education levels, contributes to better environmental outcomes by supporting emission reduction and improving air quality in urban areas.
RT2	Motivated by the high frequency of public awareness actions observed in the analysed plans, I examined, as an exploratory analysis, the role of public awareness and education in urban climate action. The comparison was conducted at the national level, in three contrasting countries (Germany, Brazil, and Kenya), because comparable education indicators are available primarily at the country scale rather than the city scale. I observed that higher awareness and education levels are associated with more favourable trends in air quality and greenhouse gas emissions. Because this finding rests on a limited number of national cases, it is presented as an associational and motivating observation rather than a causal claim. On this exploratory basis, the thesis shows that social and educational dimensions are a relevant supporting factor alongside technical actions.
RQ3	What kind of decision-support tools can be developed from the analysis of existing climate action plans to help cities identify more appropriate and evidence-based climate actions?
RA3	Urban climate action planning can be improved by using decision-support tools based on the analysis of existing climate action plans, as these tools allow cities to identify more appropriate and evidence-based climate actions.
RT3	I developed a data-driven decision support model for urban climate action

	planning based on a structured database of 454 climate action reports from 443 European cities in 32 countries, characterised by 24 features organised into three groups: geodemographic, spatial-distribution, and action-related variables. Using this database, I constructed an interpretable Gini-based classification tree of depth 12, refined through feature importance (SHAP) analysis and post-pruning, which increased the testing accuracy to 32.9% while improving readability. The analysis identified budget and population density as the most influential drivers of the selected category. The resulting model translates empirical patterns in published plans into a transparent, context-based tool that indicates the climate action category most consistent with the observed practice of cities sharing similar characteristics. This thesis demonstrates that combining large-scale empirical analysis with interpretable model development transforms past municipal experience into a practical decision-support tool for more consistent and evidence-based planning.
RQ4	How does the use and intensity of construction materials influence the environmental impacts of different types of climate action projects?
RA4	The environmental performance of climate action projects is strongly influenced by the type and amount of construction materials used, and a material-based evaluation at the project level allows a more consistent comparison between different types of interventions.
RT4	I developed a material-based evaluation framework to assess the environmental performance of climate action projects at the project level. I analysed different types of interventions and demonstrated that environmental impacts are strongly influenced by the type and intensity of construction materials used, rather than by project category alone. I showed that projects within the same category can have significantly different environmental impacts depending on their material composition and structural design. The analysis also highlights that interventions relying on heavy structural materials tend to concentrate higher environmental burdens, while others, such as green infrastructure, are associated with lower material intensity. This thesis demonstrates that the use of normalized functional units allows consistent comparison between projects and supports more accurate environmental evaluation in climate action planning.

Appendix

Appendix A



Appendix B

The confusion matrix described in section 4.2.5, is defined as follows:

True \ Model Prediction	**Br**	**Ci**	**Da**	**Fa**	**Fi**	**Hi**	**Re**	**Str**	**To**	**Tp**
Br	1	0	2	0	0	0	3	4	1	0
Ci	1	**11**	0	0	0	0	0	1	1	0
Da	1	1	0	0	0	0	1	0	0	0
Fa	0	0	0	0	0	0	2	0	1	0
Fi	0	1	0	0	1	0	1	0	3	0
Hi	1	0	0	0	1	1	2	4	2	0
Re	0	1	0	0	2	2	**6**	2	6	0
Str	1	2	0	0	0	0	1	**4**	0	0
To	0	2	0	0	1	0	2	2	**5**	0
Tp	1	0	0	0	0	0	1	0	1	**1**

Bibliography

Abbasi, M. A. (2021). Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology. *Sustainable Energy Technologies and Assessments* , *48*, 101630.

Aboagye, P. S. (2024). Urban climate adaptation and mitigation action plans: A critical review. *Renewable and Sustainable Energy reviews*,*189*, 113886.

Actu-environnement. (2019, 06 05). *Changement climatique*. Retrived in Actu-environnement.com:https://www.actu-environnement.com/ae/dictionnaire_environnement/definition/changement_climatique.php4

Ahad, M. P. (2020). Enabling technologies and sustainable smart cities. *Sustainable cities and society* ,*61*, 102301.

Akomea-Frimpong, I. A. (2022). A review of studies on green finance of banks, research gaps and future directions. *Journal of Sustainable Finance & Investment*,*12*, 1241–1264.

Alberti, M. B.-M. (2022). The challenge of urban food production and sustainable water use: Current situation and future perspectives of the urban agriculture in Brazil and Italy. *Sustainable Cities and Society*,*83*, 103961.

Alqahtani, N. B.-O. (2021). Assessment of rooftop solar power generation to meet residential loads in the city of Neom, Saudi arabia. *Energies*,*14*, 3805.

Alvares, C. S. (2013). Köppen's climate classification map for Brazil. *Meteorologische zeitschrift*,*22(6)*, 711-728.

Amatuni, L. O. (2020). Does car sharing reduce greenhouse gas emissions? assessing the modal shift and lifetime shift rebound effects from a life cycle perspective. *Journal of Cleaner Production*,*266*, 121869.

Andersson-Sköld, Y. &. (2016). Effective and sustainable flood and landslide risk reduction measures: An investigation of two assessment frameworks. *International Journal of Disaster Risk Science*, *7(4)*, 374-392.

Anguelovski, I. &. (2011). Urban Climate Governance: The Role of Local Authorities. *In Climate Change and Cities. CUP.*

Antons, D. G. (2020). The application of text mining methods in innovation research: Current state, evolution patterns, and development priorities. *R&D Management*, *50(3)*, 329–351.

Arbelaez Velez, A. P. (2021). Car sharing as a strategy to address ghg emissions in the transport system: Evaluation of effects of car sharing in Amsterdam. *Sustainability*,*13*, 2418.

Asmelash, E. G. (2021). International oil companies and the energy transition. . *International Renewable Energy Agency, Abu Dhabi* .

Avashia, V. G. (2020). Implications of land use transitions and climate change on local flooding in urban areas: An assessment of 42 Indian cities. *Land use policy*,*95*, 104571.

Barnes, T. (2005). Experimental analysis of the Q-matrix method in knowledge discovery. *International Symposium on Methodologies for Intelligent Systems*, 603–611.

Belle, V. a. (2021). Principles and practice of explainable machine learning. *Frontiers in big Data*, *4*, 688969.

Berardi, U. J. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*,*121*, 109681.

Berdejo-Espinola, V. S.-C. (2021). Urban green space use during a time of stress: A case study during the COVID-19 pandemic in Brisbane, Australia. *People and Nature*,*3*, 597–609.

Betsill, M. B. (2003). Cities and climate change. *Routledge*,*4*.

Betsill, M. B. (2006). Cities and the multilevel governance of global climate change. *Global governance*,*12*, 141.

Betsill, M. M. (2005). Rethinking sustainable cities: Multilevel governance and the “urban” politics of climate change. *Environmental Politics*, *14(1)*, 42-63.

Bhagaloo, K. A. (2022). Powering the sustainable transition with geothermal energy: A case study on Dominica. *Sustainable Energy Technologies and Assessments*, *51*, 101910.

Biecek, P. G. (2020). Why is this tree behaving strangely? a local interpretability method for explaining individual decisions. *Journal of Machine Learning Research 21*, 1-57.

Bielinski, T. K. (2021). Electric bike-sharing services mode substitution for driving, public transit, and cycling. Transportation research part D. *transport and environment*,*96*, 102883.

Bigazzi, A. W. (2020). Electric bicycle mode substitution for driving, public transit, conventional cycling, and walking. Transportation research part D. *transport and environment*,*85*, 102412.

Boyd.E, H. O. (2008). Resilience and ‘climatizing’ development: examples and policy implications. *Development*, 390-396.

Bulkeley, H. &. (2013). Revisiting the Urban Politics of Climate Change. *Routledge*.

Byrne, A. B. (2016). Case studies of cavity and external wall insulation retrofitted under the Irish home energy saving scheme: Technical analysis and occupant perspectives. *Energy and Buildings,130*, 420-433.

Cabeza, L. F. (2014). Life Cycle Assessment and Life Cycle Energy Analysis of Buildings. *Elsevier*.

Carli, R. D. (2020). A dynamic programming approach for the decentralized control of energy retrofit in large-scale street lighting systems. *IEEE Transactions on Automation Science and Engineering,17*, 1140–1157.

Carter, J. G. (2011). Climate change adaptation in European cities. *Current Opinion in Environmental Sustainability*, 193-198.

Castán Broto, V. &. (2013). A survey of urban climate change experiments in 100 cities. *Global Environmental Change,23(1)*, 92–102.

Chen, J. W. (2020). The influence of increased population density in China on air pollution. *Science of the Total Environment,735*, 139456.

Chrispim, M. S. (2021). Biogas recovery for sustainable cities: A critical review of enhancement techniques and key local conditions for implementation. *Sustainable Cities and Society ,72*, 103033.

Cisse, G. M.-L. (2022). Health, wellbeing, and the changing structure of communities. *Climate change*, 1041-1170.

Coelho, G. H. (2021). Performance of passive retrofit measures for historic buildings that house artefacts viable for future conditions. *Sustainable Cities and Society,71*, 102982.

Colocci, A. B. (2025). Local alliances against climate change: exploring urban experiments within the Covenant of Mayors initiative in Piedmont. *Territory, Politics, Governance*, 1-20.

Coutts, A. D. (2013). Assessing practical measures to reduce urban heat: Green and cool roofs. *Building and Environment,70*, 266–276.

Criminale, S. L. (2017). Challenges with BIM implementation: a review of literature. *53rd ASC annual international conference proceedings*, 329–335.

Dang, S. &. (2014). Text mining: Techniques and its application. *International Journal of Engineering & Technology Innovations*, 22-25.

de La Rocque S, R. J. (2008). Climate change: effects on animal disease systems and implications for surveillance and control. *Revue Scientifique et Technique (International Office of Epizootics)*.

Devos, L. D. (2024). Reclaimed or new? life cycle assessment of ceramic bricks. *Journal of Cleaner Production,476*, 143764.

Dong, B. P. (2019). A review of smart building sensing system for better indoor environment control. *Energy and Buildings,199*, 29–46.

Esmaeili, M. G. (2011). Feature selection as an improving step for decision tree construction. *International Conference on Machine Learning and Computing. Singapore 3.*

Eštoková, M. F. (2023). Life cycle assessment and environmental impacts of building materials: Evaluating transport-related factors. *Engineering Proceedings*,*57*, 5.

Fantke, L. A. (2018). Advancements in life cycle human exposure and toxicity characterization. *Environmental health perspectives*,*126*, 125001.

Fleuchaus, P. G. (2018). Worldwide application of aquifer thermal energy storage–a review. *Renewable and Sustainable Energy Reviews*,*94*, 861–876.

Flury.F, K. R. (2012). Life Cycle Assessment of Rock Wool Insulation, Technical Report. *ESU-services Ltd.*, 7.

Gagliardi, G. L. (2020). Advanced adaptive street lighting systems for smart cities. *Smart Cities* ,*3.*, 1495–1512.

Gaur, A. F. (2021). Heat pumps and our low-carbon future: A comprehensive review. *Energy Research & Social Science*,*71*, 101764.

Ghadami, N. G.-F. (2021). Implementation of solar energy in smart cities using an integration of artificial neural network, photovoltaic system and classical delphi methods. *Sustainable Cities and Society*,*74.*, 103149.

Gorgulu, S. K. (2020). An energy saving potential analysis of lighting retrofit scenarios in outdoor lighting systems: A case study for a university campus. *Journal of Cleaner Production*,*260*, 121060.

Gouldson, A. C. (2016). Cities and climate change mitigation: Economic opportunities and governance challenges in asia. *Cities*,*54*, 11-19.

Griffiths, B. K. (2023). Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options. *Renewable and Sustainable Energy Reviews*,*180*, 113291.

Griffiths, J. G. (1962). The climate of Kenya Masailand. *East African Agricultural and Forestry Journal*,*28(1)*, 1-6.

Grimmond, C. (2014). Contributions of coastal megacities to environmental changes at regional and global scales, in: Megacities and the Coast. *Routledge*, 100-129.

Gupta, A. A. (2024). Adaptive Planning for Resilience and Sustainability: Lessons from India - Project CAP-RES and Network. *Springer Nature Singapore*, 607–629.

Hamlington, B. D. (2024). Rate of global mean sea level rise has more than doubled over the satellite altimeter record. *Communications Earth & Environment*, *5(1)*, 601.

Harangozo, G. Z. (2015). Cooperation between business and non-governmental organizations to promote sustainable development. *Journal of Cleaner Production,89*, 18-31.

Harrison, P. H. (2013). Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. *Regional Environmental Change,13*, 761–780.

Hassan, Q. V.-M.-J. (2024). The renewable energy role in the global energy transition. . *Renewable Energy Focus*, 100545.

Head, B. W. (2016). Toward more "evidence-informed" policy making? *Public Administration Review*, *76(3)*, 472–484.

Heidrich, O. R. (2016). National climate policies across Europe and their impacts on cities strategies. *Journal of environmental management,168*, 36–45.

Hemmati, M. E. (2020). The role of urban growth in resilience of communities under flood risk. *Earth's Future,8*.

Hoicka, C. C. (2021). Reconfiguring actors and infrastructure in city renewable energy transitions: A regional perspective. *Energy Policy,158*, 112544.

Hoornweg, D. B. (2010). Cities and climate change: An urgent agenda. *The World Bank*.

Hotho, A. N. (2005). A brief survey of text mining. *LDV Forum*, *20(1)*, 19–62.

Huang, J. W. (2021). Thermal performance optimization of envelope in the energy-saving renovation of existing residential buildings. *Energy and Buildings*, *247*, 111103.

IPCC. (2021). *IPCC, 2021 : Intergovernmental Panel Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Jacobson, D. B. (2012). APIs: A strategy guide. *O'Reilly Media*.

Jalaei, A. J. (2014). Integrating building information modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings. *J. Inf. Technol. Constr.* ,*19*, 494–519.

Jalaei, M. Z. (2021). Life cycle environmental impact assessment to manage and optimize construction waste using building informationm modeling (BIM). *International Journal of Construction Management,21*, 784-801.

James, G. W. (2013). An introduction to statistical learning. *Springer*.

James, G. W. (2013). An introduction to statistical learning. *Springer,112.*

Janssen, M. &. (2018). Innovating and changing the policy-cycle: Policy-makers be prepared! *Government Information Quarterly, 35(4)*, S99–S105.

Johnson, A. (2023). *An evaluation of EPA communication on climate change from 1997 to 2022.* Brigham: Brigham Young University.

Kabisch, N. F. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and society 21.*

Kaspar, F. M.-W.-W. (2013). Monitoring of climate change in Germany–data, products and services of Germany's National Climate Data Centre. *Advances in Science and Research ,10(1)*, 99-106.

Keya, K. N. (2019). Natural fiber reinforced polymer composites: history, types, advantages and applications. *Materials Engineering Research*, *1(2)*, 69-85.

Khosla, R. M.-S. (2021). Cooling for sustainable development. *Nature Sustainability*,*4*, 201-208.

Kim, D. K. (2018). Integrating climate change adaptation into community planning using a participatory process: The case of saebat maeul community in Busan, Korea. *Environment and Planning B: Urban Analytics and City Science*,*45*, 669-690.

Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*,*79(1)*, 1-14.

Kitzing, L. J. (2020). Multifaceted drivers for onshore wind energy repowering and their implications for energy transition. *Nature Energy*,*5*,1012-1021.

Kona.A, F. M.-F. (2021). Global Covenant of Mayors, a dataset of greenhouse gas emissions for 6200 cities in Europe and the Southern Mediterranean countries. *Earth system science data*, 3551-3564.

Kozarcanin, S. H. (2020). Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. *Energy Policy*,*140*, 111386.

Kronenberg, J. H. (2020). Environmental justice in the context of urban green space availability, accessibility, and attractiveness in postsocialist cities. *Cities*,*106*, 102862.

Kumar, M. A. (2020). Comparative analysis of building insulation material properties and performance. *Renewable and Sustainable Energy Reviews*,*131*, 110038.

Kutlu, E. D. (2022). Technical potential of rooftop solar photovoltaic for Ankara. *Renewable Energy*,*185*, 779–789.

Lane, L. (2015). Stratospheric ozone depletion. *Life Cycle Impact Assessment*, 51-73.

Leal Filho, W. B. (2019). Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries. *Science of the Total Environment*,*692*, 1175-1190.

Leandro, J. C. (2020). A scalable flood resilience-index for measuring climate change adaptation: Munich city. *Water Research*,*173*, 115502.

Lee, D. L. (2020). Analytic hierarchy process-based construction material selection for performance improvement of building construction: The case of a concrete system form. *Materials*,*13*, 1738.

Leichenko, R. (2011). Climate change and urban resilience. *Current Opinion in Environmental Sustainability*, 164-168.

Lenzholzer, S. C. (2020). Awareness of urban climate adaptation strategies – an international overview. *Urban Climate*,*34*, 100705.

Levy, J. G. (2002). The importance of population susceptibility for air pollution risk assessment: a case study of power plants near Washington, dc. . *Environmental Health Perspectives*,*110*,1253-1260.

Li, Z. L. (2021). Determinants of carbon emission in China: how good is green investment. *Sustainable Production and Consumption*,*27*, 392-401.

Lundberg, S. L. (2017). A unified approach to interpreting model predictions. *Advances in Neural Information Processing Systems*.

Makunda, C. (2020). The unsustainability of urban habitat transformation: A case study of Kileleshwa in Nairobi, Kenya. *AFRICA HABITAT REVIEW* .

Mansour, S. A.-B.-A. (2020). Monitoring land use and land cover changes in the mountainous cities of Oman using GIS and CA-Markov modelling techniques. *Land use policy*,*91*, 104414.

Manzan.M, G. B. (2022). Climate Change Risk and Vulnerabilities Analysis in Trieste SECAP. *Environmental Governance for Sustainable Development*, 1-14.

Mcsweeney, C. N. (2010). The UNDP climate change country profiles: Improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bulletin of the American Meteorological society*,*91*, 157–166.

Meerow, S. N. (2016). Defining urban resilience: A review. *Landscape and urban planning, 147*, 38-49.

Meisel, K. M.-L. (2020). Future renewable fuel mixes in transport in Germany under red ii and climate protection targets. *Energies*,*13*, 1712.

Menoufi, K. A. (2011). *Life cycle analysis and life cyle impact assessment methodologies: a state of the art.* Lleida: LLeida university.

Michael, S. H. (2018). Crack control in concrete walls through novel mixture design, full-scale testing, and finite element analysis. *Construction and Building Materials,166*, 301-314.

Mlecnik, E. S. (2019). Collaborative business model development for home energy renovations. *Energy Efficiency*,*12.*, 123–138.

Molteni, E. C.-M. (2017). Urban CO2 mitigation strategies under the Covenant of Mayors: An assessment of 124 European cities. *Journal of Cleaner Production*, 161-177.

Mueller, N. R.-R. (2020). Changing the urban design of cities for health: The superblock model. *Environment international*,*134*, 105132.

Muganyi, T. Y. (2021). Green finance, fintech and environmental protection: Evidence from China. *Environmental Science and Ecotechnology*,*7*, 100107.

Mutschler, R. R. (2021). Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake. *Applied Energy*,*288*, 116636.

Nations, U. (2022). *The Sustainable Development Goals Report 2022.* United Nations.

Nelson G.C, H. V.-C. (2013). Climate change effects on agriculture: Economic responses to biophysical shocks. *Hans Joachim Schellnhuber, Potsdam Institute for Climate Impact Research, Potsdam, Germany.*

Neubauer.C, J. P. (2015). Moving beyond global warming potentials to quantify the climatic role of ecosystems. *Ecosystems*,*18*, 1000-1013.

Niamir, L. M. (2024). Energizing building renovation: Unraveling the dynamic interplay of building stock evolution, individual behaviour, and social norms. *Energy Research & Social Science*,*110*, 103445.

Olden, J. D. (2008). Machine learning methods without tears. *The Quarterly Review of Biology*, *83(2)*, 171–193.

Oxfam. (2021). *Changement climatique : cinq catastrophes naturelles qui demandent une action d'urgence.* Récupéré sur oxfam.org: https://www.oxfam.org/fr/changement-climatique-cinq-catastrophes-naturelles-qui-demandent-une-action-durgence

Carvalho.P, M. A. (2021). Bim-based energy analysis and sustainability assessment—application to Portuguese buildings. *Buildings*,*11*, 246.

Pagden, M. N. (2020). Changing the colour of night on urban streets-LED vs. part-night lighting system. *Socio-Economic Planning Sciences*,*69.*, 100692.

Pataki, D. A. (2021). The benefits and limits of urban tree planting for environmental and human health. *Frontiers in Ecology and Evolution*,*9*, 603757.

Patil, D. W. (2010). Evaluation of decision tree pruning algorithms for complexity and classification accuracy. . *International Journal of Computer Applications*,*11*, 23-30.

Phap, V. H. (2020). Assessment of rooftop solar power technical potential in Hanoi city, Vietnam. *Journal of Building Engineering*,*32*, 101528.

Poo, M. Y. (2024). Optimising the resilience of shipping networks to climate vulnerability. *Maritime Policy & Management*, *51.*, 15–34.

Pour, S. A. (2020). Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustainable Cities and Society*,*62*, 102373.

Pulselli, R. B. (2021). Future city visions. the energy transition towards carbon-neutrality: Lessons learned from the case of Roeselare, Belgium. *Renewable and Sustainable Energy Reviews*,*137*, 110612.

Ragheb, A. E.-D. (2016). Microclimate and human comfort considerations in planning a historic urban quarter. *International Journal of Sustainable Built Environment*,*5.*, 156–167.

Rajamani, R. &. (2017). A study of text mining methods, applications, and techniques. . *International Journal of Engineering Sciences & Research Technology*, *6(6)*, 623–628.

Ranjgar, B. N. (2023). Large-scale rooftop solar photovoltaic power production potential assessment: A case study for Tehran metropolitan area, Iran. *Energies 16*, 7111.

Reckien, D. e. (2018). How are cities planning to respond to climate change? *Climatic Change, ,147*, 1-17.

Ribas, A. O. (2020). More exposed but also more vulnerable? climate change, high intensity precipitation events and flooding in Mediterranean Spain. *Disaster Prevention and Management: An International Journal*,*29.*, 229-248.

Rivas, S. U. (2022). Covenant of Mayors 2020: Drivers and barriers for monitoring climate action plans. *Journal of Cleaner Production*,*332*, 130029.

Rosenzweig, C. S.-L. (2018). Climate change and cities: Second assessment report of the urban climate change research network. *Cambridge University Press*.

Roser, M. O.-O. (2016). *Global Education*. Récupéré sur Our world in data: https://ourworldindata.org/global-education

Roy, D. C. (2020). Feasibility and performance of ground source heat pump systems for commercial applications in tropical and subtropical climates. *Renewable Energy*,*152*, 467–483.

Ruoso, A. D. (2022). The impact of landfill operation factors on improving biogas generation in Brazil. *Renewable and Sustainable Energy Reviews*,*154*, 111868.

Ruparathna, R. H. (2017). Rethinking investment planning and optimizing net zero emission buildings. *Clean Technologies and Environmental Policy*,*19*, 1711–1724.

Sanchez-Sutil, F. C.-O. (2021). Smart regulation and efficiency energy system for street lighting with lora lpwan. *Sustainable Cities and Society*,*70*, 102912.

Santamaría-Gómez, A. G. (2017). Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth and Planetary Science Letters*, *473*, 24-32.

Santamouris, M. P. (2020). Heat mitigation technologies can improve sustainability in cities. an holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related m. *Energy and Buildings,217*, 110002.

Santopietro.L, F. S. (2020). A Place-Based Approach for the SECAP of Potenza Municipality: The Case of Green Spaces System. *Computational Science and its Applications*, 226-234.

Satterthwaite, D. (2008). Cities' Contribution to Global Warming. *Earthscan*.

Schwarz, M. N. (2020). Innovative designs of building energy codes for building decarbonization and their implementation challenges. *Journal of Cleaner Production ,248.*, 119260.

Scorza.F, L. S. (2021). A systematic perspective for the Sustainable Energy and Climate Action Plan (SECAP). *European Planning Studies*, 1-21.

Seto, K. D. (2016). Measuring and monitoring progress in climate change mitigation. *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*, 76–105.

Sha, H. Z. (2021). Optimal control of high-rise building mechanical ventilation system for achieving low risk of COVID-19 transmission and ventilative cooling. *Sustainable cities and society,74*, 103256.

Shen, Y. S. (2021). Does green investment, financial development and natural resources rent limit carbon emissions? a provincial panel analysis of China. *Science of the Total Environment,755*, 142538.

Silva, H. H. (2014). Microclimatic analysis of historic buildings: A new methodology for temperate climates. *Building and Environment 82*, 381–387.

Smerdon, B. (2017). A synopsis of climate change effects on groundwater recharge. *Journal of Hydrology*, 125-128.

Sotiriou, C. Z. (2021). A multi-objective optimisation approach to explore decarbonisation pathways in a dynamic policy context. *Journal of Cleaner Production,319*, 128623.

Spielhofer, R. S.-R. (2023). How spatial policies can leverage energy transitions-finding pareto-optimal solutions for wind turbine locations with evolutionary multi-objective optimization. *Environmental Science & Policy,142*, 220–232.

Stemmle, R. B. (2021). Environmental impacts of aquifer thermal energy storage (ATES). *Renewable and Sustainable Energy Reviews,151*, 111560.

Strielkowski, W. V. (2020). Economic efficiency and energy security of smart cities. *Economic research-Ekonomska istrazivanja,33*, 788-803.

Sundararajan, M. N. (2020). The many shapley values for model explanation. *International conference on machine learning, PMLR*, 9269–9278.

Taghizadeh-Hesary, F. Y. (2020). Sustainable solutions for green financing and investment in renewable energy projects. *Energies*,*13*, 788.

Takao, Y. (2020). Low-carbon leadership: Harnessing policy studies to analyse local mayors and renewable energy transitions in three Japanese cities. *Research & Social Science* ,*69*, 101708.

Talib, R. H. (2016). Text mining: Techniques, applications and issues. *International Journal of Advanced Computer Science and Applications*, *7(11)*, 414–418.

Telleria, J. (2023). Defining and measuring human development: A genealogical analysis of the UNDP's human development reports. . *The European Journal of Development Research*,*35*, 520-544.

Thellufsen, J. L. (2020). Smart energy cities in a 100% renewable energy context. *Renewable and Sustainable Energy Reviews*,*129*, 109922.

Thépaut, J. D. (2018). The Copernicus programme and its climate change service, in IGARSS. *IEEE International Geoscience and Remote Sensing Symposium (IEEE)*, 1591-1593.

Ugural, N. (2024). Life cycle assessment analysis based on material for sustainable airport buildings. *Buildings*,*14*, 2728.

UN-Habitat. (2024). *Urban content of NDCs: Local climate action explored through in-depth country analyses.* . Récupéré sur United Nations Human Settlements Programme.: https://unhabitat.org/urban-content-of-ndcs-local-climate-action-explored-through-in-depth-country-analyses-2024-report.

Urbikain, M. (2020). Energy efficient solutions for retrofitting a residential multi-storey building with vacuum insulation panels and low-e windows in two European climates. *Journal of Cleaner Production*,*269*, 121459.

Urge-Vorsatz, D. H. (2014). Measuring the co-benefits of climate change mitigation. *Annual Review of Environment and Resources*, *39*, 549–582.

Tran.V.V, T. A. (2024). A review of challenges and opportunities in BIM adoption for construction project management. *Engineering Journal*,*28*, 79–98.

van den Bergh, J. (2023). Contribution of global cities to climate change mitigation overrated, in: The Barcelona School of Ecological Economics. *Springer*, 335-346.

Villagrán-Zaccardi, A. T. (2022). Complete re-utilization of waste concretes–valorisation pathways and research needs. *Resources, Conservation and Recycling*,*177*, 105955.

Vogel, C. M. (2021). Creating a climate of change in the city of Johannesburg: Co-learning to adapt to climate change. *South African Journal of Science*,*117*, 1–12.

Vullo, E. a.-F. (2022). Greenhouse Gases Emission Factors for Local Emission Inventories: Covenant of Mayors Databases : Version 2022. *Publications Office of the European Union*.

Wang, P. L. (2021). Sustainability of compact cities: A review of inter-building effect on building energy and solar energy use. *Sustainable Cities and Society*,*72*, 103035.

Wang, T. Q. (2020). Climate change research on transportation systems: Climate risks, adaptation and planning. *Transportation research part D: transport and environment ,88.*, 102553.

Wannous, C. V. (2017). United nations office for disaster risk reduction (unisdr)—unisdr's contribution to science and technology for disaster risk reduction and the role of the international consortium on landslides (icl), in: Advancing Culture of Living with Landslides. *Volume ISDR-ICL Sendai Partnerships 2015-2025, Springer.*, 109-115.

Yang, G. Y. (2020). How can urban blue-green space be planned for climate adaption in high-latitude cities? a seasonal perspective. *Sustainable Cities and Society*,*53.*, 101932.

Yuan, Y. W. (2021). Gini-impurity index analysis. . *IEEE Transactions on Information Forensics and Security*,*16*, 3154–3169.

Yudha, S. T. (2022). Sustainable transition from fossil fuel to geothermal energy: A multi-level perspective approach. *Energies*,*15*, 7435.

Zahoor, Z. K. (2022). Clean energy investment and financial development as determinants of environment and sustainable economic growth: evidence from China. *Environmental Science and Pollution Research*, 1–11.

Zhang, R. F. (2020). The role of transport electrification in global climate change mitigation scenarios. *Environmental Research Letters*,*15*, 034019.