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DIPLOMARBEIT

Application of Virtual Reality in the Urban Analysis Process: A Tool for Supporting Architects in the Early Stages of Project Development

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer
Diplom-Ingenieurin unter der Leitung von

Ass.Prof. Dipl.-Ing. Dr.techn. Peter Ferschin
E259.1 Digitale Architektur und Raumplanung

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Fakultät für Architektur und Raumplanung

von
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Wien, 18. Dezember 2023

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Abstract

The process of urban analysis, which involves gaining an understanding of the existing surrounding urban structure, is an essential foundation for successful urban planning and architectural design. However, this process can be labour-intensive, as it requires accessing various sources of data and information about the urban environment. Furthermore, current visualization methodologies are largely two-dimensional, which can pose challenges in interpreting the scale and morphology of the urban fabric. In an effort to streamline this process and improve efficiency, this master's thesis proposes the development of a Virtual Reality (VR) tool, making necessary data easily accessible on a single platform for architects, urban planners, and the public.

The practical part of the thesis aims to evaluate the effectiveness of the proposed VR tool in the urban analysis process, with a particular focus on its usefulness at the early stages of project development and its potential integration into the broader workflow. The tool is tested in a typical urban setting in Vienna's 15th district to explore its practical implications. This assessment aims to explore the potential benefits and limitations of using VR for urban analysis and to investigate its ability to support architects in the early stages of project development.

Keywords: Virtual Reality, Urban Analysis, Architectural Design

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Kurzfassung

Der Prozess der städtebaulichen Analyse, der das Verständnis der bestehenden umgebenden städtischen Struktur erfordert, ist eine wesentliche Grundlage für erfolgreiche Stadtplanung und Architektur. Allerdings kann dieser Prozess arbeitsintensiv sein, da er den Zugang zu verschiedenen Datenquellen und Informationen über das städtische Umfeld erfordert. Darüber hinaus sind die aktuellen Visualisierungsmethoden größtenteils zweidimensional, was Herausforderungen bei der Interpretation von Maßstab und Morphologie des städtischen Gefüges darstellen kann. Um diesen Prozess zu optimieren und die Effizienz zu verbessern, schlägt diese Arbeit die Entwicklung eines Virtual Reality Tools vor, welches notwendige Daten auf einer einzigen Plattform für Architekten, Stadtplaner und die Öffentlichkeit leicht zugänglich macht.

Der praktische Teil der Arbeit zielt darauf ab, die Effektivität des vorgeschlagenen VR-Tools im Prozess der städtebaulichen Analyse zu bewerten, mit einem besonderen Fokus auf seine Nützlichkeit in den frühen Phasen der Projektentwicklung und seine potenzielle Integration in den breiteren Workflow. Das Tool wird in einer typischen städtischen Umgebung im 15. Bezirk von Wien getestet, um seine praktischen Auswirkungen zu erkunden. Diese Bewertung zielt darauf ab, die potenziellen Vorteile und Einschränkungen der Verwendung von VR für die städtebauliche Analyse zu ermitteln und seine Fähigkeit zu untersuchen, Architekten in den frühen Phasen der Projektentwicklung zu unterstützen.

Schlagwörter: Virtuelle Realität, Städtebauliche Analyse, Architektonischer Entwurf

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3. Methodology

4. Case study

5. Conclusion and outlook

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01 Introduction

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1.1. Motivation and Research Question

The global population is increasingly urban, with 55% living in urban areas as of 2018, a figure projected to reach 68% by 2050 [United Nations Department of Economic and Social Affairs, 2019]. This rapid change highlights the importance of cities and urban environments in shaping our societies.

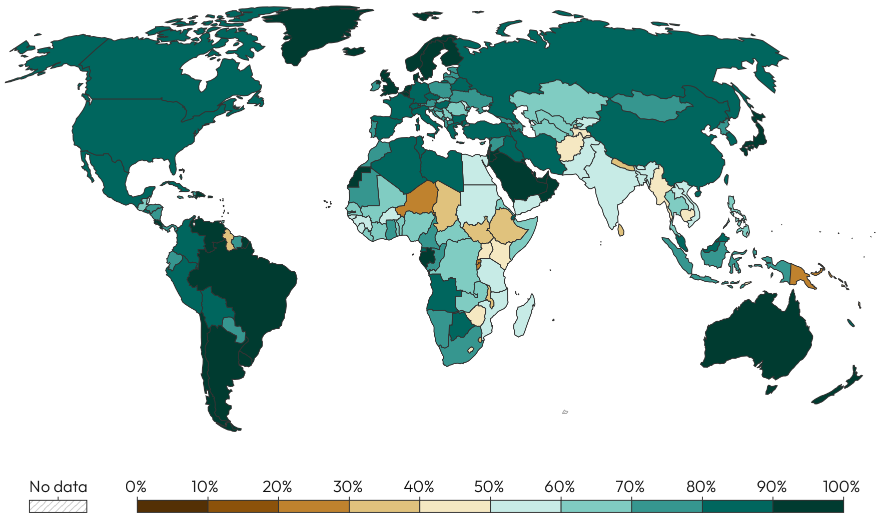

Figure 1: Share of the population living in urban areas, 2050 [Our World in Data, n.d.]

However, urban growth also presents considerable challenges in today's architectural design and urban planning fields. The complexity of urban landscapes, the fast-paced nature of architectural competitions, and the constant changes in the built environment all place significant pressure on architects and urban planners. As a result, there is a need for tools that assist in quick, effective, and sustainable decision-making.

Urban analysis, the methodical examination and understanding of urban spaces, is central to informed decision-making regarding our built environment. It supports successful urban planning and architectural design by translating the complexities of urban structures into meaningful, usable insights from data.

However, conventional urban analysis methods come with their own challenges. Traditionally, they primarily rely on static 2D representations and 3D models, both failing to truly immerse the user in the urban context or display the temporal evolution of urban landscapes over time. Moreover, these techniques can be time-consuming, requiring architects and planners to sort through many different data sources to get necessary information about the urban environment [Li et al., 2013].

The growing importance of decision-making in urban environments underlines the crucial need for immersive, efficient tools to support this process. While there is ongoing research in the field of immersive analytics and urban visual analytics [Chandler et al., 2015; Chen et al., 2017], the primary challenge identified in this thesis is the limited exploration of integrating data to create meaningful immersive urban analysis visualisations for architects.

This thesis aims to bridge that gap by developing and testing a VR tool tailored to aspects of urban analysis for architectural development. This will involve the evaluation of the current literature, workflow, methods, and digital tools used in urban analysis, focusing on the effective integration of urban data

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in a VR environment. The potential of this tool to assist architects in the early stages of project development will also be evaluated.

To guide this investigation, the research is structured around a primary question and several sub-questions. The primary research question is:

“How can Virtual Reality help in understanding the urban context and data during the early stages of architectural design, and what are the potential limitations of its application, as demonstrated through a case study in Vienna?“

This main question is further broken down into the following sub-questions:

1. What are the challenges of traditional urban analysis methods and data collection processes?
2. What are the current methods and tools used in urban analysis, and what is the current role of Virtual Reality in urban analysis?
3. In developing a VR tool for urban analysis, what methodological approach can be used to efficiently collect, process, and visualize urban data?
4. How effective is the proposed VR tool in enhancing aspects of the urban analysis process in a real-world context, specifically in Vienna‘s 15th district?
5. What are VR‘s opportunities, limitations and future implications in urban analysis?

Each of these sub-questions corresponds to a specific aspect of the research and will be addressed in the corresponding chapters of this thesis. Together, they aim to answer the primary research question.

1.2. Importance and Goals of Urban Analysis

Urban analysis is an essential tool in architectural development, as it provides a comprehensive understanding of the urban context, which is required for informed decision-making.

Its primary goal is to understand the complex dynamics of urban environments, which include the physical aspects of city planning and the built environment, as well as the social, economic, and political forces that influence urban life. This comprehensive understanding allows architects and urban planners to design structures that respond effectively to their urban context‘s specific needs and characteristics.

Urban analysis also aims to identify and address challenges in urban environments. These can range from urban decay and environmental sustainability issues to social inequality and economic development concerns. By understanding these challenges, architects can propose solutions through their designs, contributing to improving urban life.

Moreover, urban analysis can help to predict future trends

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Figure 2: Urban Analysis of Sofia, Bulgaria: Historical Development, Green amenities, Pedestrian network, Public Space Photos [Gehl, 2017]

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and changes in urban environments. Recognising trends is particularly relevant in our rapid urbanisation and climate change era, which profoundly transforms cities worldwide. By analysing these trends, architects can design adaptable and resilient buildings, ensuring long-term sustainability.

Within the architectural development process, urban analysis informs the stages of the design process. From the basic evaluation task and the development of design concepts to the final execution and post-construction supervision, urban analysis provides valuable insights that guide decision-making and ensure the project's success.

In conclusion, the importance and goals of urban analysis lie in its ability to understand, respond to, and shape urban environments. Through urban analysis, architects can contribute to creating more livable, resilient, and inclusive cities.

1.3. Challenges of Traditional Urban Analysis Methods

Traditional urban analysis methods present several challenges, affecting the efficiency and accuracy of the process. Field surveys, manual measurements, and data collection often take up substantial amounts of time and energy. These can slow the urban analysis and, consequently, the decision-making process.

Furthermore, manually capturing, analysing and displaying data across different scales, ranging from individual buildings to entire urban regions, is challenging. This limitation can restrict the comprehensive understanding of urban areas, which is necessary for effective planning and design.

Additionally, traditional methods often depend on 2D maps and drawings. While these can be very useful for the abstraction and quick understanding of data, they can also pose challenges in interpreting spatial relationships and context. They also provide a static representation of the urban environment, which may not fully capture its complexity or changes in a certain timeframe.

Data accuracy is crucial for effective urban analysis. However, traditional methods can sometimes lead to reliance on older information due to delays in data collection and updates. These might lead to using outdated information in decision-making, which can negatively affect the quality of urban planning.

Finally, traditional urban analysis methods can sometimes exhibit a certain level of subjectivity, particularly in qualitative evaluations such as visual surveys. The variability of these manual assessments among different observers can lead to inconsistencies, further complicating the urban analysis process.

1.4. Challenges in Data Collection and Processing

Data collection, a crucial part of urban analysis, presents its own challenges. Access to accurate and up-to-date spatial data can be limited, particularly in developing countries

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or areas with restricted access. Integrating and harmonising data from various sources, formats, and scales can be difficult, impacting data interoperability.

Data quality is another concern. Collecting accurate, consistent, and complete data from multiple sources is difficult. The issue of data privacy and security also arises when collecting comprehensive and granular data. There is a need to balance gathering detailed information with privacy concerns and legal constraints.

Finally, the processing of data in urban analysis can be resource-intensive. The complexity of urban environments often demands significant computational resources for processing and analysing large datasets. These can be a hurdle for small architectural offices with limited computational capacity or needing more data processing expertise.

The availability of free data sources like Open Government Data (OGD) has significantly eased the data collection process. Cities like Amsterdam, Vienna, San Francisco, and Singapore are places where OGD initiatives provide spatial data at no cost. Such data includes details about urban infrastructure, public services, and environmental indicators, which are crucial for comprehensive urban analysis. The European Union‘s Urban Data Platform provides access to urban-related data and metadata at the EU, national, and city levels.

Similarly, Open Street Maps, a community-driven mapping project, provides geospatial data from around the globe. Its crowd-sourced approach means that the data can be very

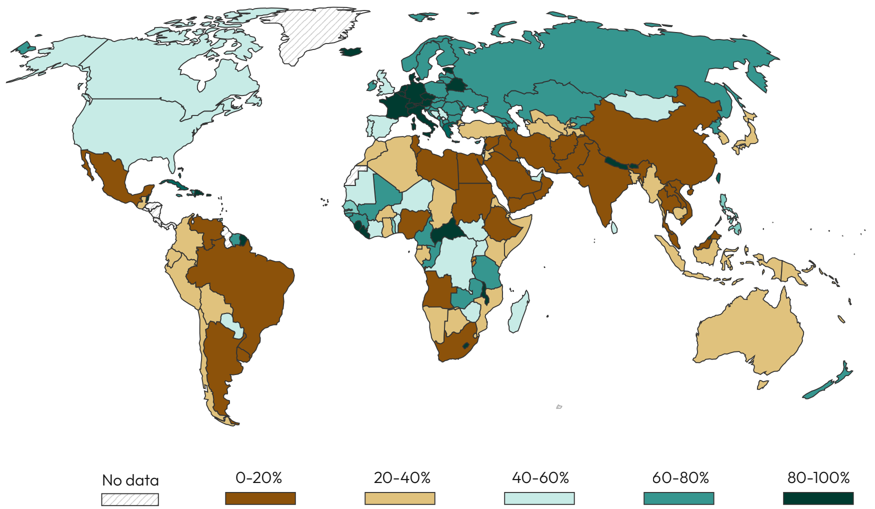

Figure 3: Estimated OSM building completeness [Herfort et al., 2023; Zhou et al., 2022]

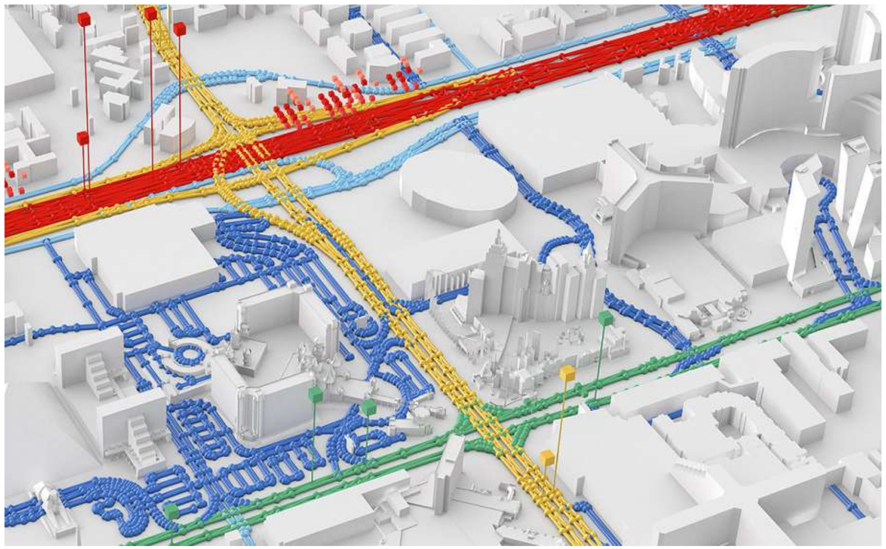

Figure 4: TomTom Traffic Data [“Navigation Technology for Ride Hailing Services,” n.d]

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often updated, capturing recent changes in the urban environment that may not yet be reflected in official datasets.

However, these free data sources may not always meet all the needs of urban analysis. They may lack certain types of data, have gaps in coverage, can vary in quality and accuracy and may require specific skills to process [Ansari et al., 2022; Herfort et al., 2023; Zuiderwijk & Reuver, 2021]. Companies such as Here, UrbanDataLab, TomTom, UrbanFootprint or ESRI offer premium spatial datasets that can provide more comprehensive or specialised data, often with guarantees of accuracy and regular updates. However, the cost of these services may be a barrier for some users, particularly small architectural companies or individual researchers.

In conclusion, the data collection and processing process, integral to urban analysis, presents various challenges. An important goal is overcoming these problems while efficiently utilising these data sources for improved urban analysis.

1.6. Structure of the thesis

This thesis is divided into five main chapters, each serving a specific purpose in exploring and discussing the application of Virtual Reality in urban analysis.

Chapter 1: Introduction provides the context and motivation for the research, outlines the research question, and discusses the challenges of traditional urban analysis methods and data collection processes.

Chapter 2: State of the Art reviews the existing literature and practices in the field of urban analysis, digital tools for urban analysis, and the role of Virtual Reality in urban analysis. It aims to provide an understanding of the current state of the field and identify gaps that this study seeks to address.

Chapter 3: Methodology details the approach taken to develop and test the VR tool for urban analysis. It discusses the conceptualization of the tool, the management of data, and the techniques used for interaction and visualization in VR.

Chapter 4: Case Study applies the methodology to a real-world context, specifically Vienna‘s 15th district. It discusses the context and characteristics of the location, the objectives and scope of the case study, and the process of implementing the VR tool.

Chapter 5: Conclusion and Outlook summarizes the main findings from the application of VR in urban analysis, highlighting achievements and limitations encountered.

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02 State of the art

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2.1. Urban Analysis in Architectural Development

2.1.1. Phases of Architectural Development

Architectural development is a complex process that involves several distinct but interconnected phases. In Germany, the building process is typically divided into nine phases defined in the HOAI (Honorarordnung für Architekten und Ingenieure) [Schwenker & Wessel, 2021]. The building process in Austria is similar and consists of nine phases, although some phases and terminology used in the two countries differ. Understanding these phases is crucial as it provides a framework for where and how urban analysis fits into the overall process.

However, before discussing the building process, it is important to mention a preliminary step, Needs Planning ("Bedarfsplanung"), as in DIN 18205 [Achatzi et al., 2017]. Although not explicitly mentioned in the HOAI, it is considered an indispensable basis for effective architectural development. Influenced heavily by urban analysis, Needs Planning is the methodical determination of the needs of both the client and future users, transforming these needs into specific requirements. The process includes clarifying the project context and goals, gathering and evaluating information, and finally, developing a needs assessment plan.

Basic Evaluation ("Grundlagenermittlung"): This initial stage involves defining the task, determining the performance requirements, identifying the specialist planners involved in the

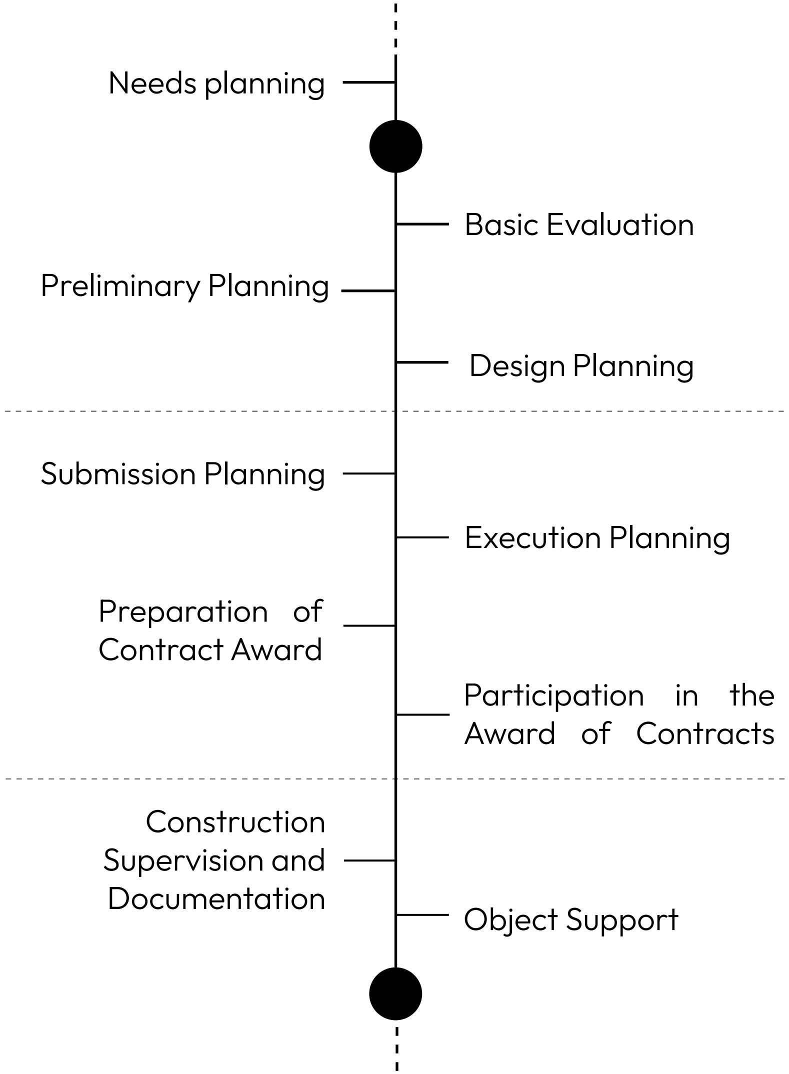

Figure 5: Phases of architectural development

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construction project, and summarising the results. This phase can include special services like site analysis, operational planning, space and function programming and environmental impact assessment. Urban analysis is crucial in this phase, providing insights about the site's urban context that guide the design process.

Preliminary Planning („Vorplanung"): This phase involves translating the basic analysis into initial design concepts, visualising form, location, and division considerations. The process includes foundational analysis, goal catalogue and planning concept creation, and integration of authorities and specialist planners. Special services may encompass unique models or renderings, financing and operational cost plans, and initial organisational structure and schedule creation. Urban analysis informs these initial designs, helping the architect to understand how the proposed object will fit into the existing urban fabric.

Design Planning („Entwurfsplanung"): This phase refines the preliminary design into a concrete plan. Drawings, typically at scales of 1:100 and 1:50, represent the overall design, covering technical, functional, aesthetic, and economic requirements. The process includes developing the planning concept, integrating specialist planners' input, creating scaled drawings, checking approval feasibility, and cost estimation. Special services may focus on optimising economic efficiency and environmental compatibility. Urban analysis continues to guide these decisions, particularly in assessing the building's impact on its surroundings.

Submission Planning („Genehmigungsplanung"): This phase involves preparing the necessary documents for obtaining building permits. It involves adjusting the design plans, contacting authorities, and submitting applications. While urban analysis is less directly involved in this phase, the insights gained from it continue to inform the design details.

Execution Planning („Ausführungsplanung"): This phase involves creating detailed drawings of the object at scales from 1:50 to 1:1 and preparing the foundation for all specialist consultants.

Preparation of Contract Award („Vorbereitung der Vergabe"): This phase involves preparing for the awarding of construction contracts: quantity determination, service description, the list of service specifications and areas.

Participation in the Award of Contracts („Mitwirkung bei der Vergabe"): This phase involves the architect's active participation in soliciting and evaluating offers from the different contractors and craftsmen for the construction.

Construction Supervision and Documentation („Objektüberwachung und Dokumentation"): This phase involves the architect overseeing the project's execution, maintaining a construction diary, managing costs, and facilitating the project handover. The architect also ensures that everything runs according to schedule, documents any defects, and verifies that what is being built corresponds to the previous approvals.

Object Support („Objektbetreuung"): In this final phase, post-

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completion, the architect conducts site inspections to identify defects before warranty expiration and oversees their correction.

In summary, urban analysis is a key element in the early stages of architectural development. It guides the design process from the Needs Planning and Basic Evaluation to the Design Planning phase, influencing decisions about the object's form, function, and location. It aims to ensure that the proposed structure integrates and contributes positively to its urban context. Therefore, urban analysis is not just a standalone process but an integral part of architectural development.

2.1.2. Definition of Urban Analysis

Urban analysis is a multidisciplinary approach that seeks to understand and interpret the complexities of urban areas. This process involves dividing urban systems into their physical, political, economic, and social components to understand them better, identify their challenges, and find solutions to those issues [Catanese, 1972].

However, closely defining urban analysis is challenging due to its multidisciplinary nature and the wide range of topics it encompasses. Different scholars and practitioners may emphasise different aspects of urban analysis based on their disciplinary backgrounds and the specific urban issues they are interested in.

For example, urban analysis involves, among others, the study of the spatial configuration of cities, including the layout of streets, buildings, and open spaces, and how these elements contribute to the overall urban form [Carmona, 2003]. This perspective emphasises the physical and spatial aspects of urban areas.

In contrast, urban analysis can be viewed as a tool for understanding the formation and dynamics of world cities, including the processes of urban growth, decline, and transformation, and how these processes are influenced by various factors such as economic reflexivity, demographic change, and technological innovation [Taylor, 2000]. This perspective emphasises the dynamic and interconnected aspects of urban areas.

Adding to the complexity, Lynch focuses on urban areas' perceptual and experiential aspects. He explores how people per-

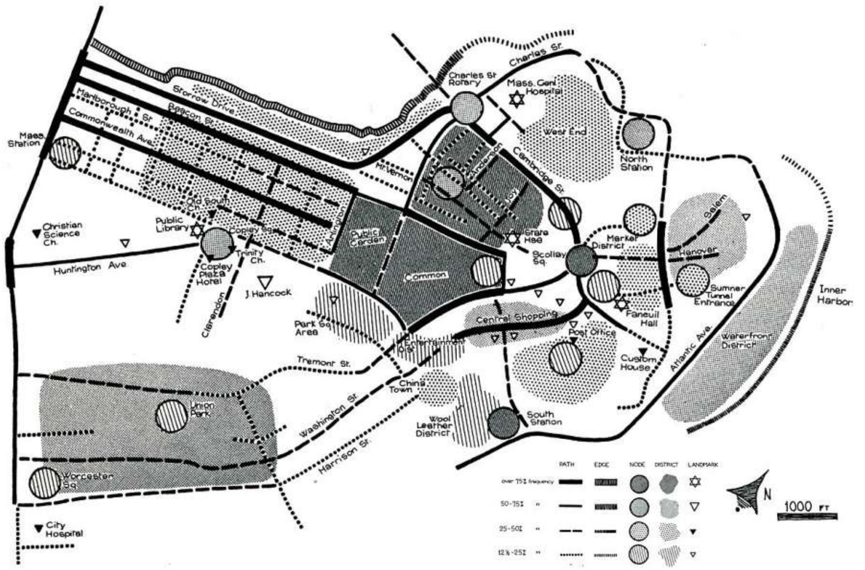

Figure 6: The Boston community map as emerged by verbal interviews [Lynch, 1964]

ceive and represent a city and how the city's physical elements contribute to the formation of mental images. Lynch introduces the concepts of legibility, the ease with which a city's parts can be recognised and organised into a coherent pattern, and imageability, the quality in an object that gives it a high probability of evoking a strong image in an observer [Lynch, 1964].

Meanwhile, in his extensive work on urban analytics, Michael Batty emphasises the inherent structure and patterns present within seemingly chaotic city landscapes [Batty, 2013]. His perspective underscores the significance of urban analysis methods. By systematically studying cities, urban analysts and planners can decode these embedded patterns, which are often responses to social, economic, and environmental challenges. Batty's statements reinforce the importance of robust urban analysis methods: to understand solutions embedded within city structures and to foresee potential problems, offering a proactive approach to urban planning.

Despite these different approaches, all definitions of urban analysis share a common goal: better understanding urban areas for a specific purpose. This knowledge can be used to inform better urban planning and design decisions.

2.1.3. Methods of Urban Analysis

Urban analysis employs various methods to gather, interpret, and present data about urban environments. These methods, which can be broadly categorised into quantitative and qualitative approaches [Baum, 2021], are chosen based on the purpose of the analysis, available resources, time constraints, and local conditions. Typically, a mix of methods provides a comprehensive understanding of urban complexities.

Qualitative methods of urban analysis focus on understanding the subjective experiences and perceptions of individuals within the urban environment. Direct observation, interviews, and case studies provide a nuanced understanding of the human experience in urban spaces.

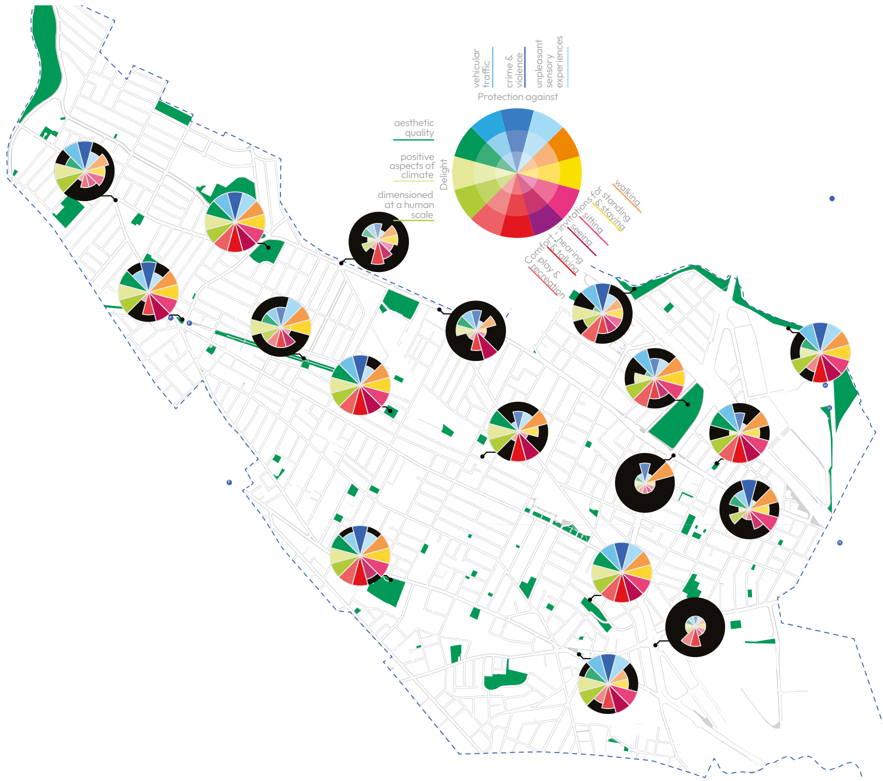

Figure 7: Analysis of Quality of Public Spaces [Gehl, 2016]

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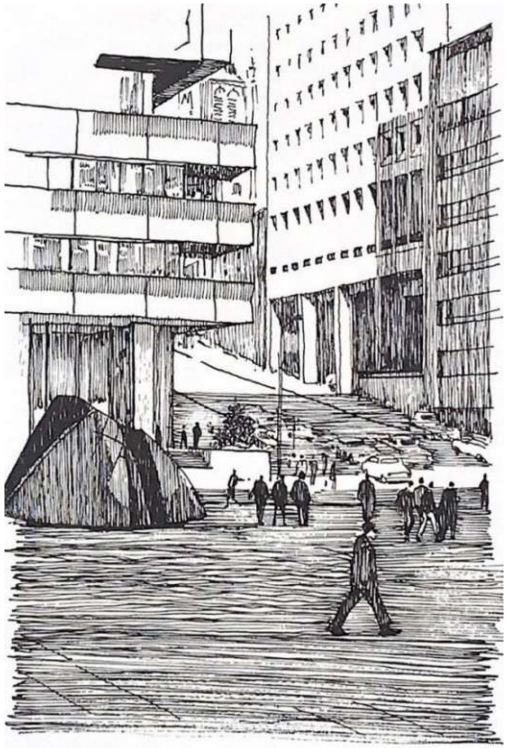

Figure 8: Sketch depicting physical comfort in the street by Allan Jacobs [Jacobs, 1995]

For instance, the work of Jan Gehl emphasises the importance of observing and understanding human behaviour in public spaces [Gehl & Svarre, 2013]. Gehl's method involves detailed observations of how people use and interact with urban spaces, providing insights into the social life of cities. Similarly, Allan Jacobs underscores the power of observation in his studies on the qualities of great streets, pointing out that detailed observation can reveal nuanced insights into the social fabric and quality of life in urban spaces [Jacobs, 1995]. This approach enables a better comprehension of how urban design impacts human behaviour and social interactions, shaping the character and identity of urban spaces.

Furthermore, qualitative methods like interviews and surveys engage residents and users, business owners, and other stakeholders to gather their perspectives on the urban context. This participatory approach provides diverse insights and fosters a sense of ownership and collaboration in the development process. Qualitative methods in urban analysis offer a human-centred approach, focusing on the lived experiences and perceptions of individuals within the urban environment.

Quantitative methods, on the other hand, involve the systematic collection and interpretation of numerical data. These methods provide objective measurements that can be used to understand urban areas' physical and socio-economic characteristics.

One such method is site visits and observation, which, depending on the methodology used, can be a quantitative method of urban analysis. This approach allows for collecting data on land use, building typologies, circulation patterns, and public spaces. It provides a direct understanding of the physical characteristics of the urban environment.

Mapping and spatial analysis is another quantitative method. It utilises tools such as Geographic Information Systems (GIS) to visualise and analyse spatial data. This data includes land use patterns, zoning regulations, transportation networks, infrastructure systems, and environmental conditions. This

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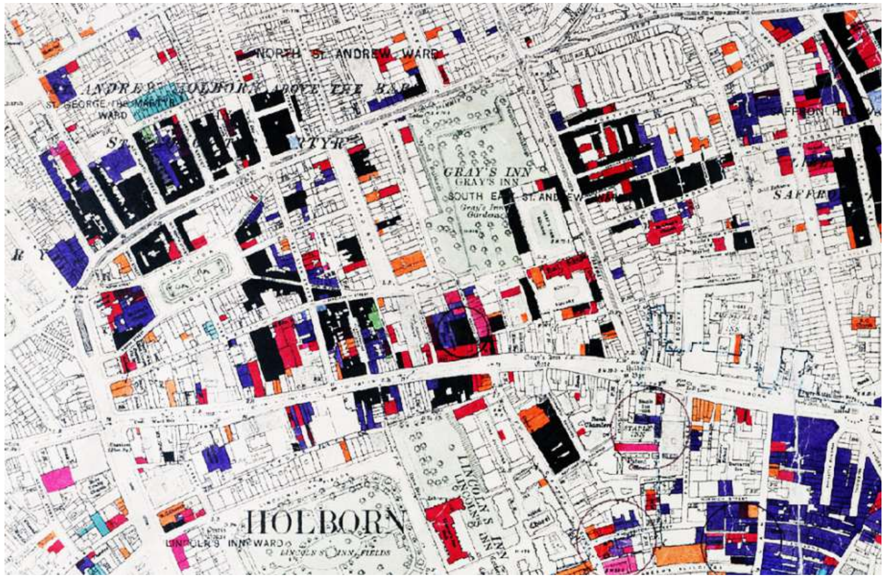

Figure 9: Historical mapping of London 1916 - 1945 [“Layers of London,” n.d.]

method provides a spatial understanding of the urban environment, highlighting the relationships between different urban elements.

Historical research involves investigating the past development and evolution of the urban context. This method includes the analysis of historical maps, photographs, and documents to understand the site‘s history and cultural heritage. It provides a temporal understanding of the urban environment, revealing how it has evolved over time.

Demographic and environmental data collection and analysis involve gathering and interpreting various numerical data types. Demographic data includes population size, density, age distribution, and other socio-economic indicators. Environmental data includes information on climate, air quality, noise levels, and other environmental factors that influence the urban context. These methods provide a socio-economic and environmental understanding of the urban environment, revealing the human and natural factors that shape it.

It is important to reiterate that these methods are not mutually exclusive. In urban analysis, a combination of qualitative and quantitative methods is often the most effective. By integrating different methods, architects can gain a more comprehensive and nuanced understanding of the urban environment, informing their designs and ensuring their success.

2.1.4. Workflow in Architecture

While previous subchapters detailed the stages of architectural development and methods for urban analysis, a closer examination of the actual workflow followed by architects for urban analysis is necessary. Architectural projects, especially in their early stages, require a thorough understanding of the urban context. This fundamental understanding informs all subsequent decisions.

Utilising Mapping Services: Architects often consult digital mapping services such as Google Maps or OpenStreetMap before physically visiting the site. These platforms offer an initial understanding of essential factors such as site topography, adjacent buildings, road networks, and other landmarks.

Architectural Competitions and Client Information: In scenarios like architectural competitions, architects might be han-

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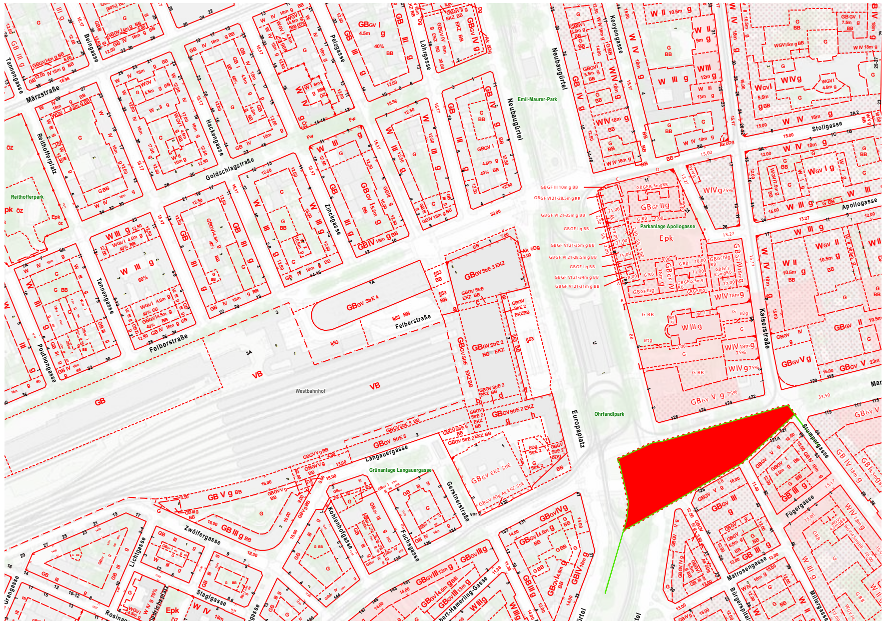

Figure 10: Vienna Land Use Plan [“Flächenwidmungs- und Bebauungsplan,” n.d.]

ded a basic urban analysis from the client or organisers. This primary data is often sourced from the client, providing initial details and context about the project site.

Initial Site Visits: An actual visit to the site is important for verifying and complementing other data. It allows architects to get a feeling of the space, observe the surroundings, gather photographs and videos and make contextual evaluations that are difficult to do remotely.

City Administration Resources: Local administrations can have a lot of information about a site or area. These sources can provide essential data, ranging from cadastral to historical plans and other relevant datasets.

Self-Created Plans and Models: When existing plans are lacking or outdated, architects may develop their own using digital mapping services, manual measurements, or 3D modelling when only 2D plans are available.

Researching the Site‘s Context: Understanding the site‘s important neighbouring functions, traffic and mobility patterns, historical background, environmental aspects, and other contextual aspects is crucial for decision-making. These vary depending on the project.

Legal and Regulatory Research: Understanding the current

Figure 11: Zürich digital 3D city model [“Zürich virtuell,” n.d.]

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Figure 12: Physical model of a site ["Laser-Cut Topography: Horizontal - Harvard GSD Fabrication Lab - Harvard Wiki," 2015]

laws and building regulations specific to the project site is crucial. This research ensures compliance with zoning laws, building codes, and regulations that impact design decisions.

Statistical Analysis: Beyond spatial information, statistics about the area, like demographics, land usage percentages, and social and economic indicators, offer a quantitative perspective.

Physical Modeling: Often, a digital or paper representation isn't enough. Architects might create physical models, usually at scales ranging from 1:100 to 1:2000, to gain a tangible understanding of the site's morphology and scale.

Typically, the first few days or weeks of any architectural project are devoted to an in-depth analysis of the project's scope and area. This analysis phase produces various types of documentation, such as maps with layered information, statistical reports, 3D models, physical models and photographs. This broad documentation serves two essential functions: first, it ensures that the entire project team has a consistent understanding of the site, and second, it establishes a data-driven foundation that guides the following stages of architectural development.

2.2. Digital Approaches for Urban Analysis

The advancement of technology has also brought changes to the field of urban analysis. Digital approaches have become

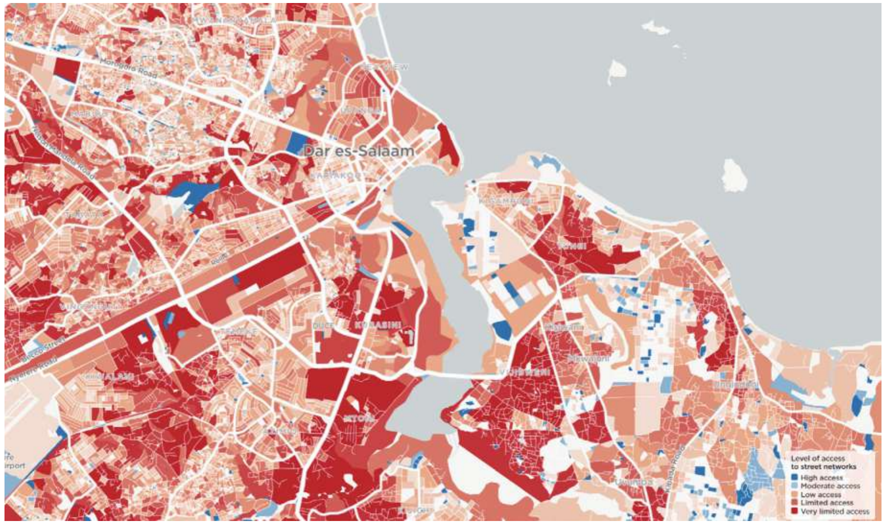

Figure 13: Map highlights neighborhoods with limited access to streets in Dar es Salaam [Mansueto Institute for Urban Innovation, n.d.]

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an asset in understanding and interpreting urban data. This chapter describes relevant examples and these tools' roles in providing insights.

The adoption of digital tools in urban analysis offers many advantages. They enhance efficiency, possess a high degree of accuracy, and facilitate real-time data processing. Their ability to handle and visualise large data sets, conduct complex calculations, and present information has led to innovative urban design and planning approaches.

However, despite their clear benefits, using digital tools in urban analysis takes time and effort. As discussed in the first chapter, issues such as data availability, specific technical skill requirements, and associated costs can pose significant barriers. The following subchapters, focusing on GIS Applications in Urban Analysis and Other Digital Tools for Urban Analysis, aim to provide an understanding of the use of these digital approaches in the urban analysis process.

2.2.1. GIS Applications

Geographic Information Systems (GIS) were first used in the 1960s with the creation of the world's first operational system in Canada [Goodchild, 2018]. This technology was initially designed for land-use planning and resource management but quickly evolved. With advances in computing, data handling, and analytical methods, GIS became a widely used tool across various fields like urban planning, environmental science, and public health.

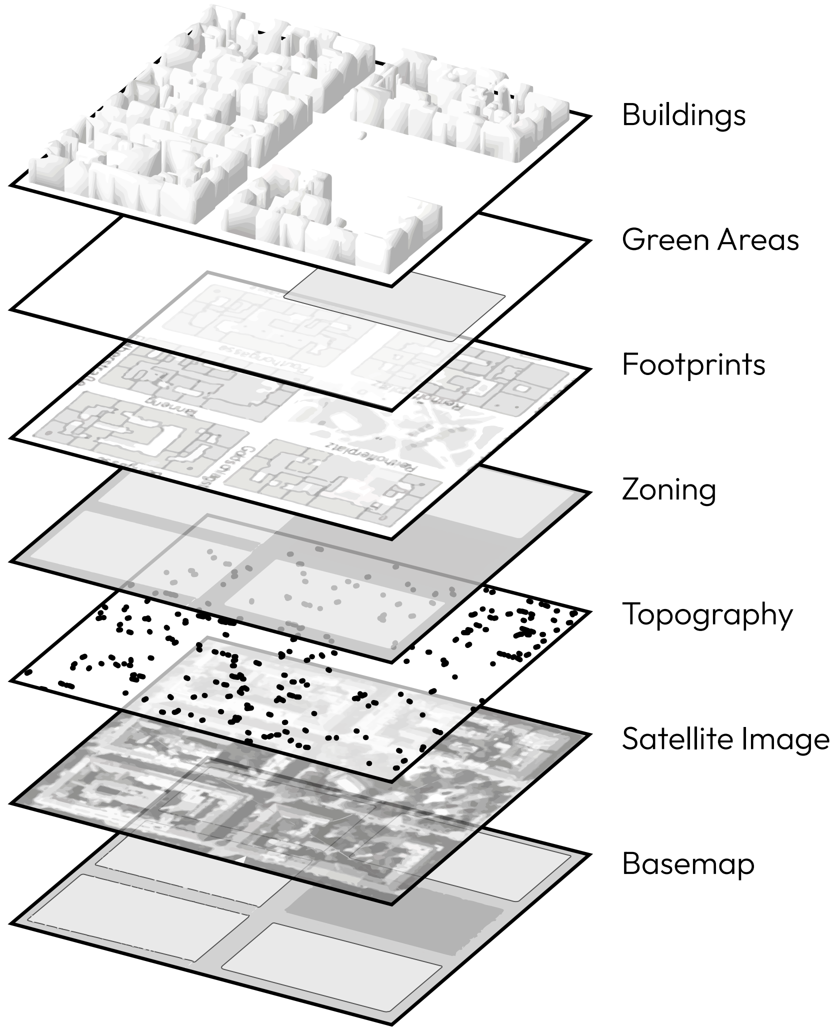

Figure 14: Example of data layers in GIS

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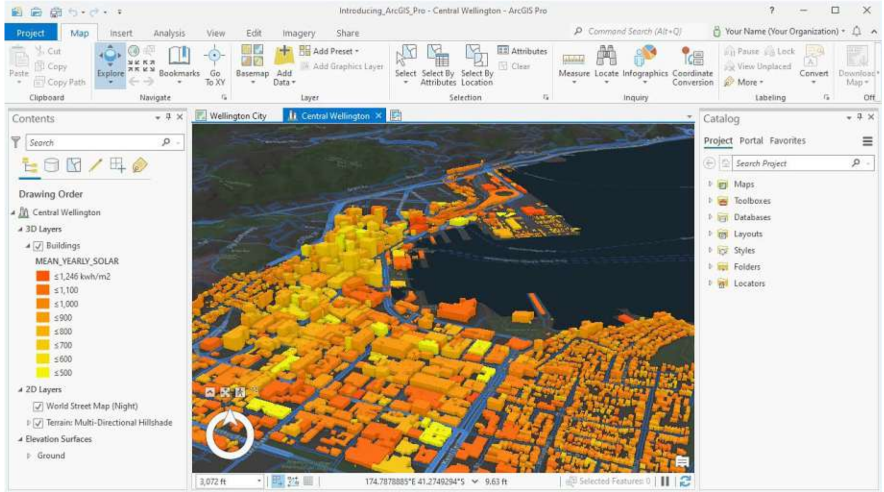

Figure 15: ArcGIS Pro Software Screenshot [Introducing ArcGIS Pro—ArcGIS Pro | Documentation, n.d.]

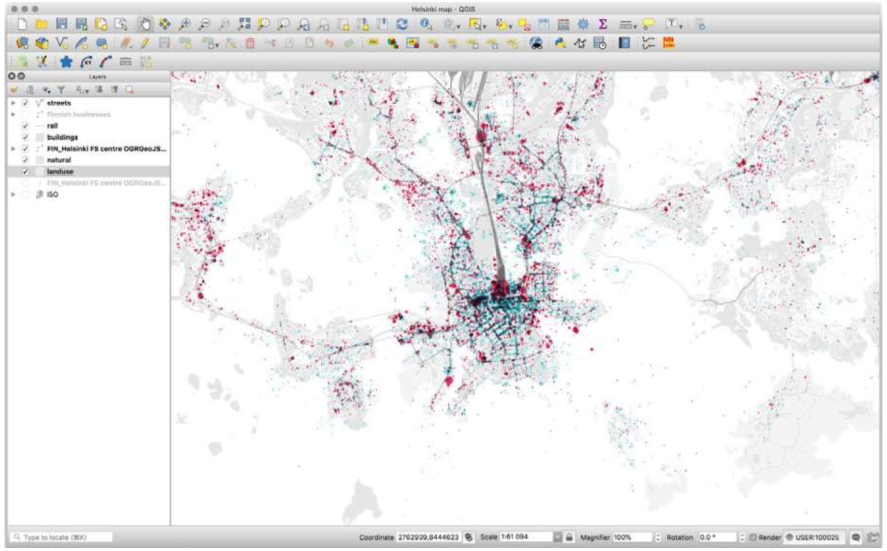

Figure 16: QGIS Software Screenshot [QGIS Map Examples, n.d.]

Today, GIS tools such as ESRI ArcGIS, Global Mapper, AutoCAD Map 3D, QGIS, or GRASS GIS are available in both commercial and open-source forms, catering to different needs and budgets and playing an essential role in understanding urban environments.

ArcGIS, a commercial software developed by Esri, is a GIS platform widely used in regional and urban planning and architectural development. Available in various versions, such as ArcGIS Desktop, ArcGIS Online, ArcGIS Enterprise, and ArcGIS Pro, it provides different tools for spatial data analysis, visualisation, and collaboration. Users can manage large spatial data sets, conduct detailed analyses, and create maps to reveal urban trends and patterns.

Beyond its core functionalities, ArcGIS offers many applications and resources [Mapping Products | GIS Software Products - Esri, n.d.]. ArcGIS StoryMaps and ArcGIS Insights enable the creation of interactive stories and intuitive data exploration. ArcGIS Living Atlas provides a collection of global geographic information, while Esri Academy offers educational resources. Its integration capabilities make it suitable for large-scale projects where multiple data sources must be synchronised.

QGIS (previously known as Quantum GIS) is an open-source alternative to ArcGIS, offering many similar features and capabilities [Khan & Mohiuddin, 2018]. It has become increasingly popular among researchers, students, and professionals as a free tool. QGIS supports various file formats and allows for advanced cartographic design and spatial analysis. Its cus-

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tomisable interface and the availability of numerous plug-ins make it a versatile choice for urban analysis. QGIS has a strong user community, ensuring continued development and support.

GRASS GIS (Geographic Resource Analysis Support System) is another open-source GIS software known for its advanced analytical functions [Neteler et al., 2012]. It's designed for professionals who require complex data processing and analysis, providing high accuracy and robust mathematical modelling. GRASS can also be added as a plugin to QGIS, allowing users to combine the advantages of both.

GIS-based urban analysis methods have expanded the ability to understand and plan urban environments. Some of the most used techniques involve Spatial, Network, Buffer, Hotspot, Overlay and Temporal Analysis, Geocoding and 3D Modeling.

Spatial Analysis: This involves analysing the spatial distribution of various urban elements, such as buildings, roads, and green spaces. It can reveal patterns and relationships that are not apparent from simple observation.

Network Analysis: This technique analyses connectivity and accessibility within an urban area. It can be used to study various types of networks, such as transportation networks, utility networks, or social networks.

Buffer Analysis: This technique is used to identify areas that are within a certain distance of a particular feature. For example, it can be used to identify all buildings within a 500-meter radius of a park.

Overlay Analysis: This involves layering multiple maps or datasets on top of each other to identify relationships or interactions between different features. For example, an overlay analysis could be used to identify areas that are both high in population density and poorly served by public transportation.

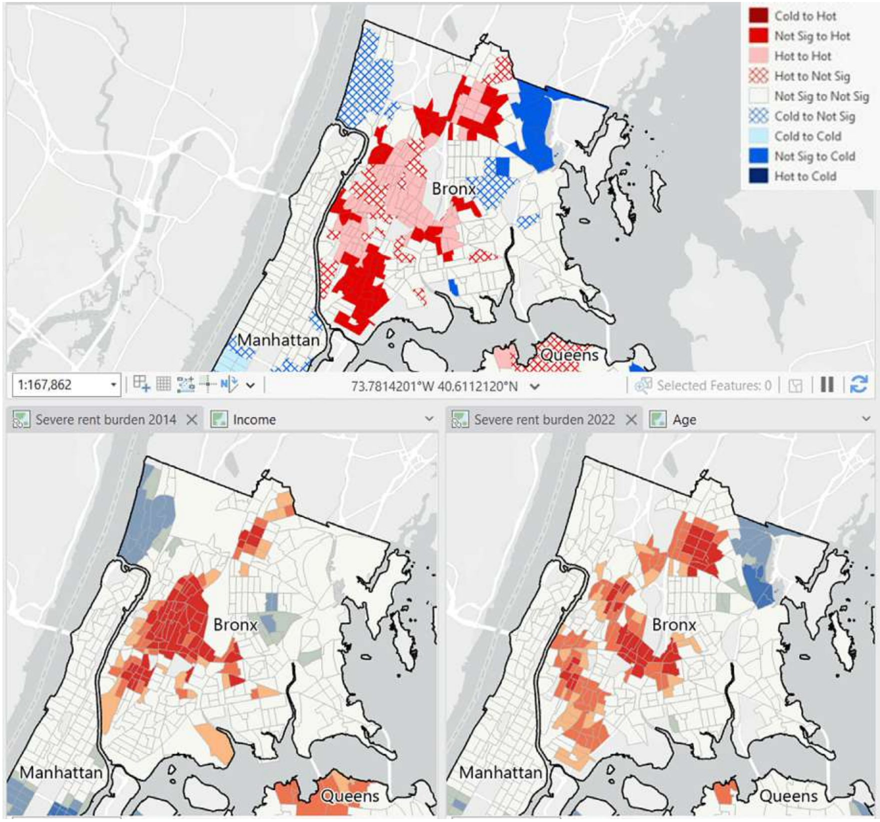

Figure 17: Hotspot Analysis Comparison [Bakshi, n.d]

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Geocoding: This involves assigning geographic coordinates to data based on address or other spatial information. This allows for the visualisation and analysis of data in a spatial context.

Hotspot Analysis: This technique is used to identify areas of high or low values for a particular variable. For example, it could be used to identify hotspots of crime or poverty within a city.

3D Modeling: GIS can be used to create 3D models of urban settings, which can be helpful for visualising proposed developments or understanding the impact of existing features.

Temporal Analysis: GIS can also be used to analyse changes in urban environments over time. This analysis can be helpful in understanding trends and predicting future changes.

The strengths of GIS in urban analysis are amplified when integrated with other data sources. Remote sensing imagery can provide real-time environmental data. Census data can overlay demographic and socio-economic insights, helping in comprehensive urban planning. Furthermore, social media data, often in real-time, can show a new perspective on human activity and behaviour in urban spaces.

2.2.2. Other Digital Tools for Urban Analysis

While GIS tools are instrumental in urban analysis, other digital techniques, frameworks and tools can also offer insights. Many of these function alongside or integrate with GIS soft-

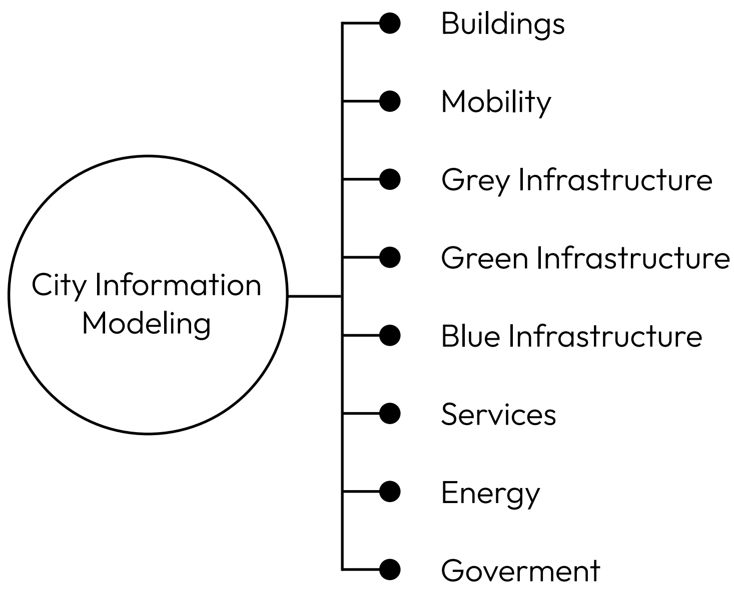

Figure 18: City Information Modeling concept

ware but come with unique features that further expand the scope of urban analysis.

City Information Modeling (CIM) is a concept that has gained popularity in recent years. It takes the idea of Building Information Modeling (BIM), used for individual buildings, and applies it to whole cities. By combining building information with GIS, CIM creates a 3D model of a city. This model can be used to understand and plan cities in an intelligent way. For example, Helsinki has used CIM to create a 3D model of the entire city, and NTU's EcoCampus has used it to manage energy use [Cousins, 2017; Cureton & Hartley, 2023; Xu et al., 2021].

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However, the adoption of CIM is challenging. Integrating multiple data sources or the continuous update of data can be complex. Despite this, the future of CIM is promising. Theoretical improvements, platform construction, enhanced data collection, integration, updating methods, and integration with emerging technologies like big data, edge computing, and machine learning are expected to drive its development and application in urban analysis [Xu et al., 2021].

While CIM provides a macro-level view and concept, other tools offer a more focused approach. Grasshopper, integrated with the Rhinoceros 3D modelling software, is a visual

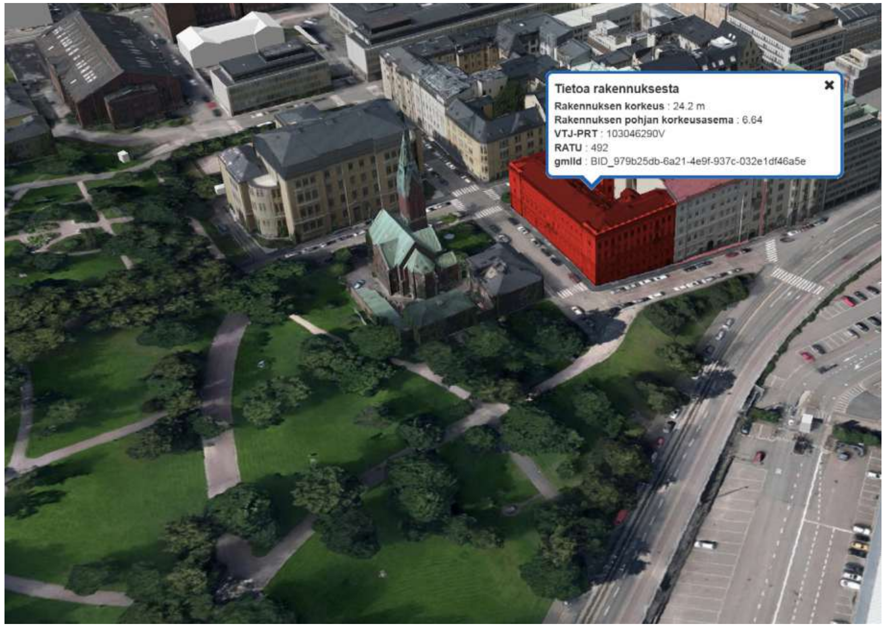

Figure 19: 3D City Model of Helsinki including building details [virtualcitySYSTEMS, 2017]

Figure 20: Urban Network Analysis toolbox for Rhino [Food4Rhino, Urban Network Analysis Toolbox, 2015]

programming language and environment. In urban analysis, Grasshopper can simulate and analyse various urban scenarios, displaying different analysis types from solar radiation studies to space syntax. A study from AIT applied to a master plan in Vienna showcases an integrated urban design process using Grasshopper to enhance the quality and efficiency of urban analysis and planning [Fink & König, 2019].

CityEngine is a commercial software developed by Esri, explicitly designed for 3D urban modelling. It allows urban planners and architects to quickly create detailed 3D city models using procedural modelling techniques [Kelly, 2021]. These

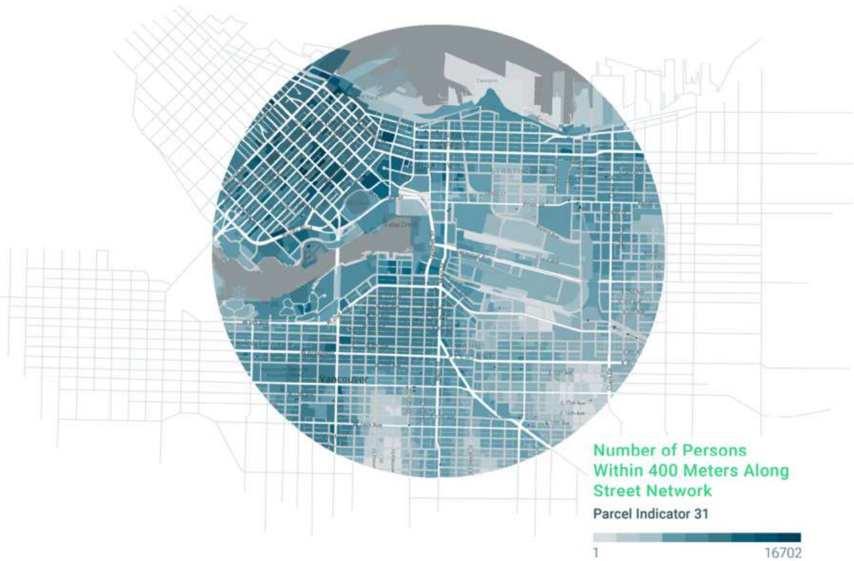

Figure 21: UrbanSim Street Network Analysis [UrbanSim Artificial Intelligence For Sustainable Development with AI, n.d.]

models can then be analysed, visualised, and shared, providing insights into urban form, function, and evolution. Due to its integration within BIM workflows, CityEngine can be efficiently integrated into architectural projects.

UrbanSim simulates urban development, helping planners predict housing market dynamics, transportation needs, and land use. It uses statistical models to simulate the interactions between residents, jobs, real estate, and transportation [Waddell, 2002]. Over the years, UrbanSim has been adopted by various cities and metropolitan areas worldwide to support their planning processes. It has been used to forecast housing demand, understand transportation investment implications, analyse land-use regulations' impact, and much more.

CityScope, developed by the MIT Media Lab, is an interactive, tangible computing platform designed to visualize complex simulations and offer real-time analytics [Alonso et al., 2018]. This tool aims to foster data-driven decision-making for urban planners, policymakers, and citizens alike. Various iterations of CityScope have been deployed in cities around the world to analyze scenarios related to transportation, housing, and public space.

Another significant contribution comes from research institutions and cities that are developing their own tools for urban analysis. For instance, some municipalities have initiated

Figure 22: CityScope by MIT City Science Group [Introduction | Here We Build CityScope , n.d.]

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Smart City programs, where urban sensors collect data on everything from air quality to pedestrian flow. This data is then integrated into custom analytics tools, allowing for real-time insights and more effective planning.

Additionally, the application of crowd simulation technologies, particularly in virtual environments like Unity, provide insights into pedestrian behavior and space utilization [Jaros, 2014]. Pedestrian flows display how people interact with their environment and the impact of architectural and urban design on human movement and behavior.

With the advancement of Big Data, Machine Learning and Artificial Intelligence have become increasingly relevant in urban analysis [Casali et al., 2022]. These technologies can process vast amounts of urban data, from traffic patterns to energy consumption, and provide previously unattainable insights. Machine learning algorithms can predict urban growth, identify patterns in urban mobility, or optimise urban infrastructure. As these technologies evolve and more and more cities create their digital twins, we can expect even more advanced, powerful and efficient tools to be available in the coming years.

2.3. Role of Virtual Reality in Urban Analysis

Virtual Reality has emerged as a new instrument in urban analysis. By offering an immersive, three-dimensional environment, VR allows architects, planners, and stakeholders to experience urban spaces in ways that traditional 2D and 3D models cannot replicate. This immersive experience is significant for urban analysis as it can enhance understanding spatial relationships, scale, and context.

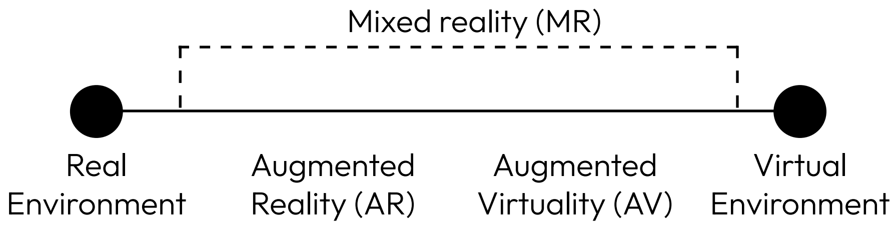

Figure 23: Simplified adapted representation of the Reality-Virtuality Continuum [Milgram et al., 1994]

Technological advancements can change the way we perceive and interact with our surroundings. An essential concept in this topic is the Reality-Virtuality Continuum, which spans from entirely real environments to entirely virtual environments, encompassing augmented reality and mixed reality in between [Milgram et al., 1994]. Within the spectrum of the virtuality continuum, this thesis focuses on analysing the application of Virtual Reality and selectively Mixed Reality in urban analysis. It is important to understand the differences between immersive technologies:

Virtual Reality (VR): VR immerses users in a fully artificial digital environment. It disconnects the user from the real world and replaces it with a simulated one, allowing for deep interaction and immersion. VR is often experienced using head-

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mounted displays (HMDs) and hand controllers that track the user's movements [Sherman and Craig, 2018].

Augmented Reality (AR): AR overlays digital content on the real world through smartphones or AR glasses. Unlike VR, AR does not replace the world around you; instead, it adds digital elements, enhancing the user's current perception of reality [Azuma, 1997].

Mixed Reality (MR): Mixed Reality allows for interaction between the physical and digital world, creating a hybrid experience [Milgram and Kishino, 1994] .

Within the context of data, analysis, and VR, the concept of „Immersive Analytics" should also be highlighted. Immersive Analytics uses VR or other display technologies to understand complex data through interactive and visually engaging experiences quickly [Chandler et al., 2015; Skarbez et al., 2019]. The goal is to allow users to immerse themselves in their data to support real-world analytics tasks and decision-making.

Immersive urban analytics [Chen et al., 2017] provides a theoretical model that combines the spatial capabilities of Virtual Reality with the data-driven strengths of Immersive Analytics. It proposes using VR devices to create a more engaging and realistic 3D visualisation of urban data, enhancing the user's sense of presence in the digital environment. This approach combines the 3D representations of physical data (like buildings) with 2D abstract data (like population density or building costs). Doing so offers a more comprehensive view of urban landscapes, providing richer insights and more informed decisions for urban planners, experts, and stakeholders.

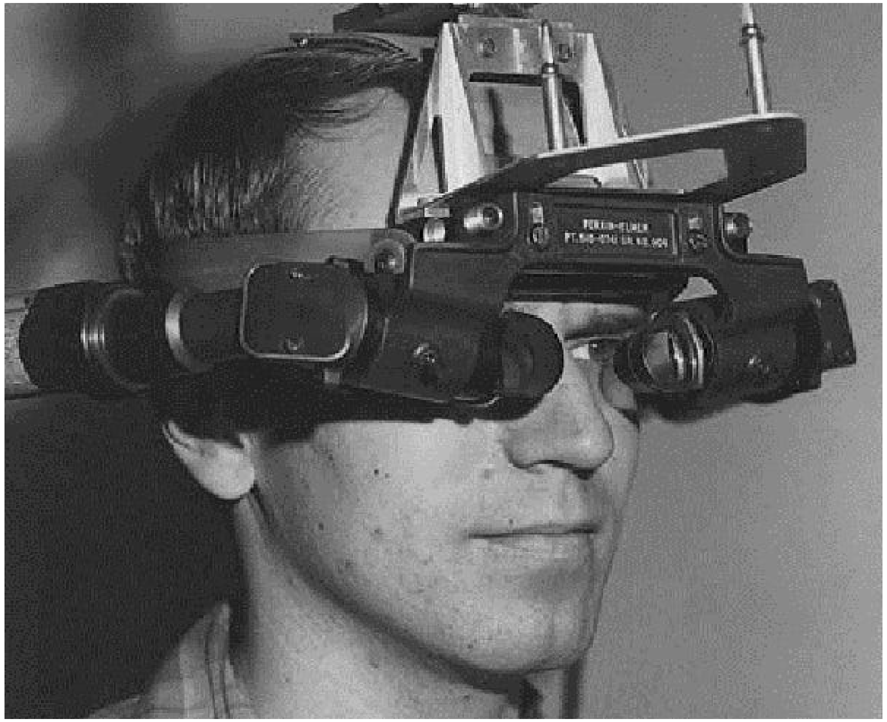

Figure 24: The Sword of Damocles, an early VR HMD and tracking system [Sutherland, 1968]

2.3.1. A Historical Overview

The concept of VR dates back to the 1960s, with Morton Heilig's "Sensorama" and Ivan Sutherland's „Sword of Damocles" being among the first VR systems [Mazuryk & Gervautz, 1996]. During this time, the use of virtual reality in urban analysis was primarily theoretical due to the technology's novelty and high costs.

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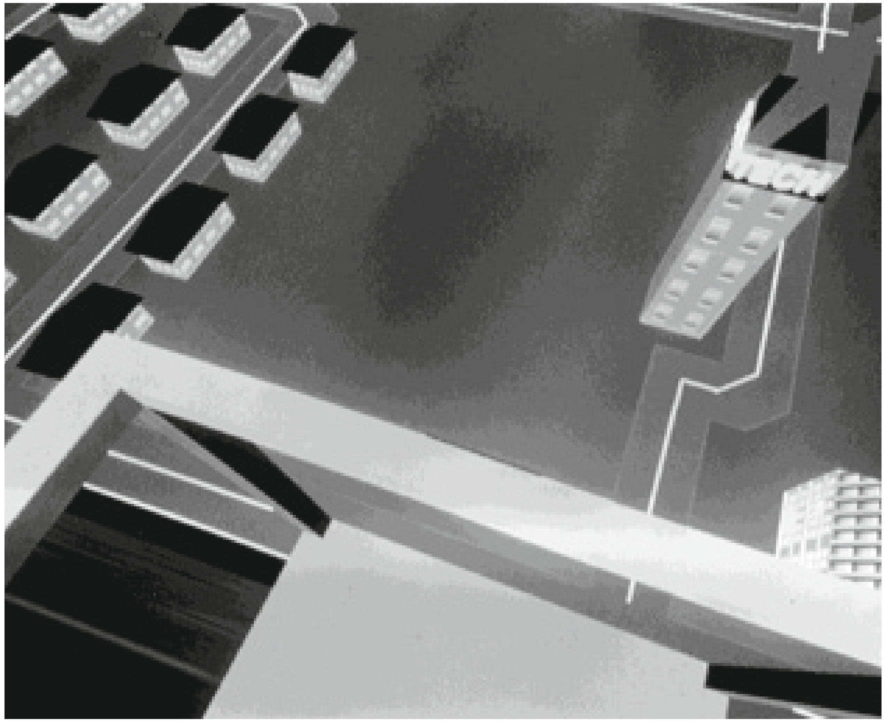

Figure 25: Virtual Reality Model of the Georgia Tech Campus, Photo courtesy of Georgia Tech Media Relations [Emory Magazine, n.d.]

The 1990s saw significant computer graphics and hardware advancements, making VR more accessible. Researchers began exploring VR's potential for architectural visualisation and urban planning [Mazuryk & Gervautz, 1996]. The first reported integration of GIS and VR was done with a system that illustrated the Georgia Tech campus area [Faust, 1995] .

The new millennium marked a turning point for VR in urban analysis. The rise of commercial VR headsets and more powerful computing made VR more affordable and widespread. Universities and research centres also began to invest in VR labs, exploring their potential for urban design, public engagement, and environmental analysis.

The integration of VR with Geographic Information Systems (GIS) and Building Information Modeling (BIM) has further expanded the scope of VR in urban analysis. Commercial tools like CityEngine have allowed for more detailed and data-driven urban simulations. Although not widely adopted, planners, architects and stakeholders can now immerse themselves in virtual urban environments, interact with data layers, simulate different urban conditions, and collaborate in real time.

As previously discussed, advancements in AI, big data, and cloud computing, combined with the ongoing evolution of VR technology, promise that VR may play a role in urban analysis. VR could become one of the standard tools in the toolbox, used for urban design, public participation, and decision-making in the future, bridging the gap between complex urban data and human-centred design.

2.3.2. Advantages of VR in Urban Analysis

A primary advantage of VR is its ability to provide a deeply immersive environment. Users can „walk“ through urban spaces, experiencing scale, distance, and spatial relationships in ways that static models or screens cannot match. This adaptability shows unique insights, whether switching from a pedestrian perspective to a bird's-eye view while still relating to your human scale or overlaying various data sets.

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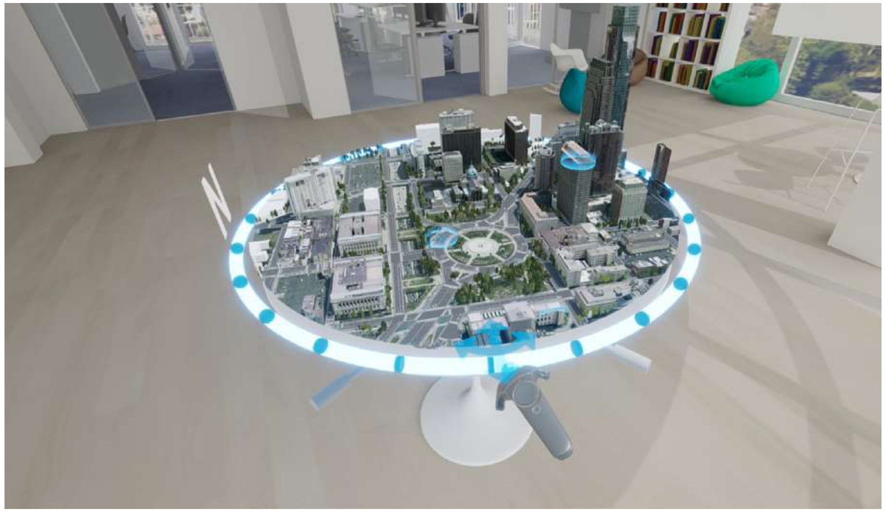

Figure 26: Interacting with the city model with CityEngine ['The CityEngine VR Experience for Unreal Engine', n.d]

Figure 27: Inspecting different scenarios with CityEngine ['The CityEngine VR Experience for Unreal Engine', n.d]

VR aims to bridge the gap between technical design and drawing and tangible, lived experiences. When users immerse themselves in urban environments, they can achieve an instinctive understanding of the information shown, leading to better feedback and more informed decisions. Such engagement ensures that all participants comprehend the information, from architects to city officials to the general public.
The core of the VR experience is interaction. Users can interact with various data layers overlaid over urban landscapes or evaluate various design possibilities as the process advances, making real-time adjustments based on feedback and new understandings.

Furthermore, VR's ability to visualise timeframes adds another advantage. With animation, VR may display urban changes or showcase data over a specified period, allowing viewers to examine this information. Later in the design process, it also allows users to look at possible future scenarios and their evolution.

VR should be integrated with other platforms like GIS and BIM to fully use its advantages rather than being used in isolation. Such integration creates a powerful toolkit for urban analysis by combining the immersive qualities of VR with the in-depth analytics of other digital tools.

Ultimately, the goal is to improve decision-making by providing a more effective urban analysis process. Immersive experiences, clearer data communication, and temporal visualisation could support this goal.

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2.3.3. Review of Existing VR Applications

With the advancement of technology and computing power and the popularisation of VR Headsets, applications and platforms catering to various aspects of urban design and planning, including urban analysis, have emerged. These tools take advantage of VR's immersive properties and incorporate other technological advancements, making urban analysis more comprehensive and interactive.

As previously mentioned, CityEngine stands out for its ability to create large-scale urban environments using procedural modelling. Its VR compatibility offers an interactive experience, allowing users to immerse themselves in urban scenarios ['The CityEngine VR Experience for Unreal Engine', n.d.]. With its GIS integrations, users can also visualise various data layers, making it a useful tool for planners and architects. However, CityEngine is a paid tool. Users need to invest both money and time to learn its functions, and currently, it doesn't support all types of data and data layers.

ArcGIS Maps from ESRI provides SDKs for both the Unity and Unreal game engines [ArcGIS Maps SDK for Unity | ArcGIS Developers, n.d.]. These plugins allow users to integrate real-world maps and 3D content from ArcGIS directly within the game environments. While they aren't standalone solutions for architects, they are foundational tools for developing new applications and products.

In recent years, Cesium, an important player in 3D geospatial visualisation, has also created integrations for Unreal and

Figure 22: ArcGIS Maps Plugin in Unity [ArcGIS Maps SDK for Unity | ArcGIS Developers, n.d]

Figure 29: Cesium Plugin in Unity using Cesium World Terrain and Cesium OSM Buildings [Cesium for Unity Quickstart, n.d.]

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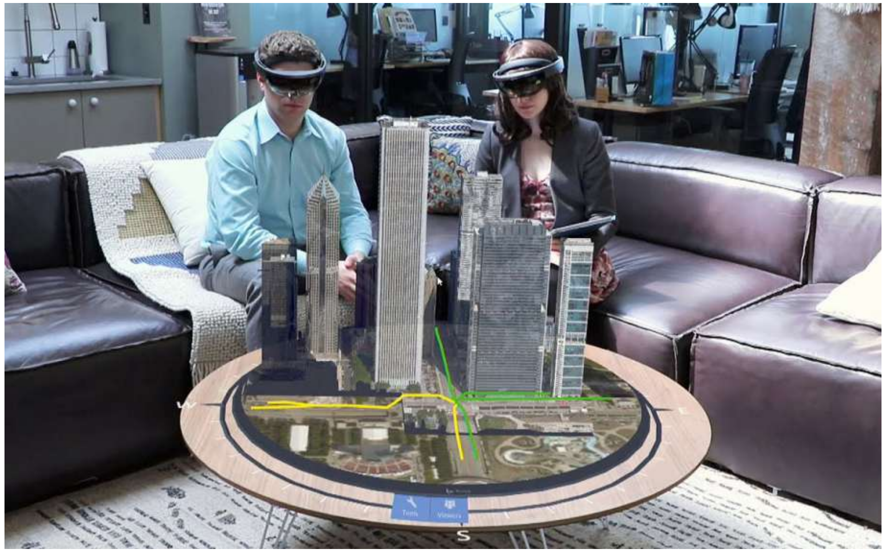

Figure 30: Holomaps [Augmented Reality 3D Map Data Visualization | Taqtile, 2021]

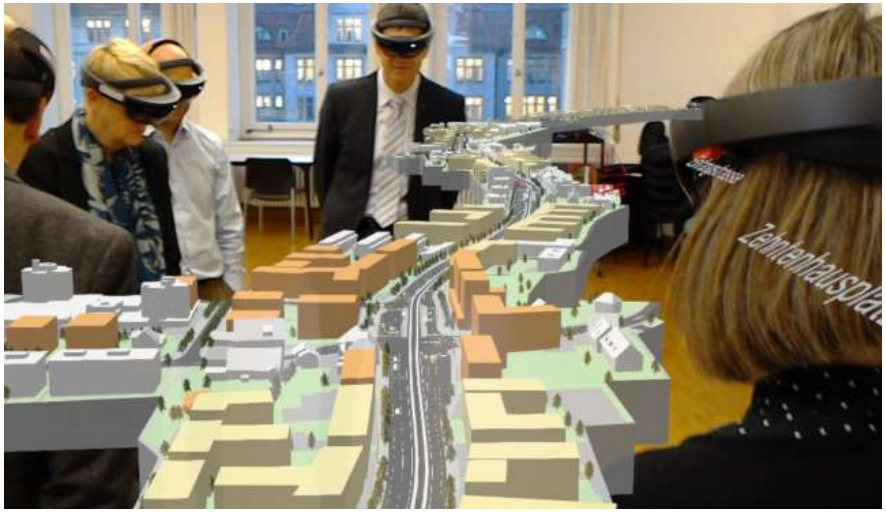

Figure 31: Holoplanning ["HoloPlanning – Mit Augmented Reality digital die Stadt der Zukunft planen | Digitaltage," n.d.]

Unity [Cesium for Unity, 2023]. While Cesium is a paid service, the plugins are free and open-source. As these releases are still new, how they will influence the development of VR tools for urban analysis remains to be seen.

Mixed Reality solutions like HoloMaps 3D, designed for Hololens, deliver interactive 3D map experiences [Augmented Reality 3D Map Data Visualization | Taqtile, 2021]. By integrating with platforms like Bing Maps, HoloMaps provides real-time data overlays and various interactive features, finding applications in sectors beyond urban planning like tourism, education, and business. Yet, the inconsistent quality of its data availability and lack of support for certain data types and layers cannot be overlooked. Similarly, Holoplanning stands out for its Hololens application, providing diverse information layers, shadow simulations, and varying zoom levels.

Cities are also exploring the potential of VR in urban analysis and participatory planning. An example of this approach is Vilnius, which used its Virtual Urban Simulation (VUS) to enhance public participation in the planning of Missionaries Park [Stauskis, 2014]. This method could provide the community visualisations of proposed projects and be a platform for feedback, ultimately leading to a more sustainable urban development approach.

Another recent development in this space is „Urban Tempo," a virtual reality tool introduced as part of the GreenTwins project. To automate and improve planning processes, the cities of Tallinn and Helsinki are constantly creating their own digital twins ["Green Twins – bringing together public space, greenery and people thorugh a digital twin," n.d.; Nummi et al.,

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Figure 32: Green Twins [Green Twins – bringing together public space, greenery and people thorugh a digital twin," n.d]

Figure 34 : VU.City London reviewing proposed changes [Virtual Reality Model - Discover a First in Accuracy and Detail | VU.CITY," n.d]

Figure 33: Virtual Reality Model VU.City London [Virtual Reality Model - Discover a First in Accuracy and Detail | VU.CITY," n.d]

Figure 35: Manhattan, layers of data visualized as overlays on the city [Bartosh and Gu, 2019]

2022]. Urban Tempo is adding another dimension to urban analysis through its emphasis on seasonal dynamics of urban greenery.

In October 2020 VU.City in collaboration with the City of London Corporation published a interactive VR digital twin of the City of London [“Virtual Reality Model - Discover a First in Accuracy and Detail | VU.CITY,” n.d.]. This digital model, displaying a 2,9 km² area, aims to facilitate collaborative design discussions, enabling stakeholders to immerse in the virtual environment, experience potential changes at a human scale, and make more informed decisions.

Using Manhattan as a test case, researchers Amber Bartosh and Rongzhu Gu explored the visualization of the city in VR, offering users a dynamic way to interact with urban data from multiple perspectives, from an aerial view to a street level [Bartosh and Gu, 2019]. They used GIS tools for city modelling and integrated the digital model into Unity. They experimented with different methods, such as piping, extrusion, and point clouds, to spatialize urban data. They conclude that the results are an in-progress research that must be applied and tested.

Arkio, a Virtual Reality collaborative design tool, allows for the sketching of buildings and urban plans. Arkio, known for its volumetric modeling for VR and mobile devices, supports importing 3D models and 2D images as well as exporting work to tools such as Unity, Rhino, and Revit. It supports up to 24 participants in collaborative design and provides a variety of modelling tools. However, Arkio primarily serves subsequent design phases rather than initial urban analysis, focusing more

Figure 36: Collaboration in Arkio [Arkio - Collaborative Spatial Design, n.d]


Figure 37: Arkio at SPINN Arkitekter [Arkio - Collaborative Spatial Design, 2023]

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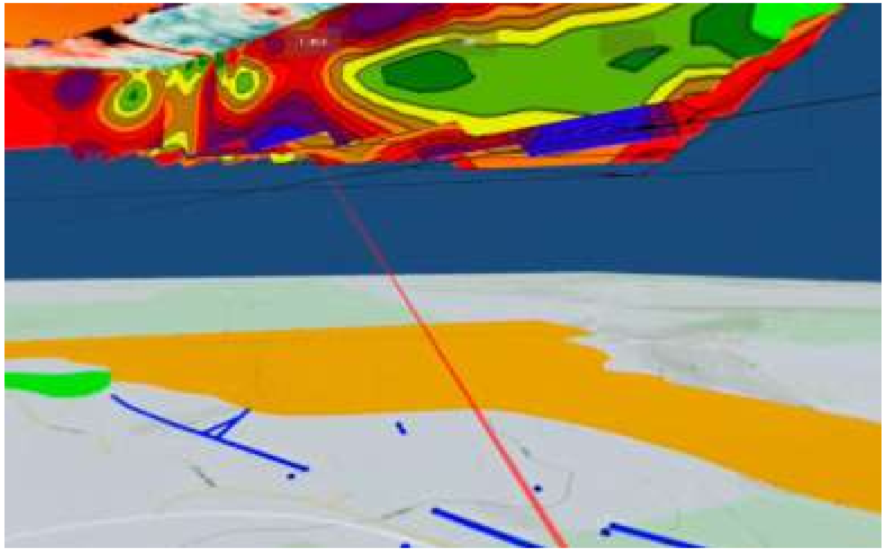

Figure 38: ViRGiS landcape [ViRGiS Virtual Reality GIS Platform, n.d]

on design development than on urban data interpretation.

ViRGIS (Virtual Reality Geospatial Information System) is a code base and package to be used in the game engine Unity to bring the GIS world into the VR world [ViRGiS Overview, n.d.].

While there is no shortage of frameworks and tools, a gap exists in ready-to-use, user-friendly VR applications tailored specifically for architects, supporting the nuanced requirements of architectural urban analysis. Existing tools either require a significant financial or time investment, lack full data support, or do not fully cater to the specific needs of architects.

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03 Methodology

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3.1. Potential Role of VR in Urban Analysis

Traditional urban analysis methods, while providing important insights, are frequently inefficient. They rely on static 2D and 3D models that don't immerse users in the actual urban context and don't effectively display the temporal evolution of urban landscapes. They are often time-consuming to produce and use and require sifting through various data sources. These constraints limit quick, effective decision-making.

With its immersive capabilities, Virtual Reality offers solutions to some challenges posed by traditional methods. The primary link connecting quantitative data and human intuition is visualisation [Donalek et al., 2014], and VR has been found to facilitate knowledge discovery in urban data use cases [Perhac et al., 2017]. By immersing users in a virtual urban environment, VR can provide a quick and intuitive understanding of urban structure and data.

Digital workflows can allow key data, like maps, statistics, and 3D models, to be automatically obtained and centralised, making the process simpler and more efficient.

The growing availability of large amounts of urban data online presents an opportunity. Still, the raw data's value in supporting decision-making is limited unless it can be synthesised and represented meaningfully. This methodology will describe a method for digitally collecting, spatialising and presenting urban data using Virtual Reality.

3.2. Conceptual Framework and Workflow

In order to establish a methodology for developing a Virtual Reality tool tailored for urban analysis, it is necessary first to define the requirements that will drive its design and functionality. These will be the foundation for developing a tool that improves the interpretation of urban data and considers the current urban planning practices:

Data Integration: Given that tools like GIS are already prevalent in urban planning, the VR platform must be capable of integrating GIS data. It should also accommodate various other forms of data, including maps, statistics, and 3D models.

Efficiency in Workflow: Streamlining data collection and representation for quicker decision-making in today's architectural and urban planning environment.

Manual Data Modification: Since urban areas constantly change, the tool should allow users to update, correct, or add data manually. This feature considers that publicly imported data may be inconsistent or may become outdated over time.

Customization: Each urban scenario has unique characteristics, so the methodology should allow for customization. Users should be able to layer different data sets or change specific parameters for analyses to create a more personalized experience.

Spatial and Temporal Visualization: Immersion is one of the main capabilities of VR. By immersing users in a virtual urban

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environment, VR can enhance the understanding of urban structure and data. Beyond that, the tool should also allow the visualization of temporal evolution in urban landscapes through animations and timelines, enabling users to understand changes in the urban context in time. Ultimately, these visualization techniques aim to enhance the understanding of urban analysis and support efficient decision-making.

User Interface and Interactivity: One significant barrier to adopting new technology is its learning curve. While the VR user interface design is outside this thesis's scope, such a tool should feature an intuitive UI. However, currently, there are no established ways of interacting with such an application. For a VR tool to be accessible to novices and experts, it should feature an easy-to-navigate interface for those unfamiliar with the technology.

Hardware Specification: Different architectural offices or users may possess different headsets. The tool should aim for broad compatibility across VR devices.

The workflow for the VR tool in urban analysis aims to maximize efficiency and minimize manual labour. It consists of three main phases, similar to traditional workflows: Data Collection, Data Processing, and Data Presentation. However, the difference lies in the automation of some of the tasks within these phases and the presentation of the data using virtual reality.

In the next subchapters, each of the three phases will be examined, and a general framework and examples for every phase will be discussed. These examples aim to explain the

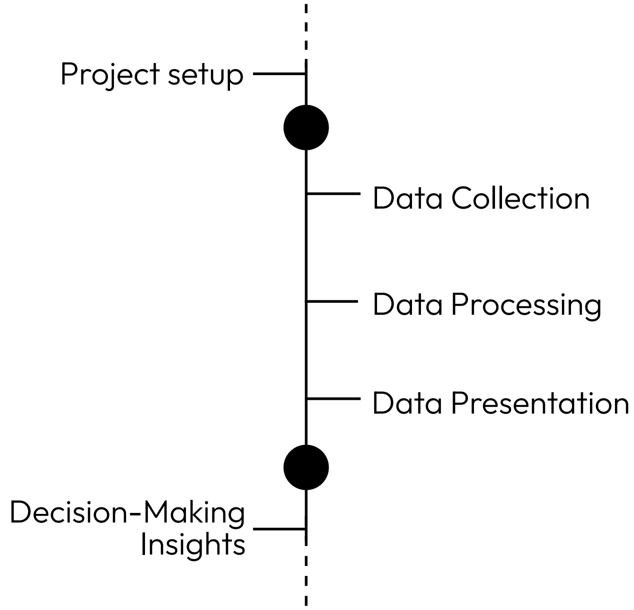

Figure 39: VR-Assisted Urban Analysis Workflow

theoretical approach, while the practical application of the methodology will be shown in the case study in Chapter 4.

3.3. Data Collection Framework

Collecting the right data is the first step in urban analysis. This step uses different methods to gather detailed and accurate data for the project. We can divide this process into several stages, as detailed below:

Location & Area: The first step is to establish the geographic coordinates for the building site, as well as the boundaries of

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the surrounding area, that are relevant for urban analysis and will be displayed.

Geometry Data: 3D morphological data of buildings and terrain is essential for 3D visualization. This information can be sourced automatically from OpenStreetMaps or CityGML files available through Open Government Data initiatives. Alternatively, it can be automatically generated, imported from other data providers, or manually modelled.

Information Layers: Depending on the project's location, scope and stakeholders, different data layers can be collected automatically or manually. These may include terrain maps, building functions, traffic patterns, environmental metrics, historical context, demographics, and building regulations.

While this thesis primarily uses Open Government Data and OpenStreetMaps as examples in the following subchapters, they represent just a subset of possible sources. Using multiple sources helps fill gaps in the data and check its accuracy. FME is the primary tool used to import data and process it in the following steps. However, other tools and manual methods can also be used.

3.3.1. OGD Data Collection

Open Government Data (OGD) Austria is a publicly accessible platform offering diverse data, including GIS data, statistics, and images. The City of Vienna has published 614 datasets on the platform as of August 2023, making it a valuable source for users seeking up-to-date and high-quality data free of

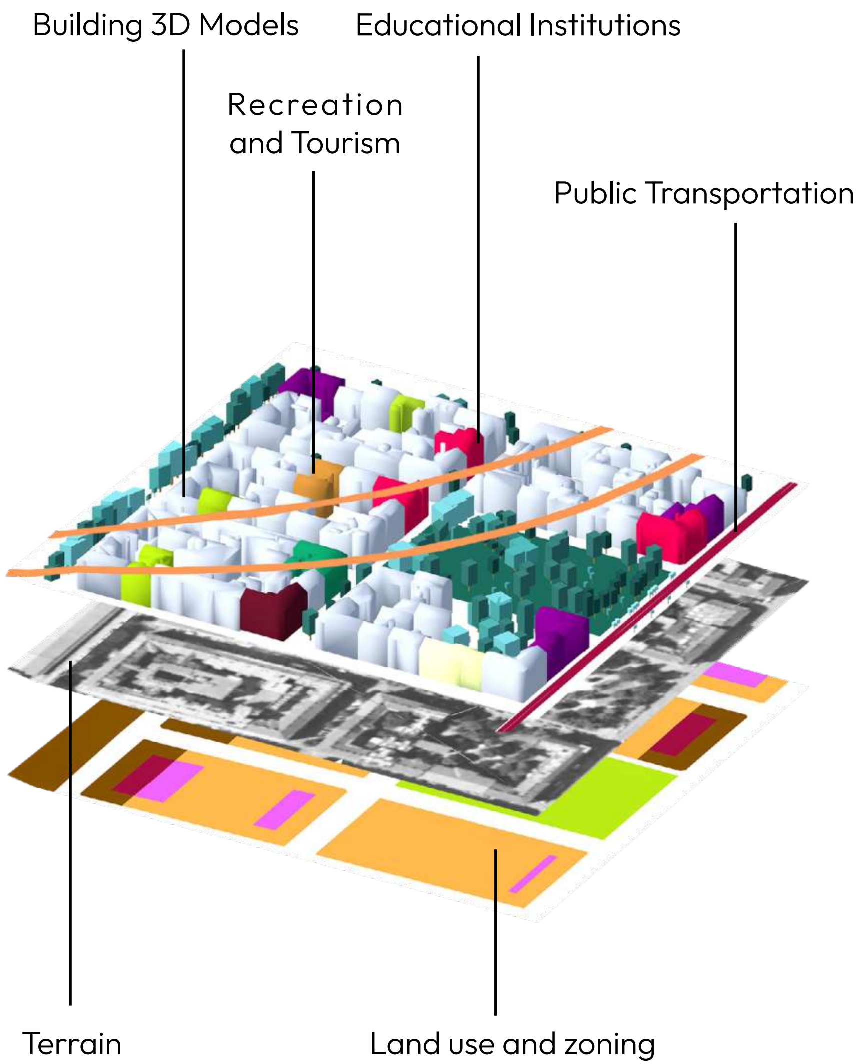

Figure 40: Examples of Open Goverment Data datasets

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charge [Datenauftritte | data.gv.at – Offene Daten Österreich, no date].

Many datasets from the City of Vienna can be the basis of a comprehensive urban analysis. Not all of them are used in the thesis, but they can be helpful in an urban analysis process following a different goal. These datasets cover many topics, including but not limited to:

- Building 3D Models: Generalized roof models (LOD2.1)
- Terrain Models, Satellite Maps
- Public Transportation: Public Transport Network Lines and Stops
- Health Facilities: Doctor and Pharmacy Locations
- Educational Institutions: Locations of kindergartens, schools, universities
- Recreation and Tourism: Details on hotels, swimming pools, artworks in public spaces, sightseeing locations
- Land Use and Zoning: Data on how land is used in different areas of Vienna
- Laser scans: geodetically located point clouds

An example of data collection is downloading 3D models of the buildings in Vienna. OGD Austria offers the dataset titled „Generalisiertes Dachmodell (LOD2.1) Wien“ [Generalisiertes Dachmodell (LOD2.1) Wien - data.gv.at, no date]. This dataset is derived semi-automatically from the building footprints of the multi-purpose map (Flächen-Mehrzweckkarte) and a surface model. It provides prototypical roof shapes, which are of LOD2.1 detail level. The user can download CityGML or DXF files.

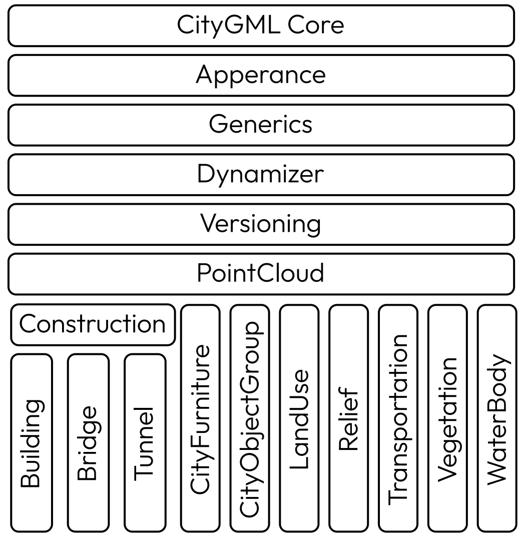

Figure 41: CityGML 3.0 module overview, simplified adapted representation [Kutzner, Chaturvedi and Kolbe, 2020]

CityGML is an open standardized data model and exchange format that defines the classes and relations for the most relevant topographic objects in cities and regional models [Gröger et al., 2012]. The primary focus is on the modelling of 3D urban objects. It is based on the XML (Extensible Markup Language) structure, allowing for easy data exchange among different software applications.

LOD stands for Level of Detail. In 3D city modelling, various LODs represent the degree of detail of a model. LOD2.1 refers to a detailed 3D model that includes the depiction of individual roof structures on buildings.

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The data in the Geodata Viewer is provided in a grid format, where each grid square corresponds to a specific section of the city. Each of these squares can be downloaded separately, offering flexibility based on the area of interest. The download links follow a consistent URL pattern, with the grid coordinates being the variable. For instance, a link such as „https://www.wien.gv.at/ma41datenviewer/downloads/geodaten/lod2_gml/105080_lod2_gml.zip“ corresponds to the specific coordinates „105-080“.

For large areas or multiple sections, the user might consider creating an automated downloading tool that iterates over the required grid coordinates. However, it might be more feasible to download the desired grids manually for smaller analysis areas, as in specific case studies.

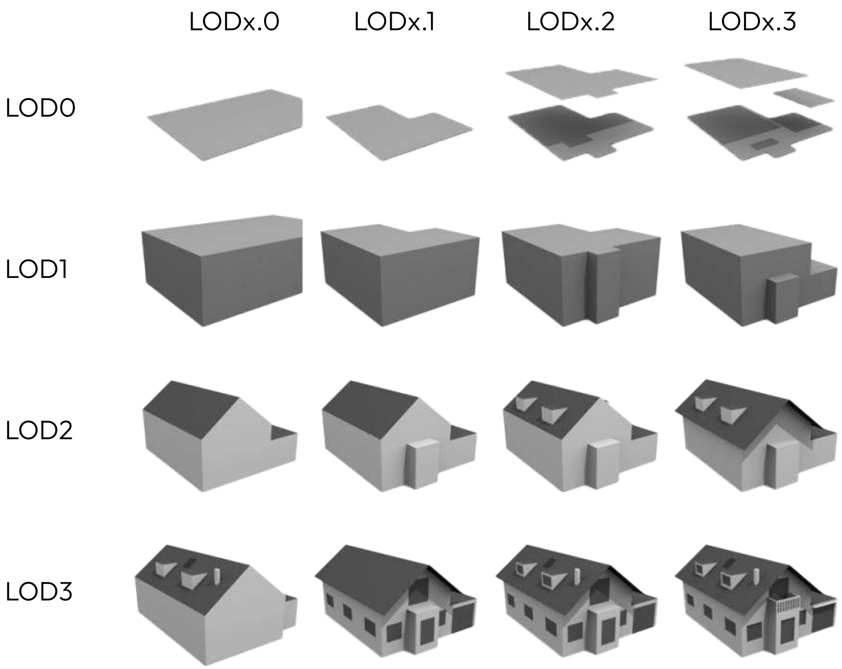

Figure 42: Visualization of LOD steps, simplified adapted representation [Biljecki, Ledoux and Stoter, 2016]

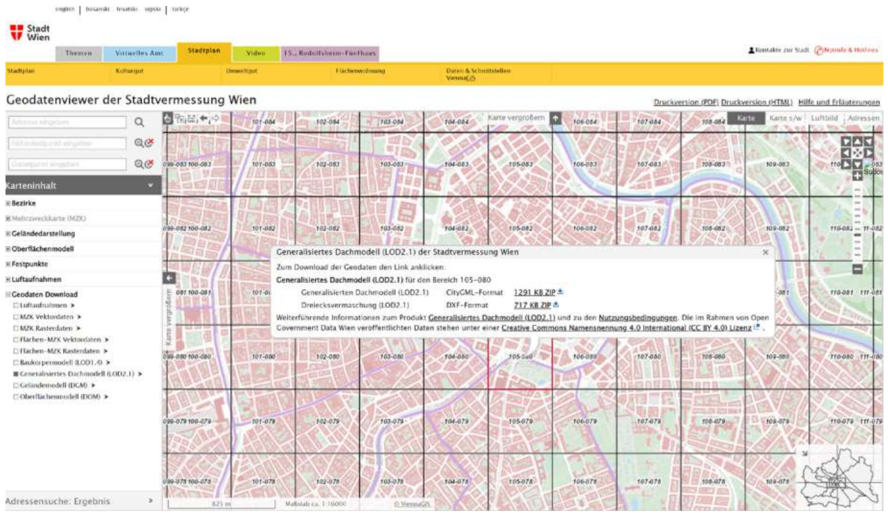

Figure 43; Geodata Viewer City of Vienna [Geodatenviewer der Stadtvermessung Wien, n.d]

3.3.2. OSM Data Collection

OpenStreetMap (OSM) is a collaborative mapping platform that provides geospatial data about urban features, including the built environment and transportation. OSM is free and open-source, offering a form of Volunteered Geographic Information (VGI) that is accessible to all without any licensing fees or restrictions. The data is constantly updated and validated by a global community of contributors, making it a valuable resource for urban analysis workflows worldwide. As

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some locations may have less accurate data, users can contribute by adding or correcting information and making it available to everyone.

As with OGD, not all data will be utilised in this thesis. However, below is an overview of the kind of relevant urban data available in OSM, which can categorised into the following categories:

- 2D Data: Building footprints, Roads (e.g. highways, secondary roads, footpaths), land use (residential, commercial or agricultural)
- 3D Data: Available information on building footprint, building height or elevation that can be then rendered in 3D
- Amenities: Medical Facilities (e.g. hospitals, clinics, pharmacies; Educational Institutions (e.g. schools, libraries); Leisure Spots (e.g. parks, swimming pools, other recreational locations)
- Cultural Sites: Museums and Art Galleries
- Commercial Areas: Shopping Zones, Markets
- Public Services: Emergency Services (e.g. police stations, fire stations), Postal Services

Complementing the data from OGD, OpenStreetMaps serves as the second main source of geospatial data. There are a few possibilities for acquiring data from OSM. Users can navigate to the OpenStreetMap website and use the "Export" tab to select specific areas for which they wish to download data. Depending on the source, the user can choose different file formats, such as .osm, .geojson, or .shp files, making it compatible with different data processing tools.

For those who require real-time or more dynamically updated data, OpenStreetMap offers several APIs that can be integrated into custom data retrieval pipelines. For specialized queries or downloading larger datasets, the Overpass API is a tool to script data retrieval, allowing for the extraction of highly specific types of data based on tags like "amenity=pharmacy" or "highway=primary". Alternatively, platforms like Geofabrik offer regional OpenStreetMap extracts, making acquiring data for larger areas easier in one go.

OSM XML files primarily consist of three elements: nodes, ways, and relations. Nodes are individual geographic points defined by latitude and longitude. Ways are ordered collections of nodes that form lines or shapes, representing roads, buildings, or other linear and polygonal features. Relations are more complex

Figure 44: Open Street Maps Export Tab Screenshot [Export, n.d]

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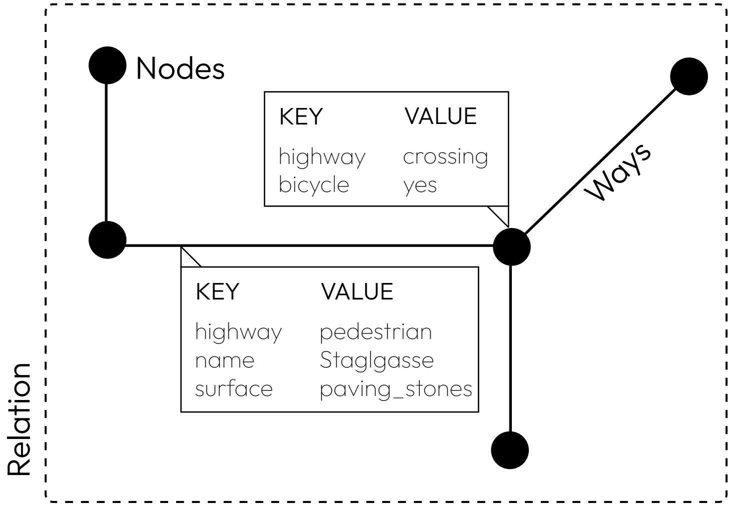

Figure 45: Example of a OSM object data structure, simplified own representation [Borkowska and Pokonieczny, 2022]

structures that indicate how nodes and ways interact or relate to each other, like a bus route composed of several road segments.

All these elements can have associated tags, which are key-value pairs that provide additional descriptive information. For instance, a tag could indicate whether a node is an amenity, its type, and its address. This organization of elements and tags allows for mapping of both physical and abstract features, from road networks and building forms to administrative boundaries and public services.

A basic understanding of the types of data available and how these files are organised is helpful in efficiently importing the required data for the project. In scenarios where automated data retrieval is required, FME offers a solution for updating and further transforming data from OpenStreetMap.

3.3.3. Data Integration Tools

This section focuses on using tools for combining different urban data sources into a single processing platform. While FME (Feature Manipulation Engine) is used as an example, it is important to note that other tools, such as ArcGIS or QGIS, can also be employed for similar purposes.

FME is a data integration platform designed to transform and move data between different software applications. It operates on the concept of „workflows", enabling the set up of automated processes that can read, transform, and write data in different formats. FME supports many data types, spatial and non-spatial, and allows for complex data transformations.

FME's OSM Reader lets users read OSM XML data directly into the FME workspace. Additionally, FME also provides an OGD CityGML Reader, which can be integrated into the same workflow. This is particularly useful for projects that require data to be retrieved and integrated from multiple sources.

Within FME, the user can set up workflows to filter out only the relevant OSM or CityGML data types, such as specific amenities, road types, or other tagged features, into the format needed. This data can then be integrated with other datasets, transformed, and automatically updated at scheduled intervals.

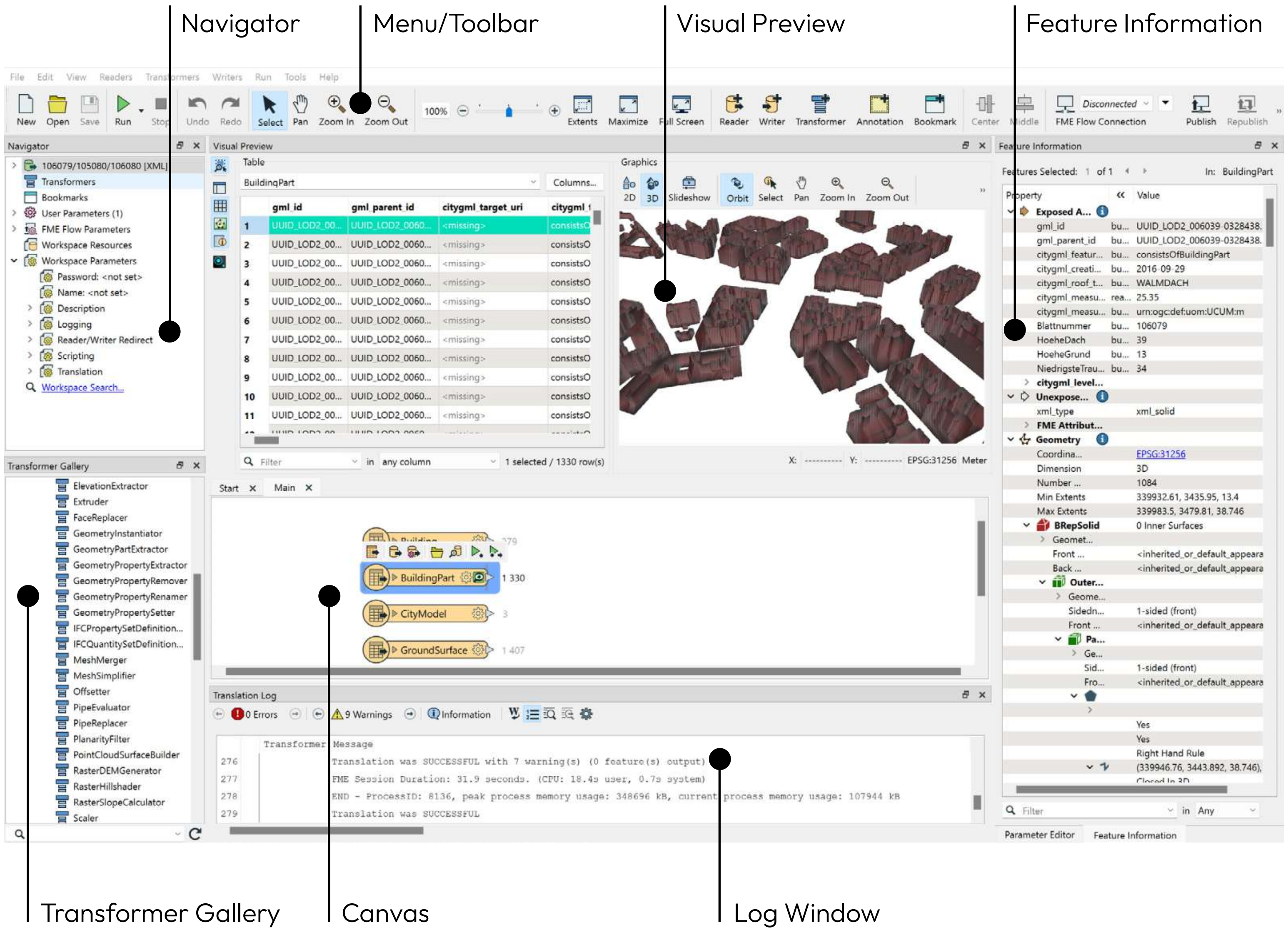

Figure 46: FME Software: major components, displaying an OGD CityGML Reader

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The benefit is the ability to create an end-to-end data pipeline, from retrieval to processing to exporting this data. However, the imported data needs to be further processed to be used in the tool.

3.4. Data Processing and Integration Framework

The second phase focuses on transforming and organising the collected data to ensure efficient incorporation into the VR tool in the last stage. The phase comprises Data Formatting and Alignment, Data Overlay and Export, and Data Integration.

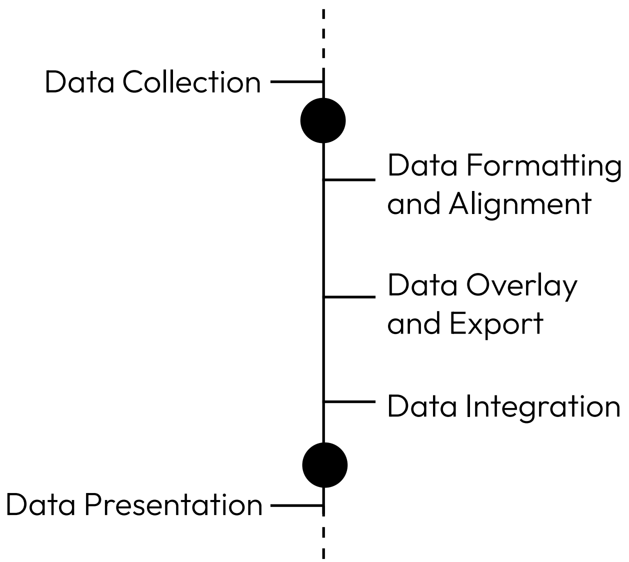

Figure 47: Data Processing and Integration Workflow

Data Formatting and Alignment: The initial step involves ensuring that all geometry and data imported are scaled correctly and transformed into one coordinate system. For terrain data, it is important that textures, UV mapping, and terrain geometry match.

Data Overlay and Export: Data should be overlaid and interconnected once initially formatted. Following this, the data will be formatted consistently for export. For instance, geometry data will be converted into FBX files and named using unique IDs. At the same time, relevant data layers will be prepared as CSV files and use IDs for future matching.

Data Integration: At this point, the FBX files representing urban elements such as buildings, streets, and parks are imported into a game engine to form a three-dimensional representation of the area. Parallel to this, the CSV files containing detailed information corresponding to each urban element are imported into the game engine. Depending on the project, these files contain information such as the number of floors or functions of a building, the type of street, or the details of public transportation available and they link to the unique IDs already assigned to the FBX files.

Two tools will be used as an example in the following two subchapters. FME is utilised for data formatting, overlaying, and exporting, automating many steps to ensure that manual adjustments are not needed for each new project when set up correctly. Unity parses and builds the scene for the next steps. However, other software tools or a partially manual workflow could also be used. The methodology is adaptable and can be applied differently depending on the specific requirements of the project.

3.4.1. Example Data Processing

In this section, an example will illustrate the process of integrating and processing OpenStreetMap (OSM) amenities data and OGD CityGML data to create a coherent urban model.

(Optional) Attribute Filtering: Data can be simplified by removing unnecessary attributes. When using FME for this phase, this can happen with the „AttributeRemover" component. For example, when working with OSM data, details such as the contributor's username who last updated an object may be irrelevant to the next steps. The data becomes more concise and easier to parse when only relevant attributes remain.

Coordinate System Alignment: OGD data from Vienna is often geo-referenced using the MGI/Austria GK East projection (EPSG code: 31256), whereas OpenStreetMap operates on the EPSG: 4326 (WGS 84) coordinate system. Coordinate systems are standardized references that enable spatial datasets from different sources to be combined on a common map. The EPSG (European Petroleum Survey Group) codes are numerical identifiers assigned to common geographic projections. To harmonize these datasets, the „Reprojector" transformer in FME can be used to align the coordinate systems.

CityGML Geometry Simplification: CityGML files contain many geometries where elements like walls, roofs, and ground

Figure 48: Building footprints of the Naschmarkt area in the EPSG 31256 and 4326 coordinate systems

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surfaces are separated. For an urban analysis, it is more efficient to represent each building as a single mesh. Only the outer shell is necessary, so this step filters and then merges all wall and roof geometries sharing the same unique ParentID into one mesh, naming the mesh using this ID.

Spatial Data Overlay: This step overlaps data sets to identify and analyze interactions between different elements. This process checks for overlaps and relationships within the spatial data, such as how specific points (like amenities) correspond with areas (such as buildings). Tools like FME offer the

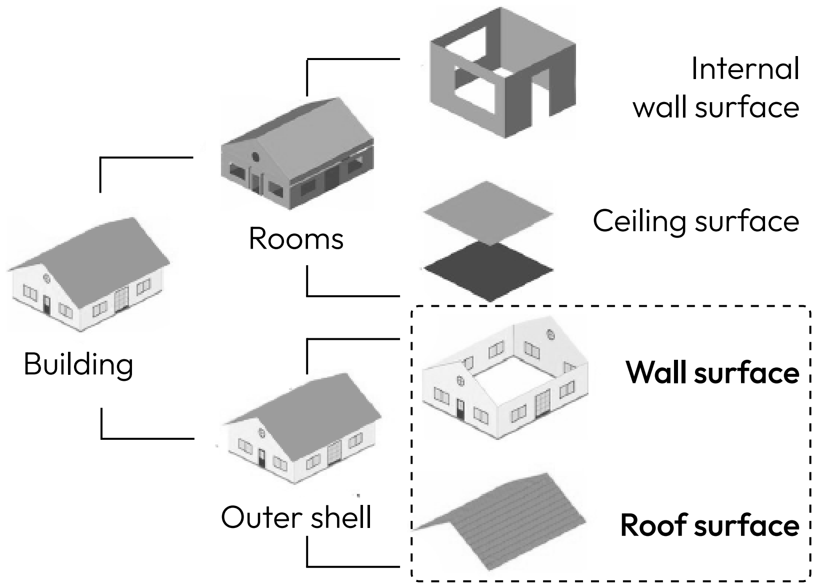

Figure 49: Basic structure of a building represented in CityGML format. simplified adapted representation [Malhotra et al., 2021]

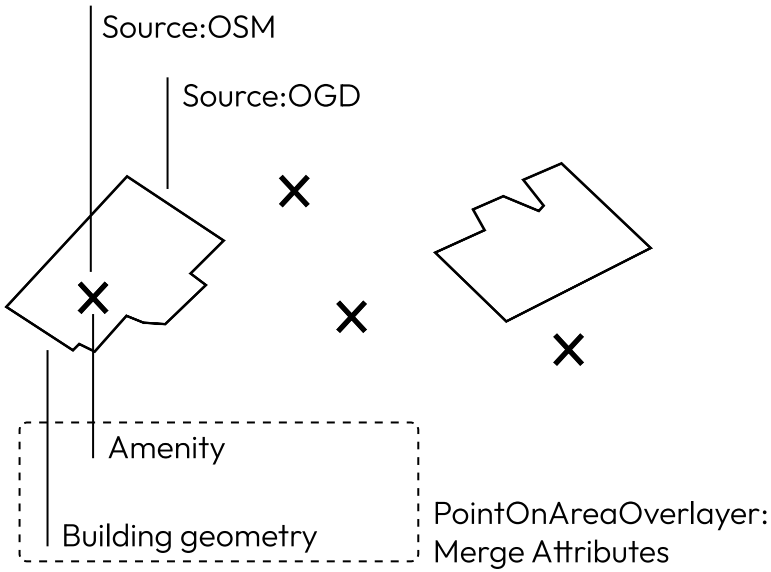

Figure 50: PointOnAreaOverlayer concept

transformers „AreaOnAreaOverlayer“ and „PointOnAreaOverlayer“ that can automate this task, for example, linking the building‘s unique ID to the amenity in a table.

Attribute Merging: All required attributes from overlapping elements from different sources, including geometry, are joined.

Data Export: The processed geometry data is converted into FBX files, and relevant data layers are prepared as CSV files. Both are named using unique IDs for further integration. The data is saved, for example, using FME Writer transformers, to be used for the next phase.

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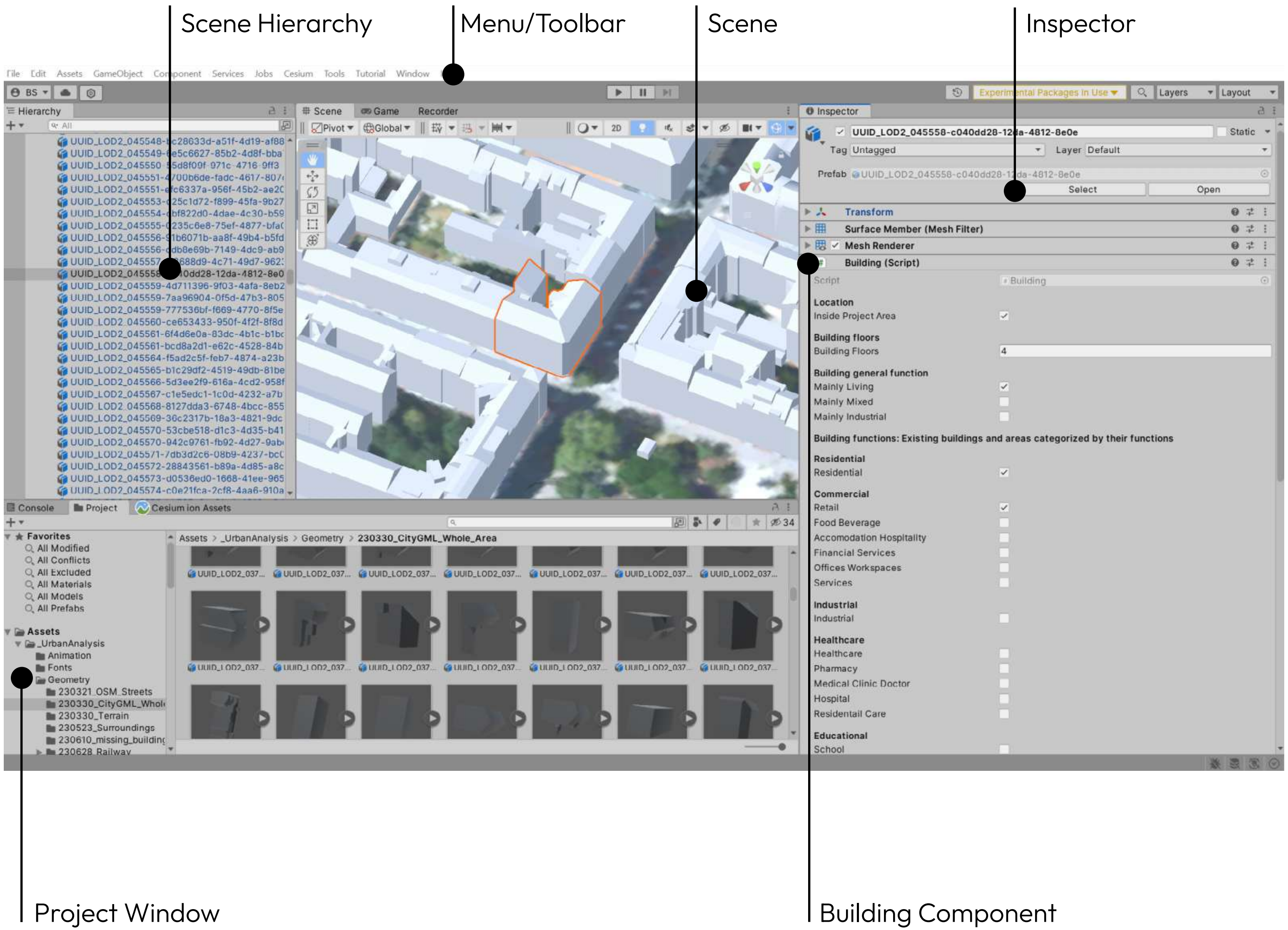

Figure 51: Unity Editor and main components, displaying a buiilding and its data

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3.4.2. Example Data Integration

This section uses Unity as a practical example to demonstrate the methodology of integrating data in a game engine. However, the principles and processes described are not exclusive to Unity. Other software or game engines, such as Unreal Engine, could also be utilized similarly.

Unity is a cross-platform game engine developed by Unity Technologies. It creates 3D and 2D experiences, including video games, simulations, and interactive visualizations. Unity provides an easy-to-use set of tools and a development environment that allows developers to bring digital content to life through interactive, real-time experiences. Its ability to deploy on different platforms, including VR devices, makes it a practical choice for many projects.

Geometry Import: The FBX files, now named using unique IDs, are imported into the Unity scene as Game Objects. In Unity, GameObjects function as the building blocks for scenes, operating as a container for functional components that determine how the GameObject looks and what it does.

Data Binding Script: A C# script reads the CSV data and identifies Game Objects through their unique IDs. It then adds a Component to each object containing relevant data. Components are scripts or modules in Unity that can be added to Game Objects to control their behaviour, appearance, or interactions. For instance, if a pharmacy is located in a building, the building game object in Unity will have a component with the attribute „bool pharmacy“ set to true.

Scene Assembly: As a result, a scene is constructed where each object not only represents its geometric form but also carries a dataset with relevant information. A Unity Scene is a container that holds all the game objects, assets, and settings arranged to create a particular interactive experience. This setup is executed initially or whenever new data is added, ensuring a dynamic and up-to-date urban model.

3.5. Data Visualization and User Interaction Framework

In the final phase of the methodology, users engage with the data integrated into the VR tool, navigating and interacting with the represented urban spaces through an immersive ex-

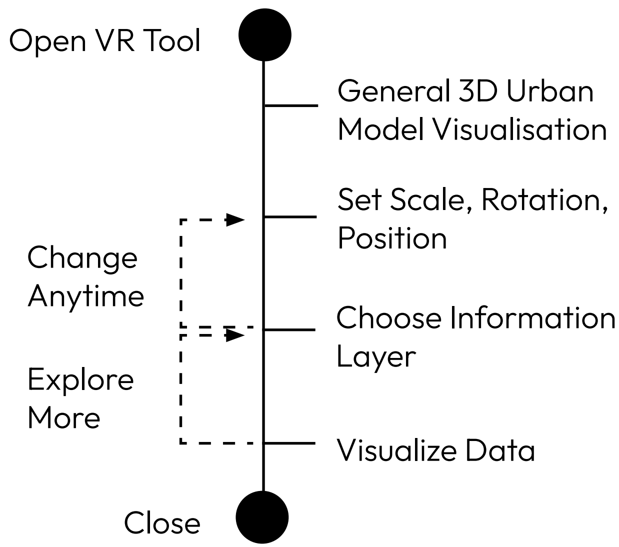

Figure 52:Schematic structure of user interaction

perience. The functionalities of this phase can be divided into three categories: user interface, data display, and application environment.

User Interface: The user interface allows interaction with the urban model. Users can choose the type of information they wish to view using controls such as toggles and dropdown menus, creating a personalised experience. Furthermore, they can alter the scale to analyse the data from different perspectives, such as a bird's-eye or pedestrian perspective.

Data display: Data visualisation intends to be organised and straightforward, encouraging quick understanding by dynamically highlighting specific data layers. Depending on the project, users can concentrate on various aspects, such as green areas, street categories, and the different functions of buildings. Additional details from laser scans, photos, videos, or other data types can be incorporated; the necessary details depend on the project requirements and goals.

Application Environment: The tool can be used within the game engine or as a standalone VR app.

3.5.1. Data Visualization

Inside the game engine, a script maps the different data types, such as street categories or building functions, to corresponding materials, allowing for a quick switch between visual representations. When a user activates a toggle corresponding to a specific data layer, the script iterates through the relevant geometry and modifies its materials to highlight and

Figure 53: OSM Street Categories, exported from FME in meshes of different widths and highlighted in Unity by category

make the chosen data visible.

For example, a green highlight on a building might indicate a recreational area, while a red line along a street could signify a high-traffic zone. A legend is automatically placed over the highlighted data, rotating to face the user. This ensures it is easily readable from any point, providing context to the visual data displayed.

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3.5.2. User Interaction

A VR User Interface is a set of elements and controls that enable users to interact with a virtual environment or application. A quick way of creating a User Interface in a game engine involves utilising its built-in UI components, such as buttons, toggles, sliders, dropdown menus, and text fields, which can be customised and adapted for 3D interactions. For instance, a toggle can be used to switch different urban data layers or settings on or off. At the same time, a dropdown menu can provide a selection of options for the user, for example, different terrain textures.

OpenXR is an open standard established by the Khronos Group, designed to facilitate AR/VR development by providing a unified interface for developers to build applications that can operate across various AR/VR devices without needing multiple APIs. For example, the OpenXR plugin in Unity integrates this standard, ensuring compatibility and simplifying the development process. Unity plugins work by extending the functionality of the Unity engine, allowing developers to incorporate additional features, tools, or external libraries into their projects. OpenXR needs to be added once to Unity at the start of the project.

The XR Interaction Toolkit package is a system for developing VR and AR experiences, providing a framework for 3D and UI interactions to be accessed via Unity input events. It offers built-in solutions and configurations for creating immersive interactions such as scaling, rotating, and moving within the virtual environment. The package also includes sample assets,

Figure 54: XR Interaction Toolkit 2D UI Examples [XR-Interaction-Toolkit-Examples/Documentation/UI-2D.md at main · Unity-Technologies/XR-Interaction-Toolkit-Examples · GitHub, no date)]

Figure 55: XR Interaction Toolkit 3D UI Examples [XR-Interaction-Toolkit-Examples/Documentation/UI-2D.md at main · Unity-Technologies/XR-Interaction-Toolkit-Examples · GitHub, no date)]

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Figure 56: Initial scale for the VR experience

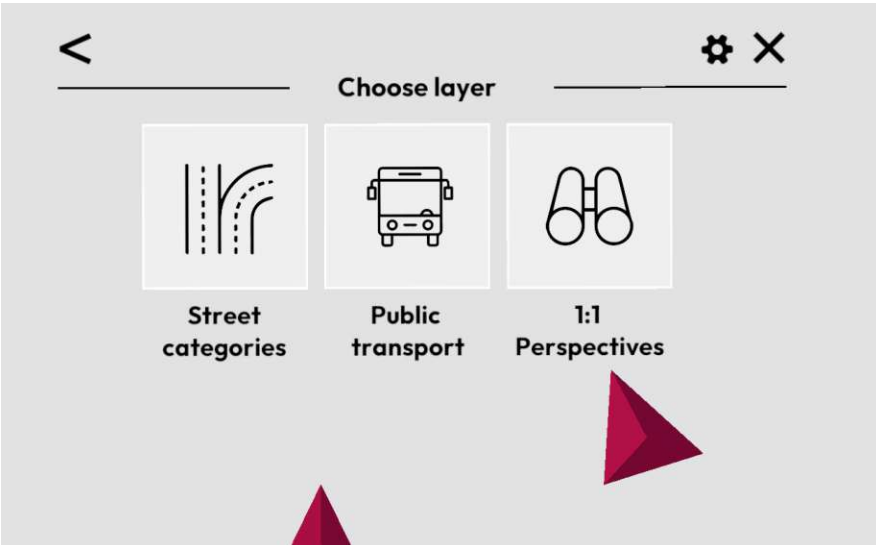

Figure 57: User interface example of a Mobility Menu

which can be adapted as needed by developers for their specific use cases. While knowledge of Unity (or other game engines) and VR terminology is needed, all XR interactions later used in this thesis could be directly configured from the Starter Assets provided with this package.

Depending on the purpose of the analysis and dimensions of the urban area, the experience begins with the user seeing a 3D urban model at a default scale, such as 1:1000. This scale should allow for an initial overview of the whole area. The user, equipped with VR controllers, can manipulate this model: hand movements and the „Select" buttons enable the user to reposition, rotate, and rescale the model. This flexibility ensures that users can closely examine specific areas or gain a broader understanding.

Anchored to the user's virtual hand, the UI can be opened by clicking a button. It provides options for selecting different data layers for visualisation and adjusting other settings, such as turning off the 1x1 km grid on the ground. This interaction allows users to tailor their analysis to specific requirements or interests.

Building refers to compiling and packaging a project into an executable application tailored for a specific platform. To create a VR app, developers configure the build settings to target the Android platform, ensuring that the application is optimised for the VR headset. The build process includes specifying the appropriate SDK, setting the desired graphical quality, and selecting other configurations necessary for the VR experience.

Once the build is initiated, the game engine generates an Android APK file that can be installed directly on the headset. However, developers also have the flexibility to test and iterate their VR experiences directly within the game engine without building the application.

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04 Case study

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4.1. Introduction to the Case Study Area

4.1.1. Criteria for choosing a case study area

The development of the proposed virtual reality tool needs a case study where its features can be tested and assessed. As outlined in the Methodology chapter, the tool should include various features to test the understanding of urban context and data in VR and its limitations. Applying these theoretical features in a real urban setting is essential for gaining insights.

Choosing the suitable case study area is based on several factors. Firstly, the chosen area should have recent, current, or future significant architectural or urban planning projects that affect the urban environment and where insights from urban analysis would be needed. The area should also offer a range of functions, such as residential, commercial, retail, educational, and religious spaces. Additionally, the availability of different transportation options, such as bike lanes, trams, trains, and cars, is important.

Moreover, the area should have a variety of street categories, including different widths, lane configurations, and shared streets. Public spaces, like squares, parks, and playgrounds, should also be present. The historical significance of the area and its demographic diversity should also be considered to address the needs and preferences of different groups of people. Finally, the building site should be a public project that would benefit from synergies with its surroundings.

These criteria guided the selection of the building site for the case study, ensuring that it represents a diverse urban environment where the VR tool can be effectively evaluated.

4.1.2. “Mitte 15” area in Vienna

The City of Vienna, in collaboration with the Austrian Federal Railways (ÖBB), has a tradition of redeveloping former train station areas into new neighbourhoods. One such opportunity is presented by the Westbahnhof area, owned by ÖBB. This area comprises 6 hectares of soon-to-be-available storage space along Felberstraße, opening up a significant opportunity for urban development.

The city has initiated the „Mitte 15“ project, which translates to „Middle 15,“ referencing its central location in Vienna‘s 15th district. With the planning and participation process beginning in 2022 and the planned completion of a definitive plan in 2023, this project seeks to create a neighbourhood development concept for Rudolfsheim-Fünfhaus. During this time, residents were invited to discuss the area‘s future development and voice their concerns with the planners at various events and participation formats.

The „Mitte 15“ project has three main objective listed on its official website [Mitte15 – Du und dein Grätzl. Gestalte mit! – Die Informationsseite zu Mitte15., n.d.]:

Create and improve green spaces
Reduce railway barriers
Promote climate protection

Figure 58: Mitte 15 Project Area, Scale 1:8000 [Mitte15 – Du und dein Grätzl. Gestalte mit! – Die Informationsseite zu Mitte15., n.d]

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Figure 59: Mitte 15 Process Overview [Mitte15 – Du und dein Grätzl. Gestalte mit! – Die Informationsseite zu Mitte15., n.d]

Figure 61: Mitte 15 Dialogue Day [Mitte15 – Du und dein Grätzl. Gestalte mit! – Die Informationsseite zu Mitte15., n.d]

Figure 60: Mitte 15 Dialogue Bike Tour [Rückblick auf die Dialogradtour – Mitte15 – Du und dein Grätzl. Gestalte mit!, n.d., p. 15]

Figure 62: Mitte 15 District Workshop [Mitte15 – Du und dein Grätzl. Gestalte mit! – Die Informationsseite zu Mitte15., n.d]

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The results of the participation process are constantly updated on the project's website. For example, during the „Quartierwerkstatt", a collaborative workshop involving residents and planners, more than 100 participants expressed their desires and needs. It provided a platform for them to share and discuss their ideas, focusing on four main themes: Connections and Crossings, Mobility and Traffic, Public and Green Spaces, and Living Together. The workshop transformed four classrooms into themed stations, each dedicated to one of these focus areas, with thematic maps available for participants to record and discuss their suggestions.

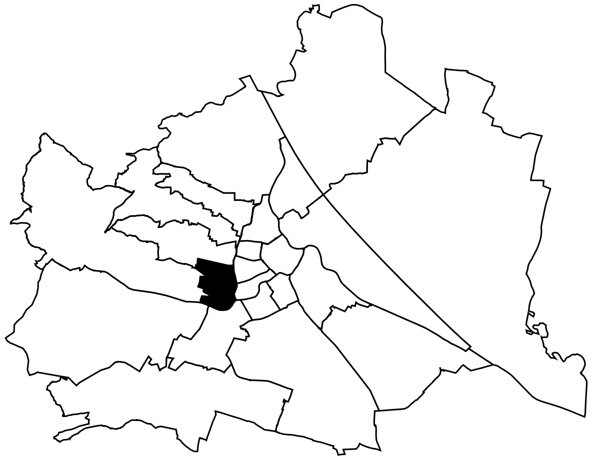
Connections and Crossings: Participants highlighted the strong need for cycling and pedestrian pathways improvements. Key issues included creating barrier-free access at Rustensteg and reconfiguring the Schmelzbrücke bridge to favour cyclists and pedestrians. There was frequent mention of a need for two additional crossings over the Westbahn primarily for cyclists and pedestrians. Some participants also proposed partial decking over the Westbahn rail tracks for multi-purpose uses like green spaces and recreational areas, although this idea met with some opposition.

Mobility and Traffic: Participants frequently called for a reduction in car traffic on the Äußere Mariahilfer Straße, alongside creating a continuous, safe cycling lane and expanding sidewalks for pedestrians. Multiple streets were marked on the thematic map where participants felt traffic calming or car-free zones should be implemented.

Public and Green Spaces: Participants expressed a consistent need for increased greenery and larger, decentralized green spaces throughout the area, with specific calls for green streets and a continuous long park space in the Westbahnareal. Besides creating new green spaces, there was an emphasis on maintaining and upgrading existing ones. The idea of greening facades and roofs was mentioned often, along with creating micro green spots everywhere to connect existing green areas.

Living Together: Participants expressed a strong desire for additional public spaces in the district free of commercial activities and reserved for children and youth to gather. Temporary uses of space, like „Wild im West," were well-received, and similar initiatives in other locations were suggested. The need for cultural hubs to promote local arts and to make existing cultural resources more accessible was also highlighted. While there was a call for more affordable housing, some participants were sceptical about further construction, advocating for moderate density and renovating existing buildings over new developments.

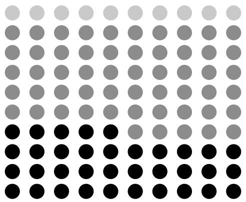
The „Mitte 15" area provides an opportunity to evaluate the proposed virtual reality urban analysis tool. The area offers a diverse range of factors for urban analysis, such as various functions and transportation options and the historical significance of Westbahnhof in the city. The evaluation will consider the data requirements of an architectural or urban planning office working on one decided development in the area in the future and provide a structured framework for evaluating the tool's effectiveness in the urban analysis process.



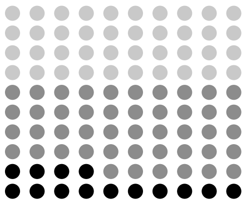
76.813
Population

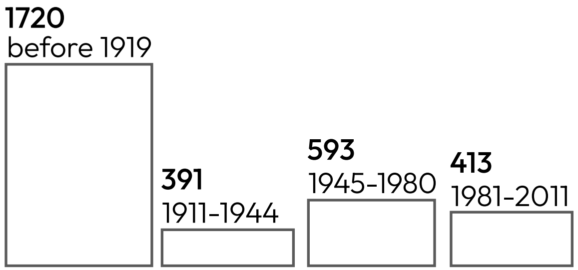
4,0%
Share of Vienna's total population

0,9%
Vienna's city area



15th district		Vienna
10%	Green area	50%
56%	Built area	36%
35%	Circulation area	14%





Buildings by construction period

31 m²
Living area/person; Vienna: 35 m²

Figure 63: The 15th district in numbers (own representation based on MA 23 data [Landesstatistik Wien (MA23), 2022])

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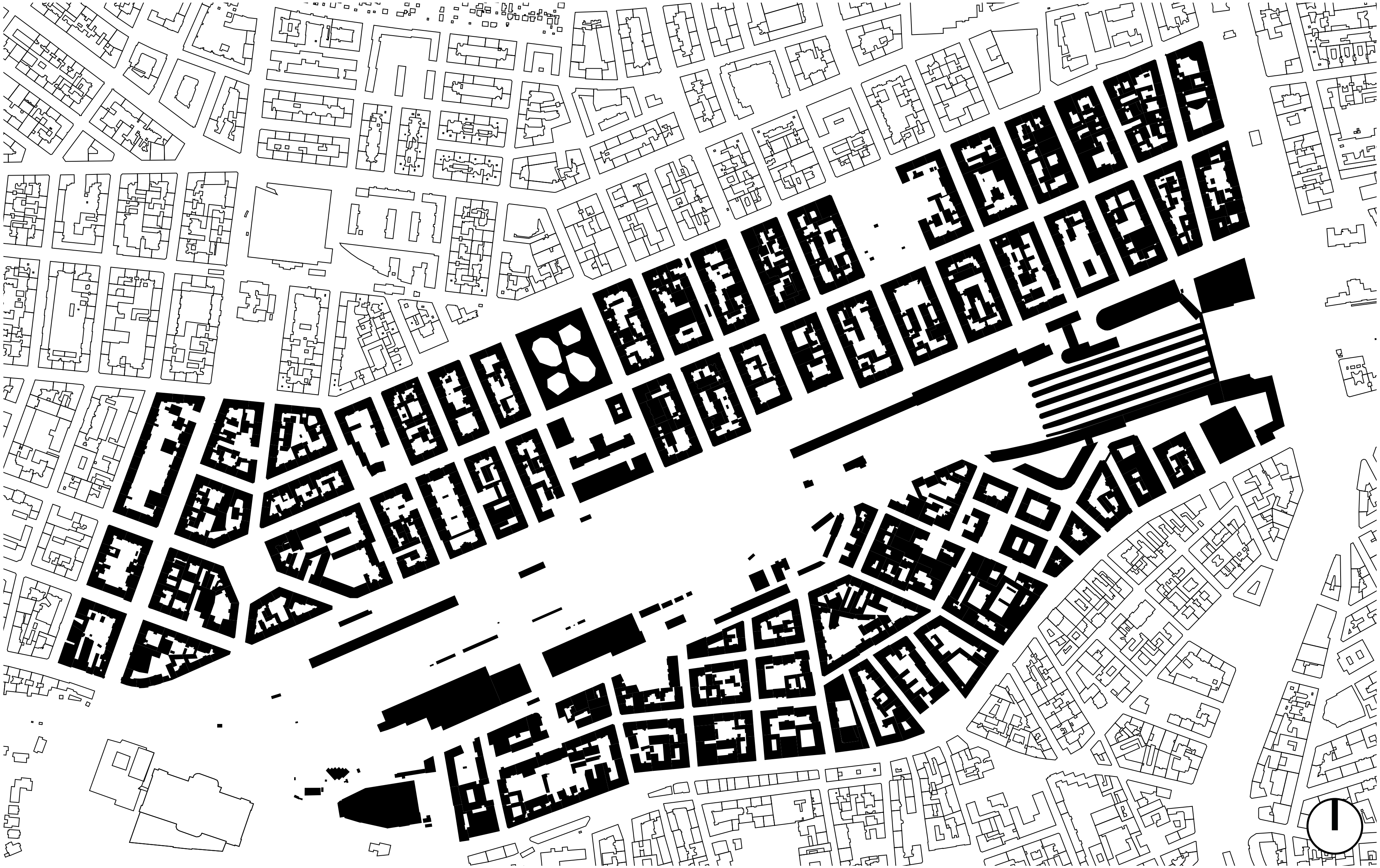

Figure 64: Case Study Area, Scale 1:8000

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Figure 65: Westbahnhof

Figure 66: Westbahn and Zwöfergasse

Figure 67: Märzstraße

Figure 68: Goldschlagstraße

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4.2. Area Analysis

4.2.1. Location Context and Characteristics

Mitte 15 is primarily situated in the 15th District of Vienna, extending from Märzstraße in the north to Mariahilfer Straße and Linzer Straße in the south, bounded by Neubaugürtel in the east and Sturzgasse in the west. The area also touches portions of the 6th, 7th, and 14th districts.

The 15th district of Vienna, known as Rudolfsheim-Fünfhaus, is a densely populated yet compact area covering 392 hectares, which accounts for only 0.9% of the city's total land area.

Figure 69: Schmelzbrücke

In 2021, the district was home to 76,137 people, or 4% of Vienna's population [Landesstatistik Wien (MA23), 2022], making it one of the most densely populated districts beyond the central „Gürtel" area. However, it has a low percentage of green space, with less than 10% of its total area.

Most of the district's land area is made up of buildings, predominantly residential structures built before 1919, with an average of 31 square meters of living space per person, which is below the city's average. Architecturally, the district is characterized by Gründerzeit-style buildings.

Traffic areas occupy 35% of the district, with the Westbahn railway line taking up a significant chunk. Regarding free space, excluding built-up areas, 78% is occupied by traffic, and only 19% remains as green space. The largest green area is the Auer-Welsbach-Park, which is somewhat challenging to access for the district's residents due to its peripheral location.

The district's population is diverse, with a high percentage (52%) of foreign-born residents, primarily from Serbia, Poland, Turkey, and Romania. In comparison, Vienna has, on average, 31% foreign-born residents.

Overall, the 15th district exemplifies the challenges and potentials of dense urban living, particularly in increasing focus on social equality and environmental sustainability.

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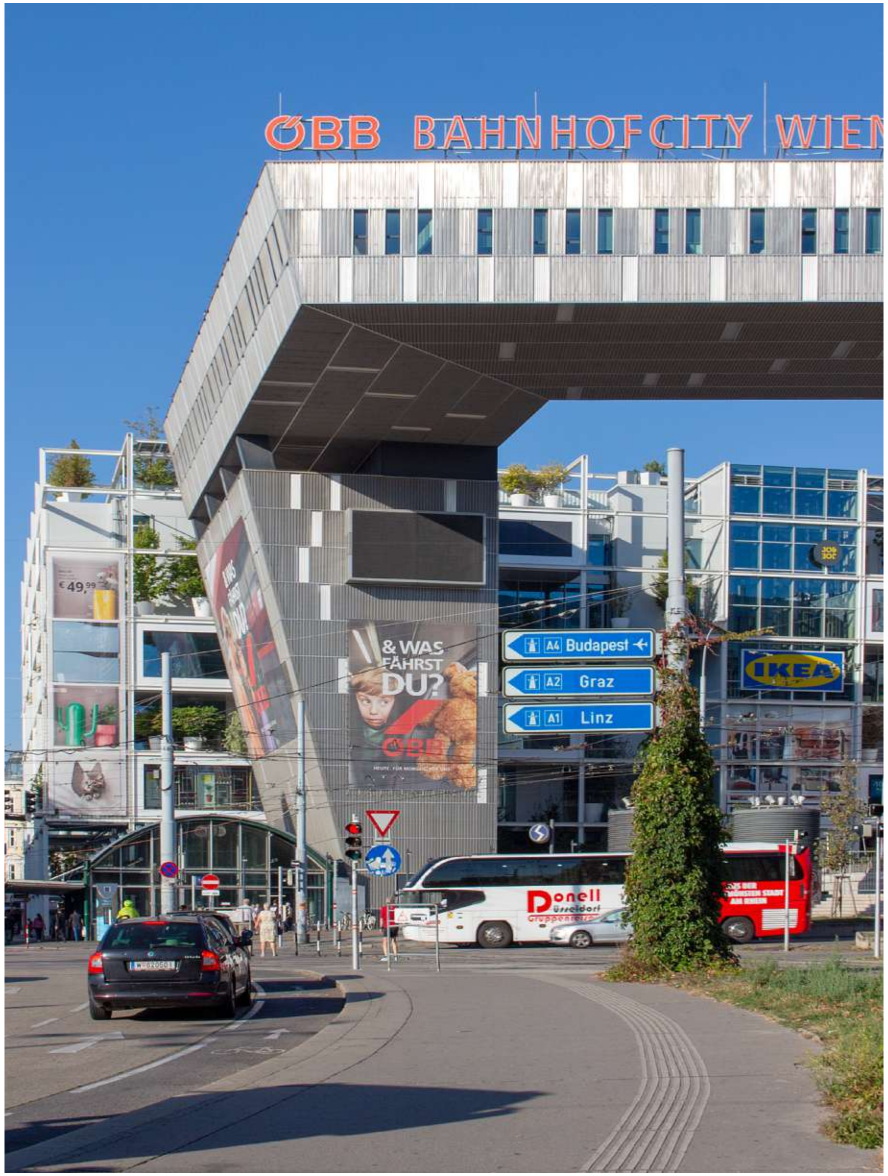

Figure 70: Bahnhofcity Wien

Figure 71: Tram Station Westbahnhof

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4.2.2. Transportation flows

The Westbahnhof area in Vienna has historical roots that go back to the 19th century, serving as a part of the city's railway infrastructure. Designed by the architect Moritz Löhr, who also played a role in constructing Vienna's Ringstraße, the Westbahnhof initially served as a link towards Western Europe. However, since the development of the Hauptbahnhof, much of the Westbahnhof area has become underutilized, although it continues to serve as an essential hub linking regional and international trains with the city's U-Bahn lines, trams, and buses.

From the start, the Westbahn railway has acted as a physical and social barrier, effectively splitting the 15th district into two parts: Rudolfsheim and Fünfhaus. The divide has historically led to unequal development and a disconnect between the two areas. Today, only two main connectors, the Schmelzbrücke and Rustensteg, exist to help residents traverse this barrier. These limited points of passage significantly impact the district's mobility infrastructure, affecting not just the flow of public transport but also hindering the movement of pedestrians and cyclists.

The Rustensteg, a pedestrian-only bridge, presents particular challenges for residents. Due to its steep, three-armed staircase and poorly-lit tunnel, the bridge is considered difficult for older people, those with mobility impairments, and families with strollers. It is considered to be a place that can feel unsafe, especially for women. Despite efforts to make the Rustensteg more accessible and safer, like adding yellow

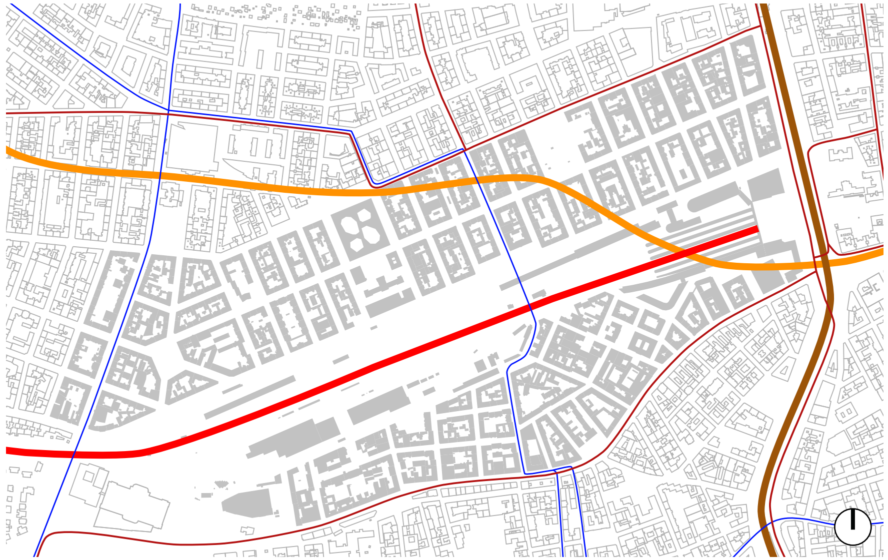

Figure 72: Public Transport Map, 1:17500 Train Bus Tram Subway

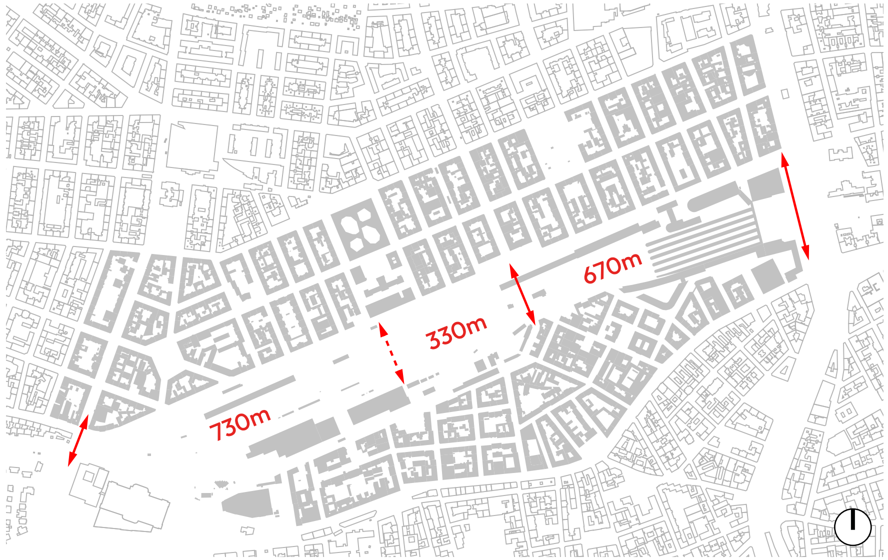

Figure 73: Westbahn as a barrier, 1:17500 Car & Pedestrian Pedestrian

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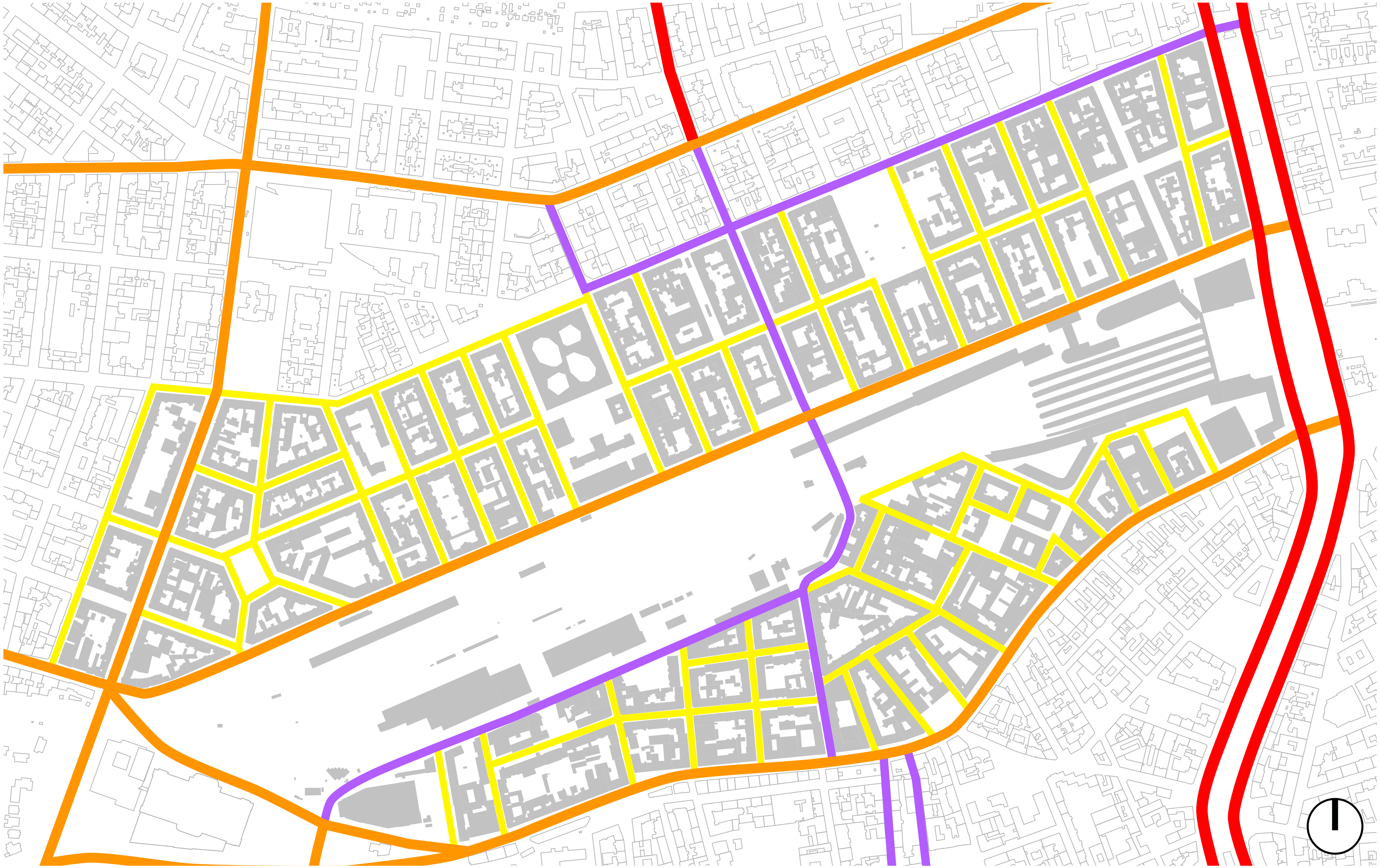

Figure 74: Street Categories Map, Scale 1:8000

Primary streets | Secondary streets | Tertiary streets | Residential street

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Figure 75: Avedikstraße/Entrance Rustensteg

Figure 76: Entrance Rustensteg

ramps and better lighting, the bridge still falls short of being a barrier-free passage. These aspects further contribute to making the Westbahn an obstacle in the 15th district.

Two U-Bahn lines, U3 and U6, intersect at Westbahnhof. The U3 line provides quick access to the city centre and Wien Mitte, while the U6 offers north-south connectivity. Complementing these is a network of trams and buses. However, despite being well-served by public transport, last-mile connectivity remains problematic. Even as Vienna aims to become more pedestrian-friendly and cycling-oriented, the 15th district lags in implementing safe and efficient bike lanes and pedestrian paths. Important streets like Felberstraße, Mariahilfer Straße, and Schweglerstraße are still primarily car-dominated.

Recognizing the need for a shift in urban mobility, Vienna targets an ambitious modal split by 2030: 85% of all travel will be via public or active transport, leaving only 15% for individual motorized travel [City of Vienna (MA20), 2022]. Realizing this goal will require significant changes in the 15th district's transportation infrastructure and planning, considering its role as a key transit hub and the existing challenges, particularly those posed by the Westbahn railway.

4.2.3. Green Area Analysis

The city's official „Green and Open Space" concept in STEP 2025 sets green space standards based on population density, prescribing minimum sizes in square meters per resident, maximum distances, and a minimum width of 25 meters [City of Vienna (MA18), 2014]. According to this framework, Ru-

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Figure 77: Green Areas Map, Scale 1:8000

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Figure 78: Westbahn and Rustensteg

Figure 79: Westbahnpark initative

dolfsheim-Fünfhaus falls short. Based on data from the tree registry, if each resident were to stand under a tree in the district, 15 people would be crowding under a single tree [City of Vienna (MA42), 2020]. This number jumps to 31 people if only street trees are considered.

Several parks, such as Reithoffer Park, Vogelweid Park, März Park, and Auer-Welsbach Park, serve as key green areas, but the district is still vastly underserved. Their impact is lessened by the limited reach of their 250-meter radius. Currently, there are only about 3 square meters of public green space per person, whereas the City of Vienna targets 8 square meters per resident.

The district mainly relies on two types of green spaces as outlined in the city's planning concepts: expansive parks and micro open spaces, typically residual spaces and courtyards. Linear connections between these areas are envisioned to create a green network facilitating gentle forms of mobility. However, the existing green network plan is not fixed and serves as a suggestion, indicating key axes where climate adaptation is particularly relevant.

An initiative known as Westbahnpark (WESTBAHNPARK.JETZT, n.d.) advocates creating a 1.2 km long park along the railway tracks behind the Westbahnhof. They argue that the 15th district is densely built, with a floor area ratio of 2.93, and experiences temperatures up to 8°C higher than surrounding areas. The Westbahnpark would be essential to offset urban heat islands and is part of the fresh air corridor from the Vienna Woods through the Wiental Valley into the city. Also,

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the railway lines currently separate the northern and southern parts of the district. The Westbahnpark aims to eliminate this barrier and create more walkable and bike-friendly connections.

4.3. Implementation of the VR Tool

4.3.1. Objectives and Scope

Implementing the VR Tool within the Mitte 15 case study aims to test if VR offers a more comprehensive, efficient or user-engaged approach to urban analysis than traditional methods. Following Michael Batty's definition of urban analysis as a proactive means to understand solutions embedded within city structures and foresee potential problems [Batty, 2013], this tool offers a complementary approach to urban analysis processes.

While in a traditional project, specific project requirements dictate the kinds of urban analysis needed, the master thesis has no such predefined projects. Therefore, the tool focuses on general urban analysis types with a wider application that could serve various future projects in the area.

Given the active participation of the Mitte 15 community and their expressed concerns, the VR tool will concentrate on a general function overview of the area and the following three topics:

Green Areas and Public Spaces: Given the community's concerns about the limited green and public spaces in the district, existing initiatives like Westbahnpark, and the city's climate adaptation goals, the VR tool will visualize existing green and public spaces.

Transport and Mobility: Addressing another principal concern, mobility and transportation, the tool will offer a view of various transportation modes. It will display information on individual mobility options, types of streets, pedestrian pathways, bike lanes, and public transport services.

Changes and Trends: Overview of different types of statistical data such as population density or mobility metrics. This feature aims to show how VR could display insights into data changing over time, helping to understand the status quo, react to current trends, and anticipate future challenges or opportunities.

4.3.2. Technical Implementation

The technical implementation of the tool follows the methodology described in the previous chapter, applied to the „Mitte 15“ area. It uses FME as a data transformation tool, Unity as a game engine for building the VR environment and the Oculus Quest 3 and the Oculus App for testing the experience.

Most of the data used for the case study was retrieved for free from the Open Government Austria Website and OpenStreetMaps. Specifically, the following datasets were used:

Geometry: Buildings LOD2.1 „Generalisiertes Dachmodell (LOD2.1) Wien“ (OGD), Terrain mesh „Geländemodell Dreie-

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cksvermaschung Wien“ (OGD), Streets categories „Highways“ (OSM), Public transport „Railway“ and „Public Transport“ (OSM)

Textures: Satellite picture „Orthofoto 2022 Wien“ (OGD), Ground Map „Mehrzweckkarte Vektordaten Wien“ (OGD)

Urban Data: Amenities (OSM), Building Functions (OSM building, office, tourism, shop, craft), Structure Plan „Stadtstrukturplan Wien“ (OGD), Playgrounds „Spielplätze Standorte Wien“ (OGD), Museums „Museen und Sammlungen Standorte Wien“ (OGD), Parks „Parkanlagen Standorte Wien“ (OGD), Trees „Baumkataster bzw. Bäume Standorte Wien“(OGD)

Administrative Boundaries: Census district boundaries „Zählbezirksgrenzen Wien“ (OGD), District boundaries „Bezirksgrenzen Wien“ (OGD)

Laser scans: „Kappazunder 2020“(OGD)

Statistical data: Population forecast „Bevölkerungsprognose 2018 bis 2028“ (OGD), Modal split „Modalsplit Wien“ (OGD), Choice of transport „Verkehrsmittelwahl Wien“ (OGD), Climate data „Klimadaten Wien“(OGD)

The collected data was imported into FME. As the data is in different formats, for example, in a shapefile format, XML, GeoJSON CityGML or CSV, the corresponding FME Readers were used. The imported data was manually checked, and unnecessary attributes or geometry were filtered to remove irrelevant or redundant data, focusing only on the relevant information for the urban analysis in the area.

All data was transformed into one coordinate system using the „Reprojector“ transformer in FME, spatially overlayed, and the attributes of overlapping elements merged. Manual checks verified that datasets from different sources were correct. Any discrepancies were resolved by revisiting the original data source for clarification.

The processed data is converted into CSV, FBX and JPEG files. It is possible to reconnect geometry with other spatial data by using unique IDs in the naming of geometry and the data in the CSV file. Using the FME Writer components, the data is saved directly into the Unity Asset Folder, the folder in the Unity project structure where imported and created assets such as textures, models, and scripts are stored and managed for use in a Unity project.

A slightly modified workflow was used for the laser scans („Kappazunder“) of the city. These were not directly transferred from FME to Unity but, by using Cesium, transformed into tiles and imported with the Cesium for Unity plugin. Cesium is a platform for tiling, visualising, and analysing 3D geospatial data, while Cesium ion is an open platform for tiling and hosting. Furthermore, Cesium ion allows access to 3D content, including Google Maps data. This modified workflow allowed the laser scans to be imported into Unity and visualised in VR without manually changing and optimising them.

The final scene was assembled in Unity. The FBX files are imported into the scene as Game Objects with unique IDs. A C# script reads CSV data, identifying Game Objects by their unique IDs. It then adds a Component to each object containing

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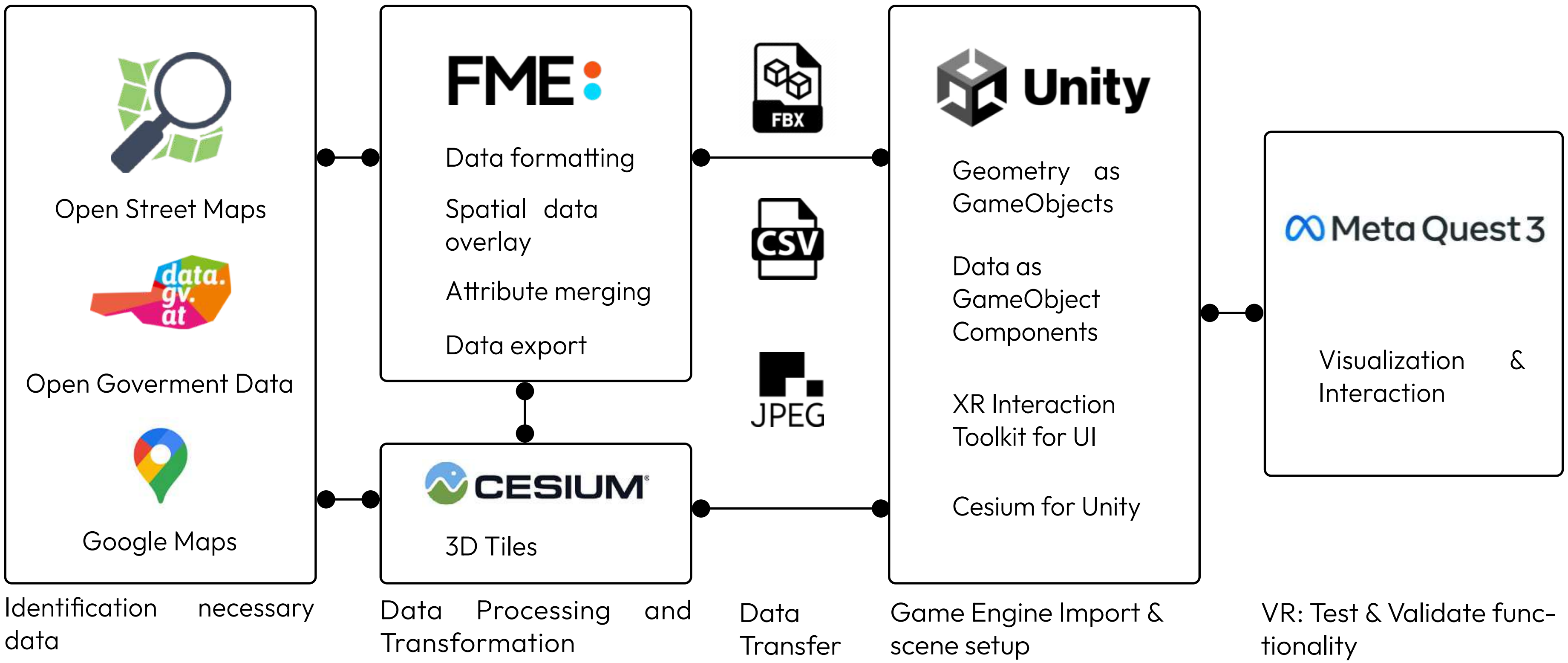

Figure 80: Workflow: from data to Virtual Environment

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Figure 81: The Meta Quest 3 headset [Meta Quest 3: Immersives all-in-one VR-Headset | Meta Store, n.d.]

relevant data. A second script links urban information to its visual or geometric counterpart. As users choose a data layer, the script updates GameObjects to display the relevant visuals for that layer.

For the user interface, Unity's default components, like toggles and buttons, were used. They were linked for direct interaction with the data layers. The XR Interaction Toolkit package provided the mechanics for VR actions such as moving and resizing, offering a way to explore the virtual model.

For testing the functionality of the tool, the Meta Quest 3, a popular headset, was chosen. The Quest 3 is developed by Reality Labs. The Quest 3 can be used as a standalone headset with an internal, Android-based operating system or paired with Oculus Rift-compatible VR software on a desktop computer. It includes Oculus Touch controllers or can be operated using hand tracking. The Quest 3 can be directly used inside of Unity when paired with the computer using the Oculus App, or Unity generates an Android APK file that can be installed directly on the headset.

4.3.3. Data Visualization and Interaction

The experience starts at a 1:2000 scale, allowing for an initial overview of 2 km long „Mitte15“ area. The user can choose to reposition, rotate, and rescale the model to experience different scales of the urban model.

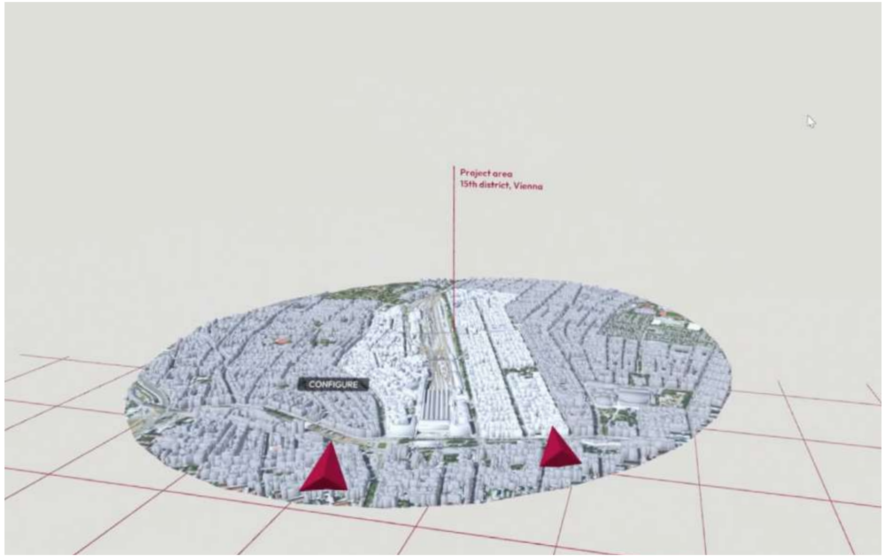

Figure 82: Initial view of the analysis area, first person perspective

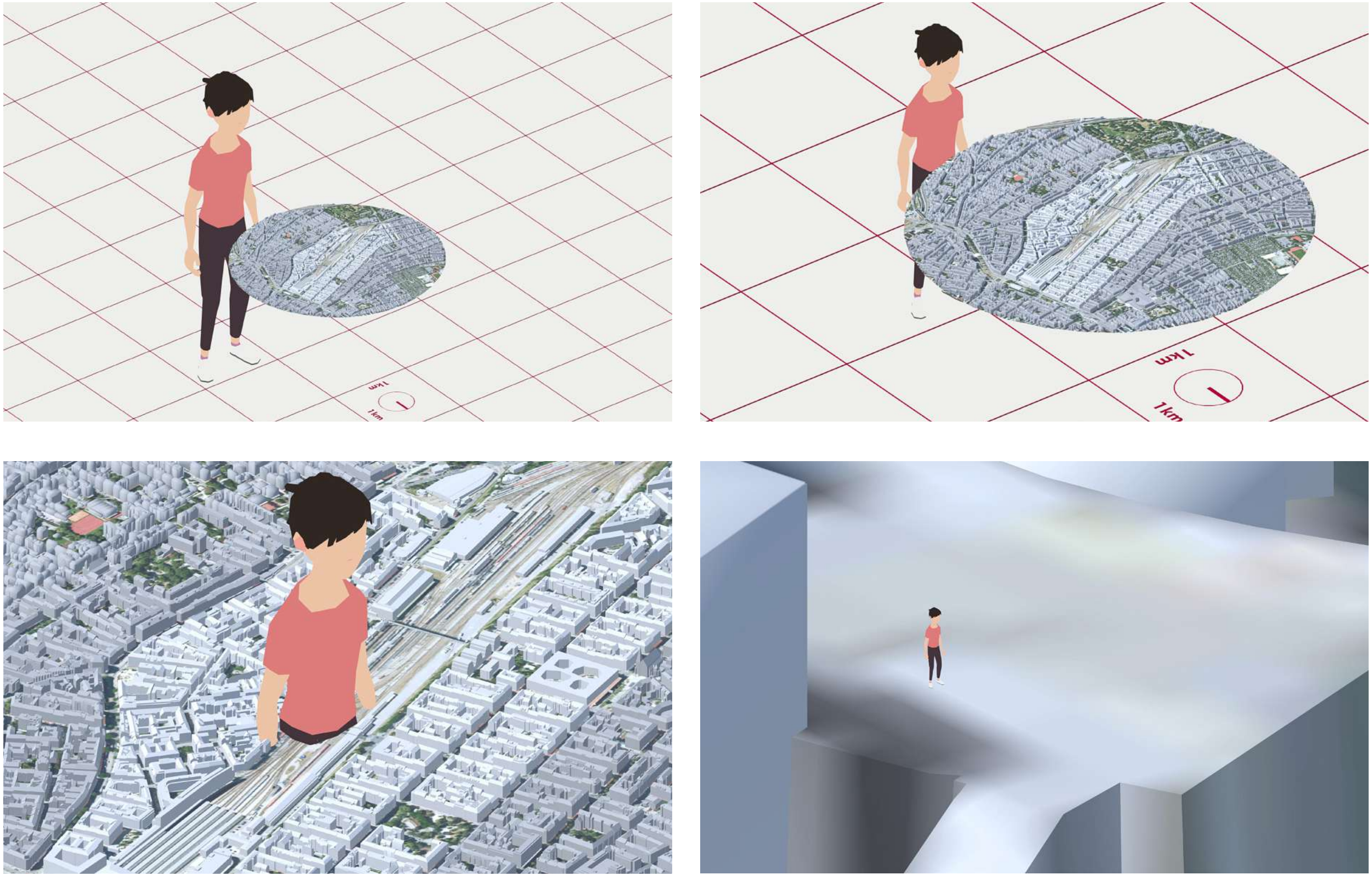

Figure 83: Experience of different scales of the urban model: 1:2000, 1:1000, 1:500, 1:1

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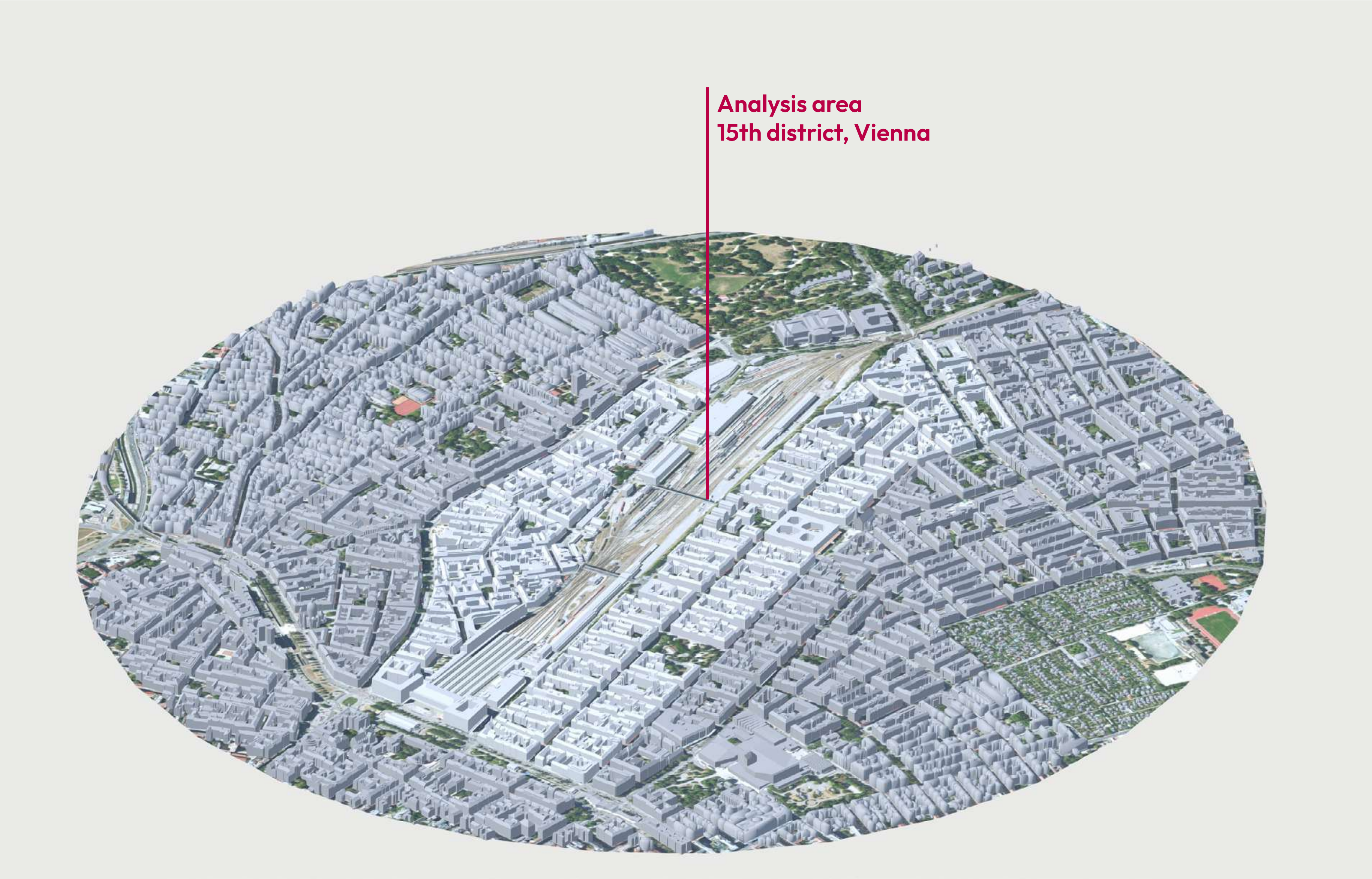

Figure 84: Initial view of the analysis area in white

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The selection of a data layer will toggle the visualization. In the Settings Tab, different terrain maps are available: satellite pictures, Google Maps, ground maps, or blank ones. Depending on the data visualized, the user can switch to the most suitable map.

The Google Photorealistic Maps View provides a lot of visual detail of the area in contrast with the more abstract geometry the rest of the views display. However, this view is only meaningful when used on its own or when visualizing data that is not building-based, such as showing a function in a building by colouring its geometry, as the building-based data would not be visible.

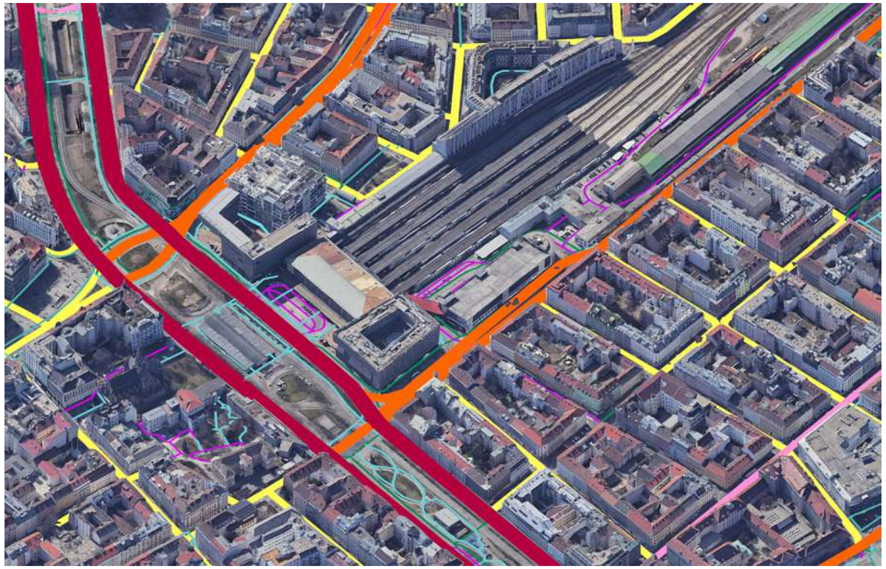

Figure 86: Urban 3D Model, Google Maps View (Cesium) and Street Categories layer on

Figure 85: Urban 3D Model, satellite picture with no data overlay

Figure 87: Urban 3D Model, ground map and Street Categories View on

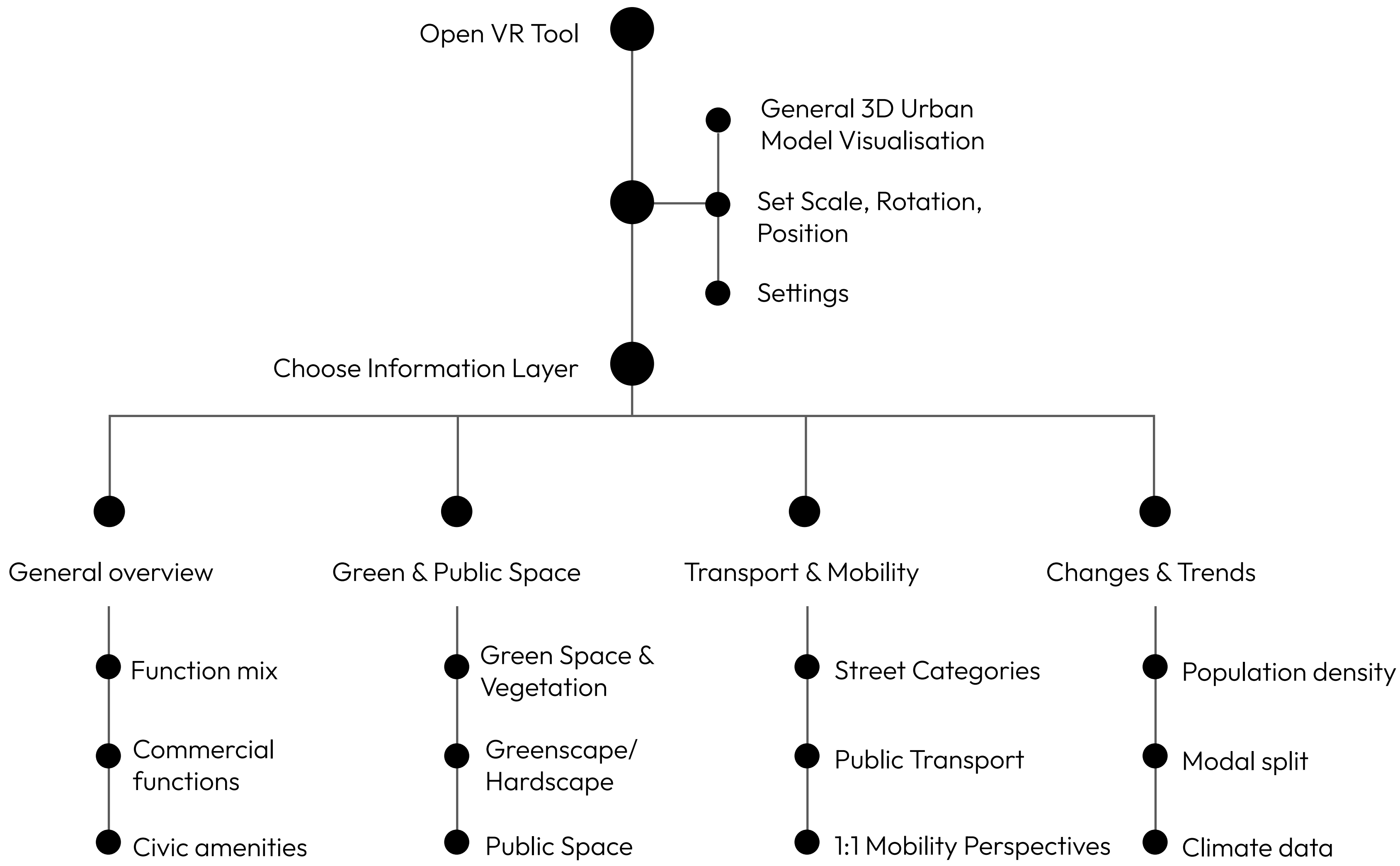

Figure 88: Schematic structure of the options in the tool

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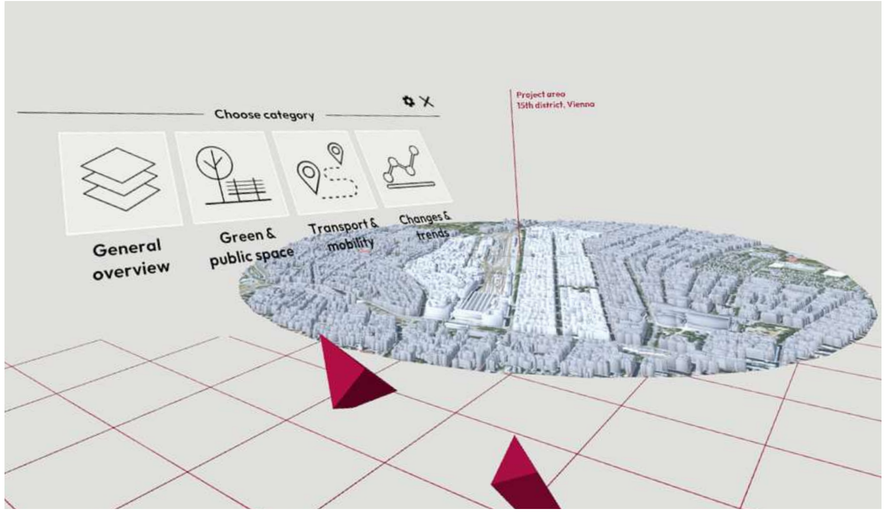

Figure 89: Hand menu in the tool, no data overlay, first person perspective

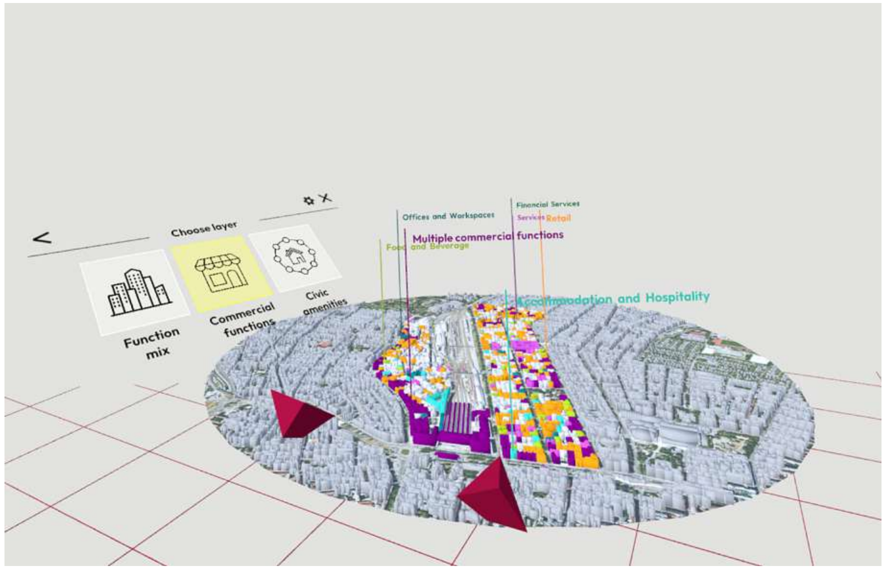

Figure 90: Commercial functions in the analysis area, first person perspective

The hand menu is on the user's left hand and provides options for visualising different data layers. It scales and moves with the user to allow for interaction in each moment. One of four categories of layers can be chosen: General Overview, Green and Public Space, Transport and Mobility and Changes and Trends.

General Overview is meant to offer a first understanding of the main functions of the area and contains three toggles, showing the Function Mix (Residential focus, Mixed focus or Industrial focus of the buildings), the Commercial uses (e.g. Retail, Offices, Accommodation, Financial Services or Multiple commercial uses), and the Civic Amenities.

Green and Public Space focuses on the Green Spaces and Vegetation in the area, on outdoor Public Spaces available and shows the ratio between Greenscape and Hardscape.

Transport and Mobility display different Street Categories, such as Primary or Secondary Streets, Residential, Pedestrian or Service streets in the area. Public transport shows the different available transportation routes. 1:1 Perspectives are bringing the user in a pedestrian role or in a moving car to experience the scale of the space.

Changes and Trends switches to another scale, showing comparisons of historical data and predictions between districts and census districts in Vienna. The scale change was due to the lack of data availability at a smaller scale, such as the analysis area.

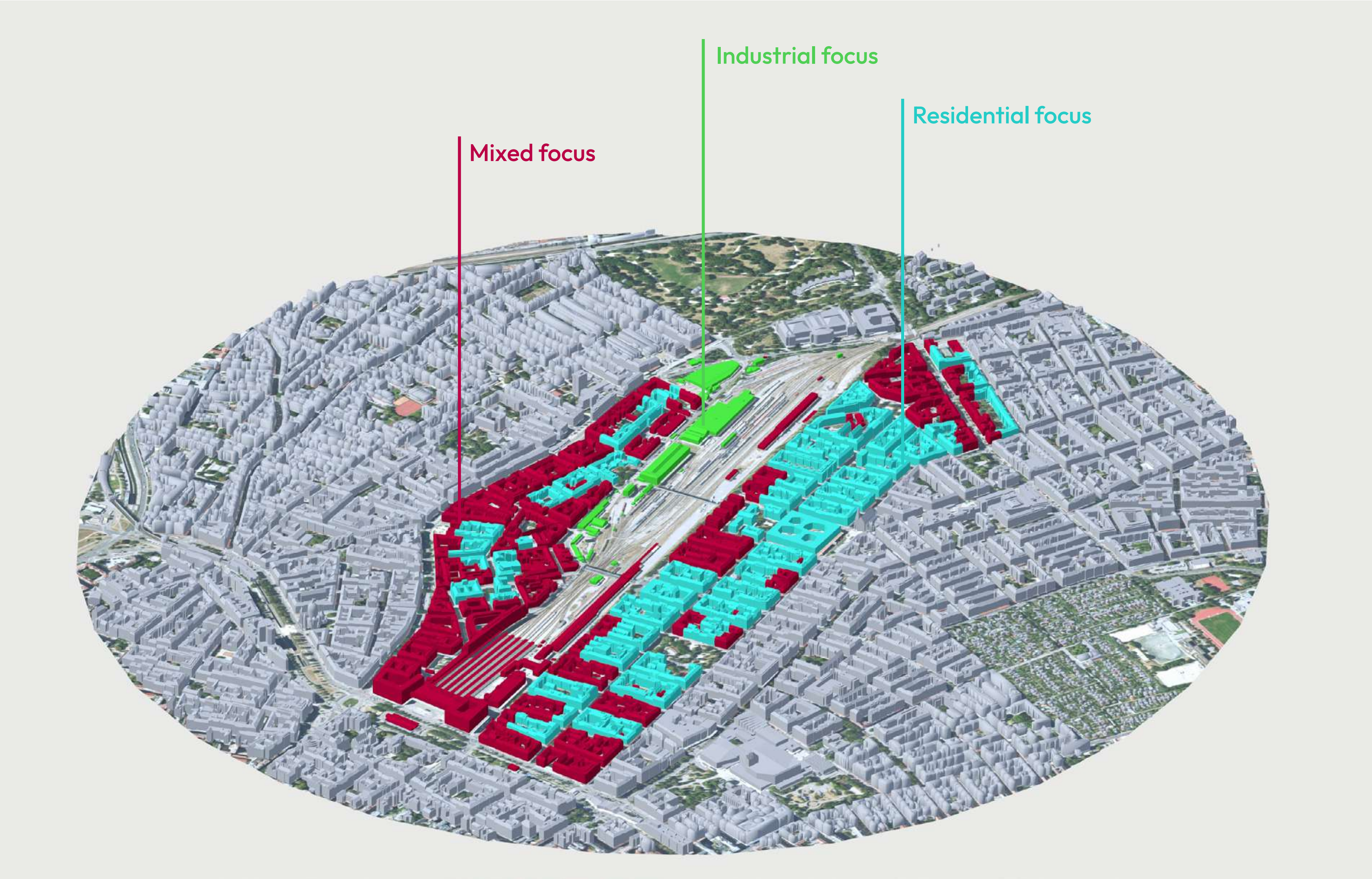

Figure 91: General Overview - Function mix view of the analysis area

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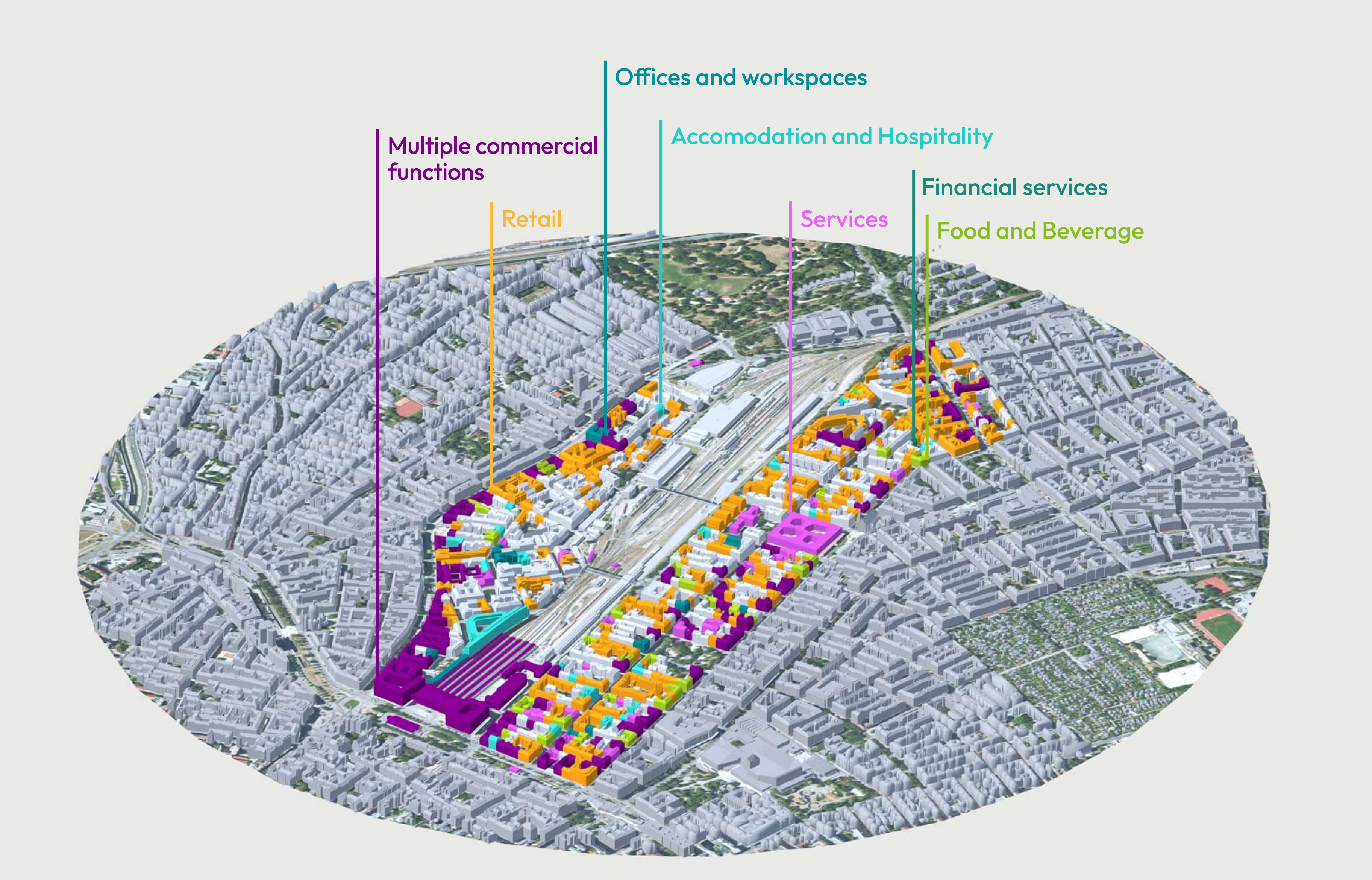

Figure 92: General Overview - Commercial functions view of the analysis area

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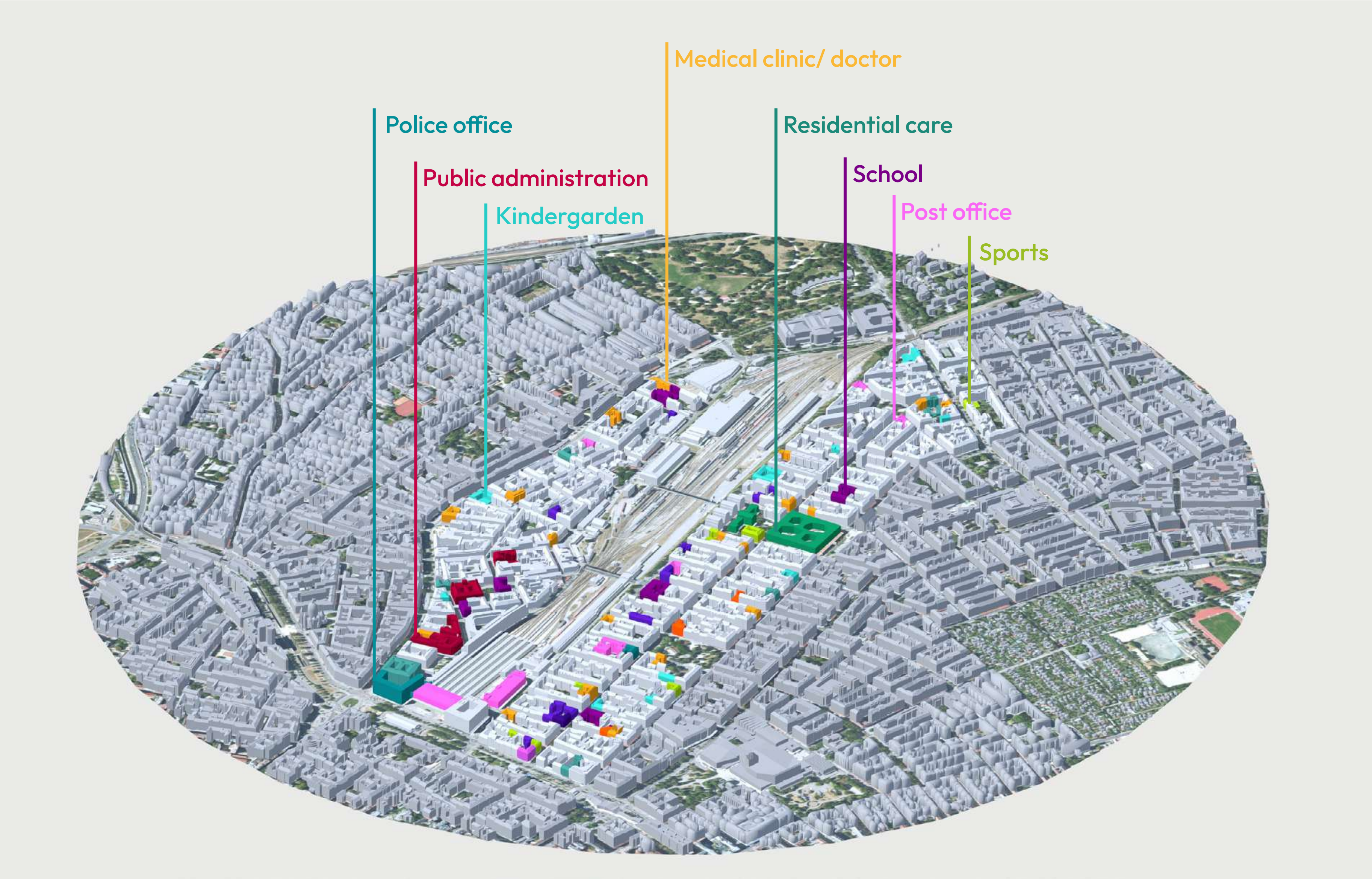

Figure 93: General Overview - Civic amenities view of the analysis area

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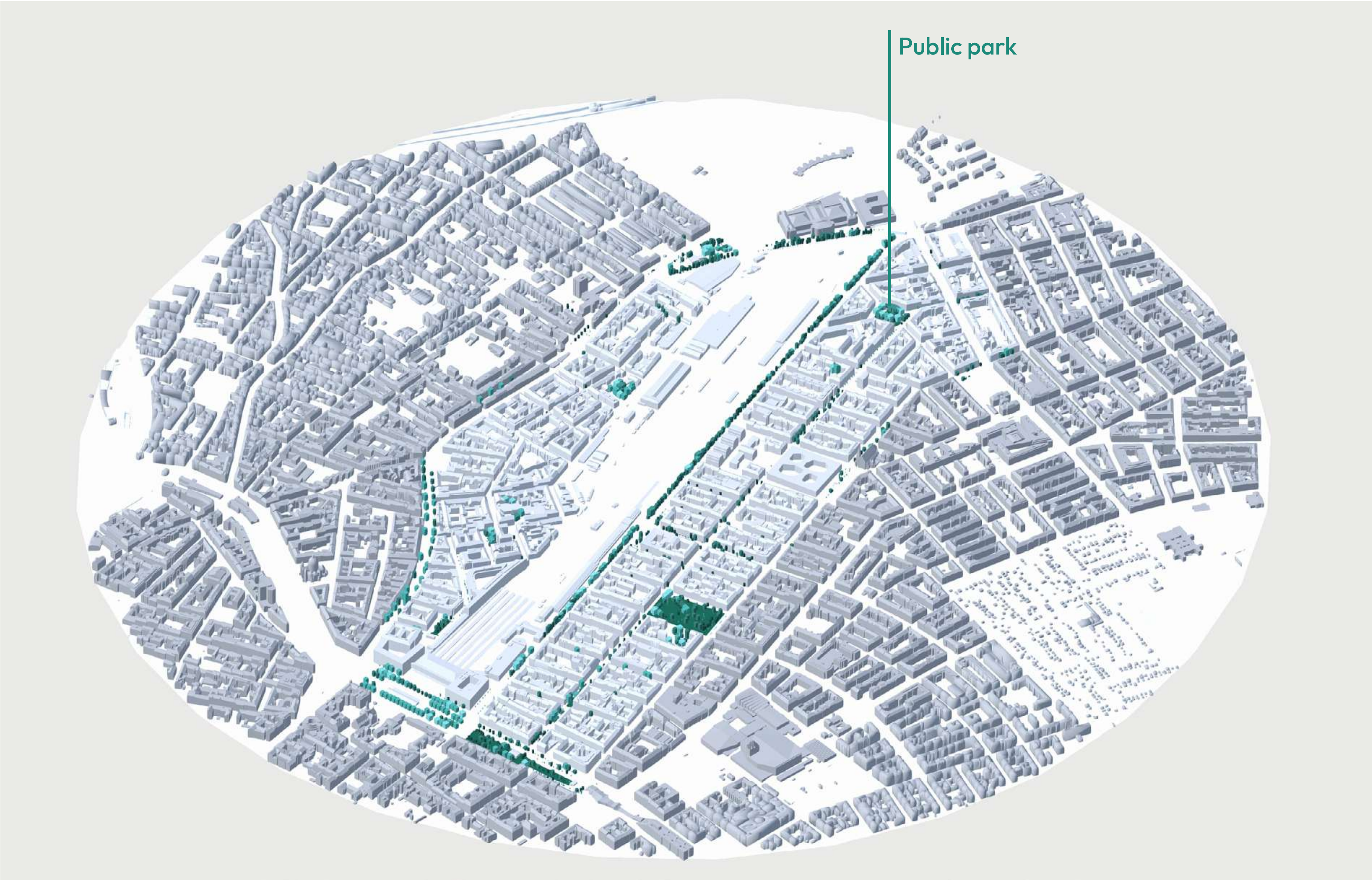

Figure 94:Green and Public Space - Green Space and Vegetation View

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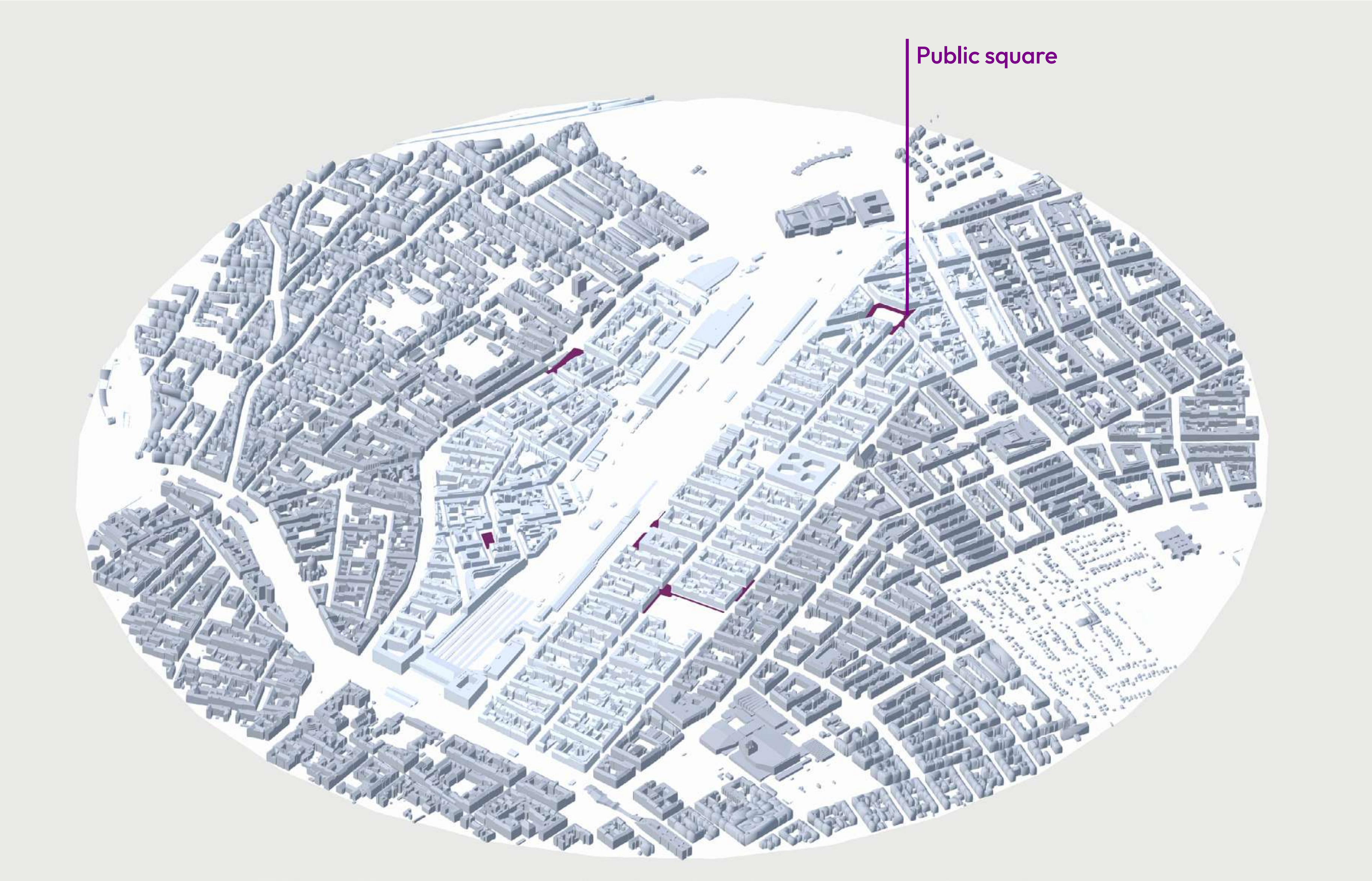

Figure 95: Green and Public Space - Public squares in the analysis area

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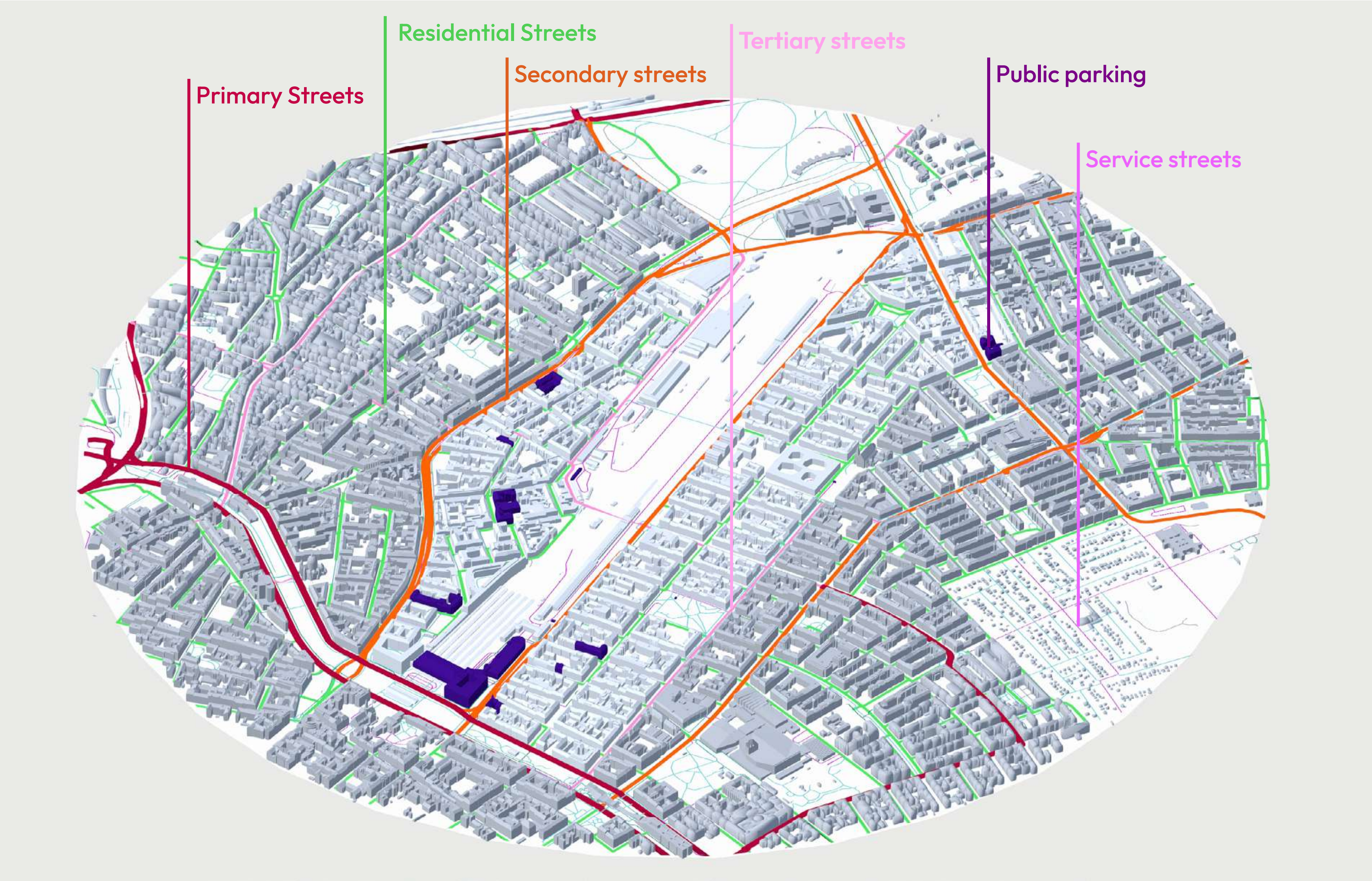

Figure 96: Transport and Mobility - Street Categories View of the analysis area

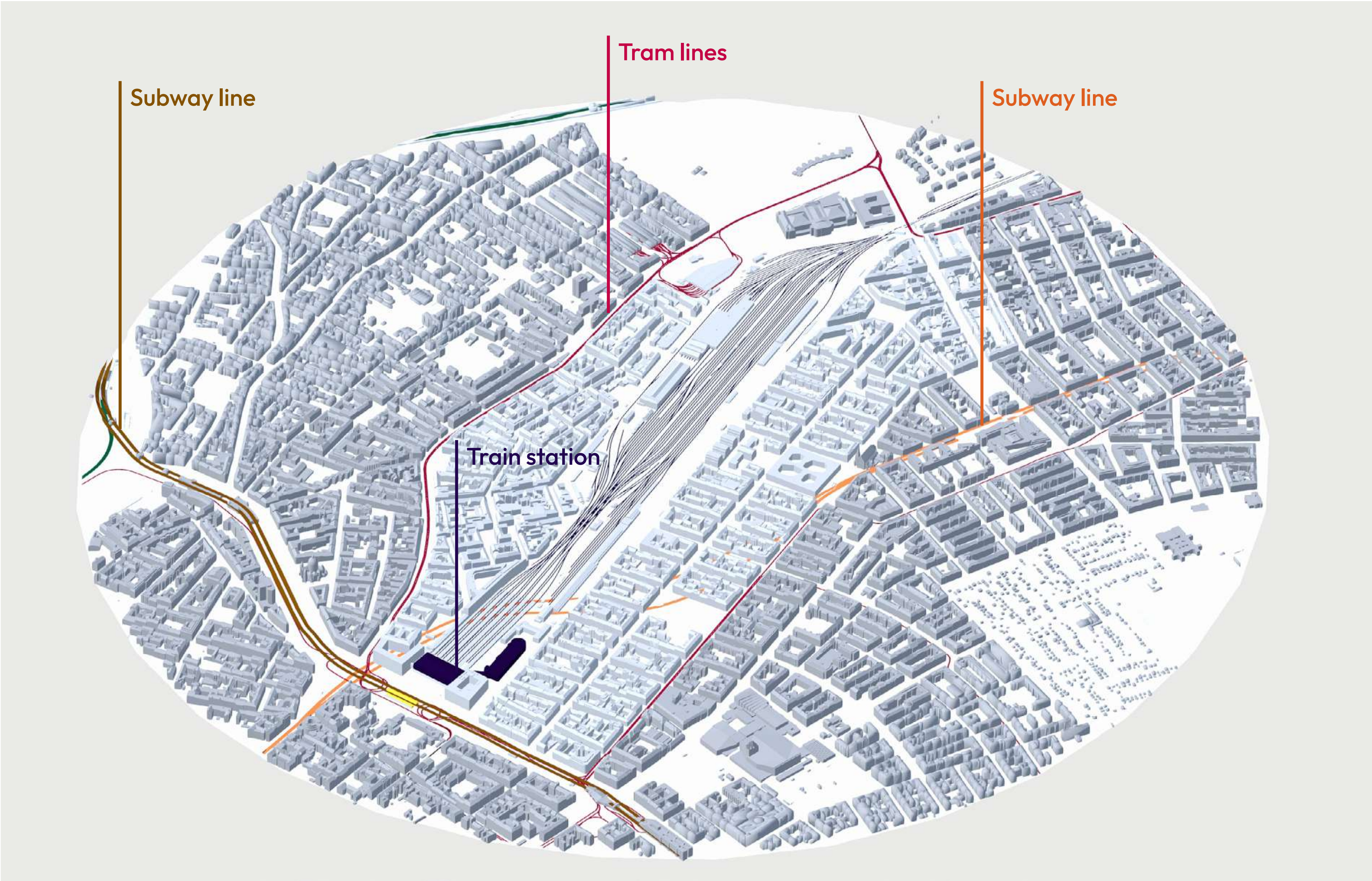

Figure 97: Transport and Mobility - Public Transport View of the analysis area

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Figure 98: 1:1 Perspectives: Animation of a car in traffic on the Mariahilferstraße

Figure 99: 1:1 scale view of the Felberstraße/Schweglerstraße Intersection

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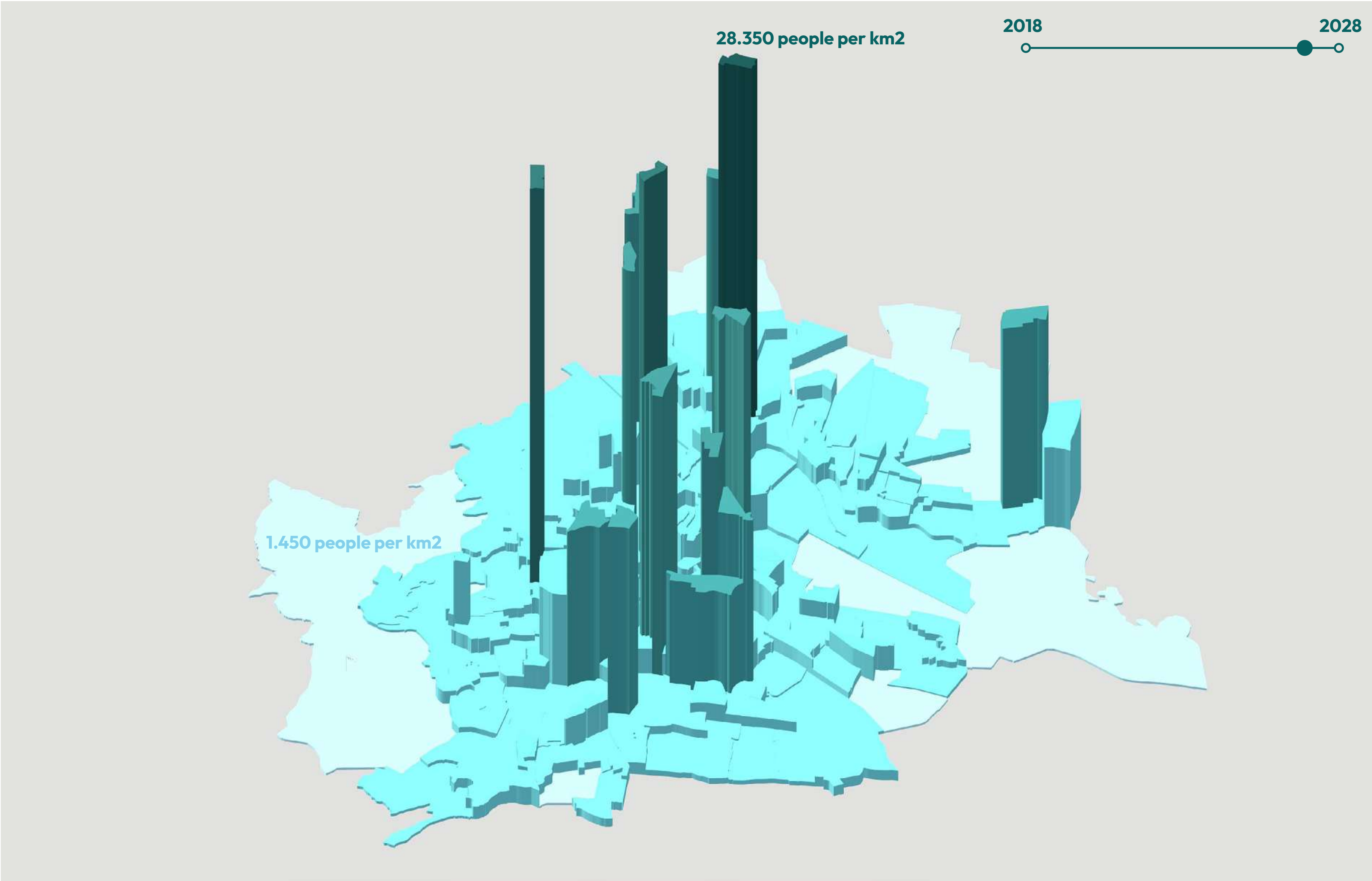

Figure 100: Changes and Trends view of the larger analysis area; population density prediction in 2027

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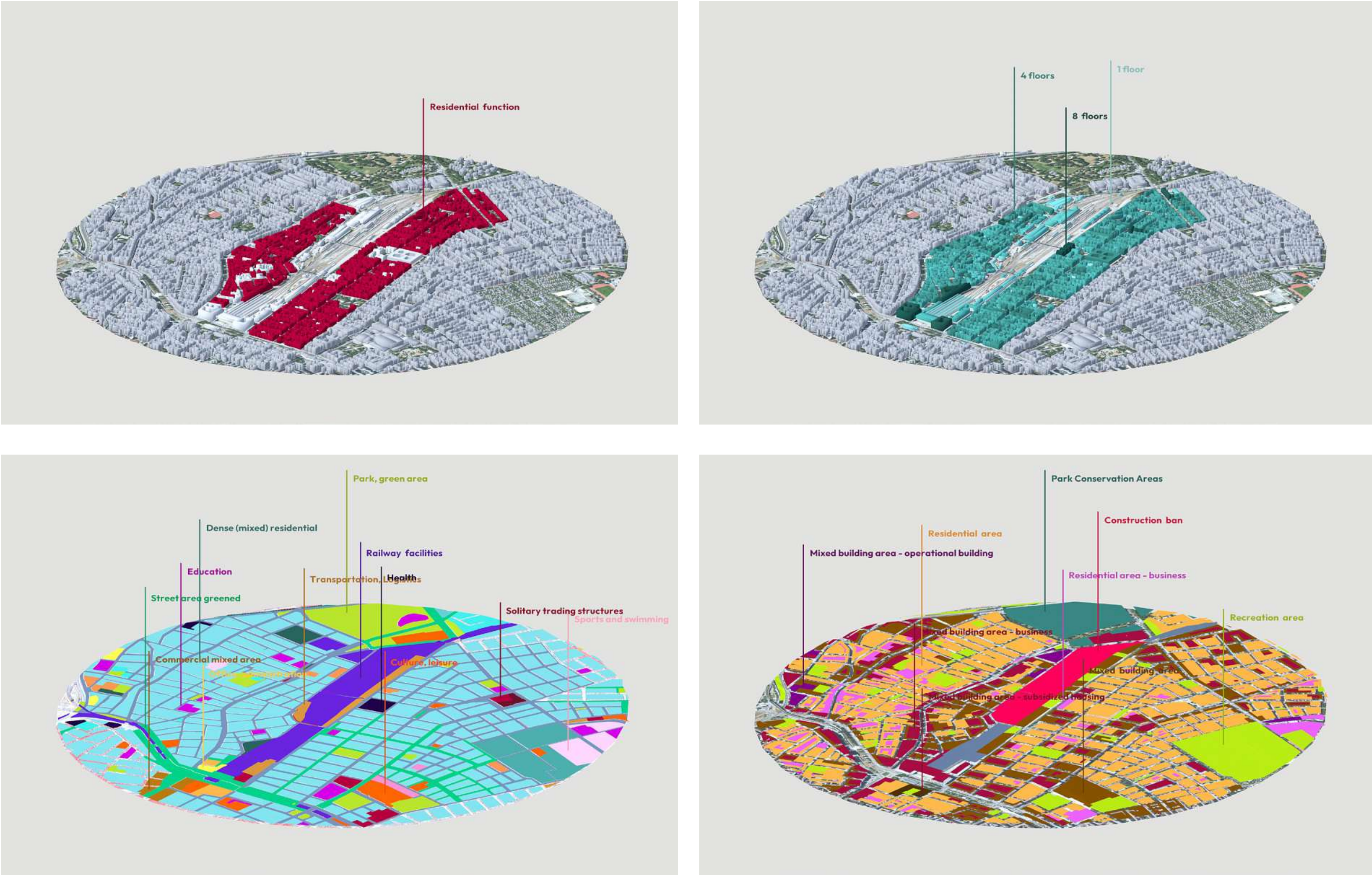

Figure 101: Other tested views in the tool: Residential functions, Land Use Mapping, Number of Floors, Land Use Plan

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4.4. User Feedback and Evaluation

The final stage of the thesis involved gathering user feedback to evaluate the practicality and effectiveness of the tool for understanding urban analysis. Six participants from the architectural field, including two experienced architects, all with little exposure to VR, tested the tool.

During the initial interaction, all users required guidance on operating the VR headset and controllers and navigating the tool‘s features. This highlighted the learning curve associated with new technology, especially for those unfamiliar with VR. The tool does not have a tutorial on how to use it, so verbal instructions on what is possible and how to interact was necessary. However, all users could independently navigate and utilize the tool within a few minutes. Each of them used the tool between 8 and 20 minutes.

The initial reactions were overwhelmingly positive, but these can also be attributed to trying a new experience. The tool‘s ability to scale the urban model was particularly appreciated; it is similar to interacting with a physical model but has more flexibility. The 1:1 scale perspective, both in pedestrian and animated car modes, was received positively, as it offers a realistic scale experience of the analysed area.

Experienced architects commented on the absence of technical CAD plans, which are important in their decision-making processes. They also noted the tool‘s need for integration into broader project workflows, such as sketching or scenario testing. The potential for collaborative use in a shared virtual space, which is currently not available, was discussed. This feature would not only allow similar interaction with colleagues as in a traditional physical discussion but also allow an improved online conversation on urban analysis by bridging the physical distance.

While the users acknowledged the tool‘s potential in project work, they expressed concerns about the practicality of its regular use. The necessity for project-specific modifications using different software, such as data processing tools or game engines, which many users need to familiarize themselves with, was seen as a significant barrier. The limited access to VR headsets was another challenge. However, they pointed out that if the know-how and hardware are available, VR supports urban data understanding and should included in the architectural workflow.

Users responded positively to the tool‘s ability to visualize and spatially understand urban data through coloured 3D geometry. Positive remarks were also made about the legend‘s display, pointing out that it facilitates faster comprehension because the legend is immediately related to the geometry. However, the effectiveness of the legend was noted to decrease at scales smaller than 1:500, where it became disproportionately large.

The „Changes and Trends“ view, which displays statistical data of the city on a larger scale, was regarded as useful but did not require VR technology, whereas the urban model view was more favourably received.

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In summary, users agreed that the tool effectively improves understanding of urban spaces through immersive visualization. However, its current technical requirements limit a broader professional use. They suggested future developments focusing on technical integration and collaborative features to increase its practical application in urban analysis.

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Conclusion & Outlook

The primary objective of this thesis was to explore how Virtual Reality can improve the understanding of urban contexts and data during the initial stages of architectural design, using Vienna's 15th district as a case study. It aimed to identify both the potential and limitations of VR in urban analysis. All insights are a work in progress that should be further researched, applied and tested.

Achievements and Limitations

Improved Understanding of Scale and Spatial Data: VR could provide an improved understanding of urban scales and spatial data. Users benefited from the 1:1 scale experience, which is not typically attainable in conventional urban analysis, and from the ability to interact with virtual models without the time-intensive construction of physical models. Navigating through data layers and scales in VR allowed users to tailor their analysis experience.

Efficient Workflow: The digital workflow with VR proved efficient after the initial setup, indicating its suitability in fast-paced architectural environments.

Dependency on Data Availability and Technical Expertise: The effectiveness of adapting the VR tool to other projects relies on data accessibility and the user's technical knowledge of software programs. The tool is easily adaptable in areas with available data; however, in regions with limited open data, the tool's utility diminishes significantly due to manual data collection and processing demands. Technical expertise needs to be available to update the tool efficiently.

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Technical Evolution and Compatibility Issues: The rapid evolution of technology presents a challenge: constantly updating the technical workflow. Even during the thesis development, software capabilities evolved, demonstrating that an ongoing assessment of available tools and plugins is necessary.

Suitability for Quantitative Analysis: VR showed improvements at presenting quantitative urban data but not at capturing qualitative aspects of urban environments, such as the atmosphere of a place, sensory experiences like smells and sounds, and subjective personal observations. These parts of urban analysis are challenging to replicate in a virtual environment.

Lack of Broader Integration: The current VR tool does not integrate into broader architectural workflows, including technical CAD plans and enabling continuous work in VR. This limitation shows a disconnect between the insights gained from VR and the following design stages.

Applicability to Other Planning Areas

Vienna Adaptation: The tool can be adapted with minimal effort in Vienna, where data availability and granularity are comparable to the one of the case study.

Adaptation to Other Cities: The methodology established for data collection, processing, and presentation can be applied to other case studies. In other cities, reliance on OpenStreetMaps or manual data input may be necessary, which could present challenges due to data accuracy and the time-consuming process of manual data preparation.

Extensions and Improvements

Enhancing Collaborative Functions: Developing networking capabilities to allow collaborative discussions and decision-making within VR environments.

Simplifying Data Integration: Further automating data collection and processing could reduce reliance on technical expertise.

Customizable Experience: Based on user feedback, non-technical users should be able to customize the tool with minimal effort for personal preferences and needs.

Final Thoughts

In conclusion, while VR shows promising advantages in urban analysis by improving spatial data visualization and workflow efficiency, its integration into extended architectural workflows and addressing technical limitations are essential for broader adoption. The research findings and user feedback indicate that VR can be a valuable additional tool in the architectural design process, complementing but not replacing traditional urban analysis methods.

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Finally, thanks to my parents and my partner for their continuous support during my studies.

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Glossary

API	Application Programming Interface
AR	Augmented Reality
BIM	Building Information Modeling
CIM	City Information Modeling
CityGML	City Geographical Markup Language
FME	Feature Manipulation Engine
GIS	Geographic Information System
GML	Geographic Markup Language
HMD	Head Mounted Display
LOD	Level of Detail
MR	Mixed Reality
OGD	Open Goverment Data
OSM	Open Street Maps
SDK	Software Development Kit
UI	User Interface
UX	User Experience

VE	Virtual Environment
VGI	Volunteered Geographic Information
VR	Virtual Reality
XML	Extensible Markup Language
XR	Extended Reality

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