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ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION
AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

DIGITAL TWINS FOR SUSTAINABLE URBAN PLANNING: INTEGRATING BLUE-GREEN INFRASTRUCTURE IN URBAN INFORMATION MODELING FOR SMART RESILIENT CITIES

ZANNAT ARA DILSHAD SHANGI

Supervision:

PROF. DR.-ING. STEFFEN HEUSCH (THM)

Giessen, July 2024



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Dedicated to
My Beloved Parents

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All praises go to Almighty Allah for giving me the strength and patience to overcome challenges throughout this journey. I want to thank my parents ('Abbu-Mamoni') and siblings (Sharna, Shafin) for always being beside me. Without their support, I would not be where I am now.

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ABSTRACT

Cities, as centers of growth and development, face escalating environmental challenges worldwide due to population increase and rapid urbanization. Issues such as the urban heat island effect, global warming, and increased natural disasters are driving energy consumption growth and economic losses, highlighting the urgent need for effective urban planning strategies. Sustainable urban planning, particularly through the integration of Blue-Green Infrastructure (BGI), offers a promising solution to mitigate adverse environmental impacts including climate change adaptation and enhance urban resilience. With the advancement of planning technologies, this research investigates the potential of digital twin technology to enhance BGI integration facilitating data-driven decision-making and predictive modeling. Employing a mixed-method action research approach, the study focuses on problem-solving through 3D modeling and simulation techniques. A framework is proposed for incorporating BGI into Urban Information Modeling (UIM), a platform aggregating diverse urban data sources. A pilot study demonstrates the framework's application, highlighting practical challenges and opportunities in BGI integration. Additionally, a framework for integrating BGI digital twins is proposed to improve maintenance and monitoring. By bridging the gap between BGI and UIM, this study contributes to the development of smart, resilient cities that are better equipped to address environmental challenges. The findings provide valuable insights for urban planners, policymakers, and stakeholders, emphasizing the need for an interactive approach to integrate BGI into UIM. This research not only addresses immediate urban environmental concerns but also presents a strategic pathway for future urban planning endeavors, fostering sustainable development in cities.

Keywords: Digital Twins, Blue-Green Infrastructures (BGI), Urban Information Modeling (UIM), Sustainable Urban Planning, Urban Resilience, Smart Cities.

ABSTRACT IN THE AUTHOR'S MOTHER LANGUAGE [IN BENGALI]

বৃদ্ধি ও উন্নয়নের কেন্দ্র হিসাবে পরিচিত শহরগুলি, যা জনসংখ্যা বৃদ্ধি এবং দ্রুত নগরায়নের কারণে, বিশ্বব্যাপী ক্রমবর্ধমান পরিবেশগত সমস্যার মুখোমুখি। বৈশ্বিক উষ্ণতা, শহুরে তাপ দ্বীপের প্রভাব এবং বর্ধিত প্রাকৃতিক দুর্যোগের মতো সমস্যাগুলি শক্তি খরচ বৃদ্ধি এবং অর্থনৈতিক ক্ষতির দিকে পরিচালিত হচ্ছে, যা কার্যকর নগর পরিকল্পনা কৌশলগুলির জরুরি প্রয়োজনকে তুলে ধরে। টেকসই নগর পরিকল্পনা, বিশেষ করে নীল-সবুজ অবকাঠামো (বিজিআই) এর একীকরণ, জলবায়ু পরিবর্তন এবং শহুরে স্থিতিস্থাপকতা বৃদ্ধি সহ প্রতিকূল পরিবেশগত প্রভাবগুলি প্রশমিত করার জন্য একটি প্রতিশ্রুতিবদ্ধ সমাধান সরবরাহ করতে সক্ষম। পরিকল্পনা প্রযুক্তির অগ্রগতির সাথে, এই গবেষণাটি তথ্যচালিত সিদ্ধান্ত গ্রহণ এবং ভবিষ্যত সম্ভাব্য ঘটনাসমূহের প্রতিনির্মাণকে সহজতর করে বিজিআই এর অন্তর্ভুক্তিকরণ বাড়ানোর জন্য ডিজিটাল টুইন প্রযুক্তির সম্ভাবনার অনুসন্ধান করে। একটি মিশ্র-ক্রিয়াগত গবেষণা পদ্ধতি ব্যবহার করে, এই গবেষণাটি ত্রিমাত্রিক মডেলিং এবং সিমুলেশন কৌশলগুলির মাধ্যমে সমস্যা সমাধানের উপর দৃষ্টি নিবদ্ধ করে। বিজিআই মডেলগুলিকে শহুরে তথ্য মডেলিং (ইউআইএম) এ অন্তর্ভুক্ত করার জন্য একটি কাঠামো প্রস্তাব করা হয়েছে এই গবেষণাটিতে, এখানে ইউআইএম হচ্ছে এমন একটি প্ল্যাটফর্ম যা বিভিন্ন শহুরে তথ্যগুলোকে একত্রিত করতে পারে। একটি পরীক্ষামূলক গঠনকাঠামোর প্রয়োগ প্রদর্শন করে, বিজিআই একীকরণের ব্যবহারিক সমস্যাসমূহ এবং সুযোগগুলি গবেষণায় তুলে ধরা হয়েছে। উপরন্তু, রক্ষণাবেক্ষণ এবং পর্যবেক্ষণ উন্নতকরণে বিজিআই ডিজিটাল টুইনকে একীভূত করার জন্য একটি কাঠামোর প্রস্তাব করা হয়েছে এ গবেষণায়। বিজিআই এবং ইউআইএম-এর মধ্যে ব্যবধান কমিয়ে, এই গবেষণাটি স্মার্ট, রেজিলিয়েন্ট শহরের বিকাশে অবদান রাখে যা পরিবেশগত সমস্যাগুলি মোকাবেলায় আরও ভালভাবে সুগঠিত। গবেষণালব্ধ ফলাফলগুলি নগর পরিকল্পনাবিদ, নীতিনির্ধারক এবং এর সাথে জড়িত সকল ধাপের অংশীদারদের জন্য মূল্যবান অন্তর্দৃষ্টি প্রদান করার মাধ্যমে বিজিআই কে ইউআইএম এ একীভূত করার জন্য একটি পারস্পরিক পদ্ধতির প্রয়োজনীয়তার উপর জোর দেয়। এই গবেষণাটি শুধুমাত্র তাৎক্ষণিক শহুরে পরিবেশগত সমস্যাগুলিকেই সমাধান করে না বরং শহরগুলিতে টেকসই উন্নয়নের জন্য ভবিষ্যতের নগর পরিকল্পনা প্রচেষ্টা কেমন হওয়া উচিত তার একটি কৌশলগত পথও উপস্থাপন করে।

মূল শব্দাবলি: ডিজিটাল টুইন, নীল-সবুজ অবকাঠামো (বিজিআই), শহুরে তথ্য মডেলিং (ইউআইএম), টেকসই নগর পরিকল্পনা, শহুরে স্থিতিস্থাপকতা, স্মার্ট শহর।

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

BGI	– Blue-Green Infrastructure
BIM	– Building Information Modelling
CFD	– Computational Fluid Dynamics
CIM	– City Information Modelling
CityGML	– City Geography Markup Language
DT	– Digital Twin
DTs	– Digital Twins
FME	– Feature Manipulation Engine
GIS	– Geographic Information Systems
GML	– Geography Markup Language
ID	– Identification
IFC	– Industry Foundation Classes
KML	– Keyhole Markup Language
LID	– Low Impact Development
LOD	– Level of Detail
NBS	– Nature-based Solutions
NOAA	– National Oceanic and Atmospheric Administration
OGC	– Open Geospatial Consortium
OSM	– Open Street Map
SDGs	– Sustainable Development Goals
SUDS	– Sustainable Drainage Systems
UDT	– Urban Digital Twin
UIM	– Urban Information Modelling
WSUD	– Water Sensitive Urban Design
XML	– Extensible Markup Language
gbXML	– Green Building XML
°C	– <i>Degree Celcius</i>
°F	– <i>Fahrenheit</i>

1

INTRODUCTION

1.1.BACKGROUND AND CONTEXT

Globally, more than half of the world's population currently lives in urban areas, having crossed this milestone around 2007 (Hannah Ritchie et al., 2024). This rapid urbanization trend is projected to continue, with the share of the global population living in urban areas is expected to increase to 60% by 2030 (United Nations, 2018). (Figure 1). Rural-Urban Migration ("Rural-Urban Migration," 2022) serves as a significant catalyst for this trend (Urbanization and Migration, 2022), driving people from rural to urban areas in search of improved living standards and economic opportunities, such as employment, healthcare, education, and urban amenities (What Causes Urbanisation?, 2023).

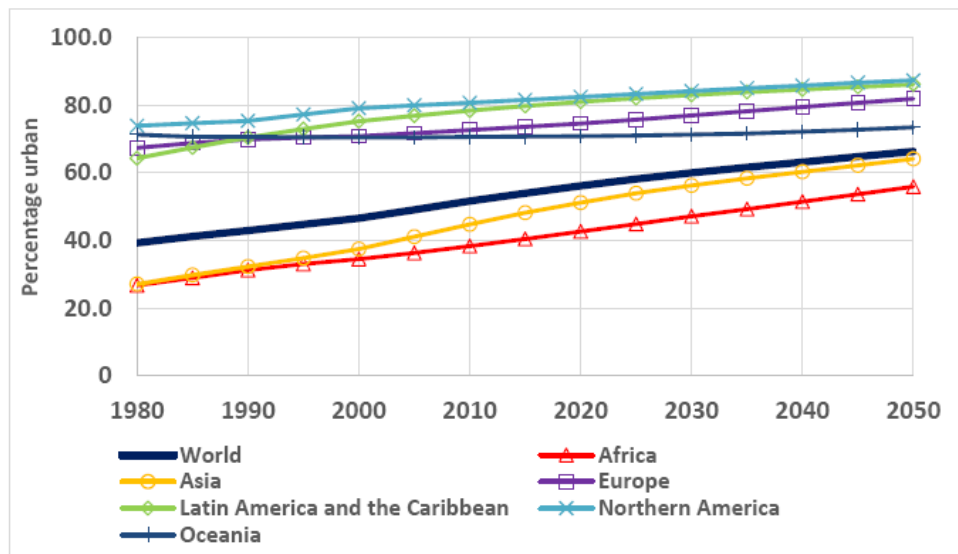


Fig. 1– Global Population Increase in Urban Areas; Source: (United Nations, 2018)

As urban populations expand, so does the demand for resources and infrastructures. This increased demand places pressure on land, housing, and the development of essential infrastructure, potentially leading to adverse impacts on natural resources and biodiversity (Seto et al., 2011). Moreover, the growing urban population correlates with increased consumption and economic activity, which in turn contributes to higher greenhouse gas emissions. This exaggerates the ongoing challenge of climate change and its associated environmental consequences (Population Growth, 2024). In urban settings,

infrastructures struggle to keep up with the rapid growth while degrading the urban environments and increasing risks of flooding, heat island effects, sea level rise, and so on.

According to NOAA’s monthly global climate report, in 2023, global temperatures reached their highest since records began in 1850, averaging 1.18°C (2.12°F) above the 20th-century norm of 13.9°C (57.0°F) as shown in Figure 2. This surpasses the previous record set in 2016 by 0.15°C (0.27°F). Additionally, the past decade (2014-2023) contains the 10 warmest years on record, which is particularly alarming.

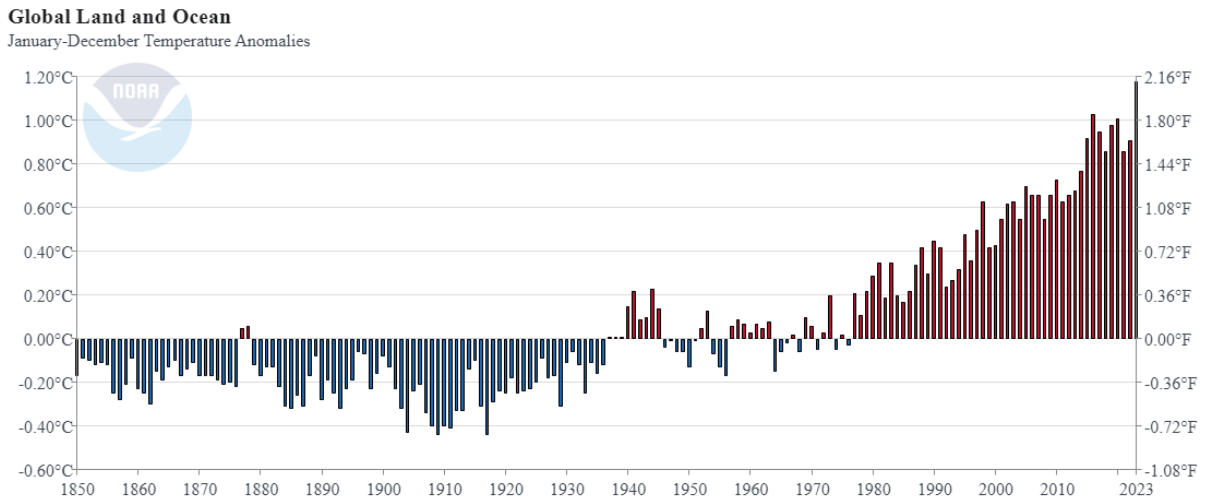


Fig. 2– Global Temperature Increase; Source: (NOAA National Centers for Environmental Information, 2024)

The table below presents the annual average temperature ranks and anomalies for the top 10 warmest years on record, combining global land and ocean measurements.

Table 1– Ten Warmest Years (1850-2023); Source: (NOAA National Centers for Environmental Information, 2024)

Year	Anomaly (°C)	Anomaly (°F)	Rank
2023	1.18	2.12	1
2016	1.03	1.85	2
2020	1.01	1.82	3
2019	0.98	1.76	4
2017	0.95	1.71	5
2015	0.92	1.66	6
2022	0.91	1.64	7
2018	0.86	1.55	8
2021	0.86	1.55	8
2014	0.77	1.39	10

An efficient way to reduce the urban heat island effect and increase resilience to extreme weather events is to incorporate natural elements into urban settings (Gunawardena et al., 2017). Urban planning integrating climate data, urban models, and optimal tree placement can enable more effective localized mitigation of the urban heat island effect (MacLachlan et al., 2021). It is vital to overcome climate change, environmental degradation, and the pressures faced by urban settings. The increasing frequency and intensity of multiple risks in urban areas require the adoption of sustainable urban planning strategies. As cities struggle with these environmental challenges, the necessity of sustainable urban planning practices that maintain a balance between social justice, economic growth, and environmental preservation is becoming more evident. For cities to maintain long-term livability and self-sufficiency, sustainable urban planning is a crucial component of development strategies and practices (Mohanty, 2020).

Although cities cover only 3% of the Earth's land area, they are responsible for 60-80% of energy consumption and 75% of carbon emissions (United Nations). The upward trend in global energy consumption, as shown in Figure 3, indicates the urgent need for solutions to mitigate this incompatible trend. Effective urban planning can play a significant role in achieving a balanced energy consumption pattern. Furthermore, most of the cities of the world with increased population density and specific locations are highly vulnerable to climate change resulting in frequent natural disasters. These growing disasters pose an immense risk to human lives, social structures, and economic stability. In 2023 alone, the global economic loss due to natural catastrophes reached a staggering USD 280 billion (Banerjee et al., 2024). To prevent these devastating consequences, enhancing urban resilience through innovative and sustainable approaches has become an urgent necessity.

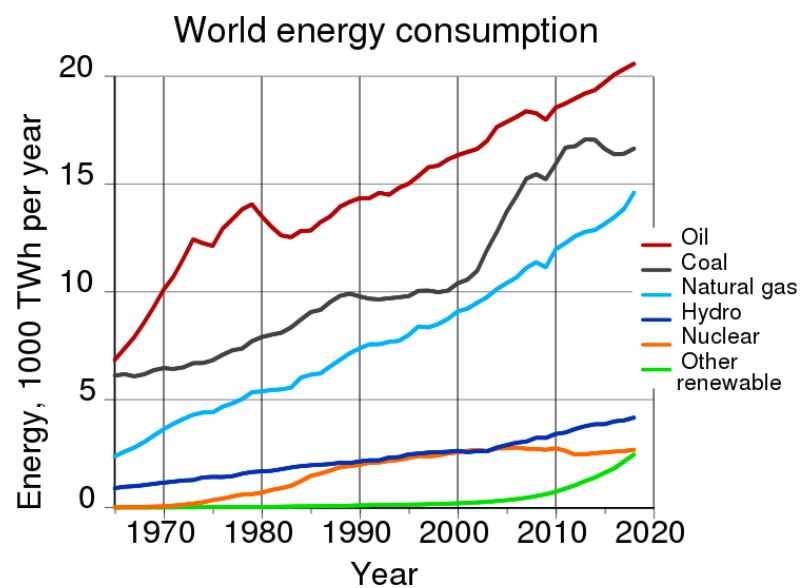


Fig. 3– World Energy Consumption; Source: (Wikipedia, 2013)

One of the significant challenges facing the 21st century revolves around identifying tools for strategic environmental planning, comprehending its inherent intricacies, and adopting a multifaceted approach encompassing urban planning, sustainability, resilience, and smart city initiatives (Ramirez Lopez & Grijalba Castro, 2020). This holistic framework is essential for effectively addressing the multifaceted challenges arising from urbanization and ensuring the sustainable development of urban environments.

Urban planning serves as a key instrument in enhancing environmental sustainability, and resilience, and working in synergy with local ecosystems by adopting stronger ecological tools and innovative approaches to energy, and resource consumption (UN-HABITAT, 2010). Planners are reinventing planning principles to add value and face new challenges. The principles of 'New Urban Planning'

emphasize the necessity of adopting a holistic approach that integrates planning efforts, promotes sustainable development, and accommodates the diverse needs of urban populations. Key aspects include achieving integrated planning, developing appropriate planning tools, and fostering inclusivity to address the complex challenges faced by modern cities (UN-HABITAT, 2010). Optimization is necessary to ensure that urban development aligns with sustainability principles while meeting the diverse needs of growing urban populations. Sustainable urban planning can be optimized through an integrated approach that leverages data, technology, and digital tools to make informed decisions and achieve optimal outcomes. Optimizing sustainable urban planning requires a data-driven approach that incorporates various datasets, such as climate data, urban models, demographic projections, resource consumption patterns, and environmental impact assessments (Lai, 2023). By analyzing and integrating these data sources, planners can make informed decisions that balance economic, social, and environmental considerations.

To improve the resilience and sustainability of urban environments, effective tools and technologies are essential. Urban digital twins (UDT) and city information modeling (CIM) are two new technologies for smart cities that aim to provide these types of services. Both provide solutions for modeling, simulation, data processing, urban analysis, planning, and design to optimize natural resources (International Electrotechnical Commission, 2021).

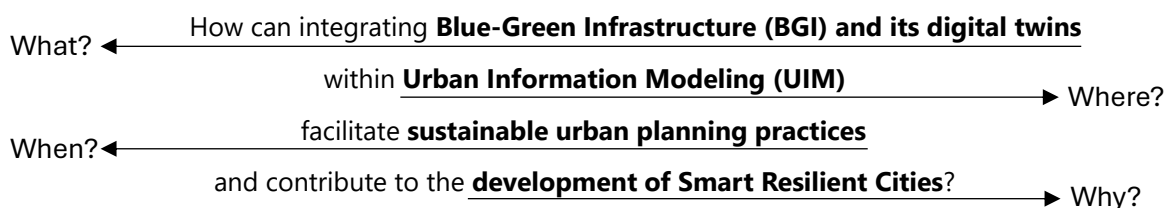
Similarly, urban blue-green infrastructure (UBGI) is recognized as a significant component of disaster risk reduction, climate change adaptation, and urban environment management (Dhyani et al., 2022). BGI elements such as parks, forests, and vegetated systems have been embraced across Southeast Asia to address flood hazards and water quality challenges resulting from growing urbanization (Hamel & Tan, 2022). Wetlands, ponds, rivers, lakes, swales, rain gardens, parks, and other BGI measures can provide various urban ecosystem services related to the environment and socio-economic well-being (Ahmad & Hassan, 2024). However, the physical expansion of urban areas often comes at the expense of natural landscapes and blue-green spaces (Kaur & Gupta, 2022). Integrated modeling tools are needed that provide a simplified way of assessing the multiple benefits of BGI across urban environments effectively (Sörensen et al., 2021). A comprehensive understanding of the synergies between digital twin (DT), urban information modeling (UIM), and blue-green infrastructure (BGI) is essential for advancing sustainable urban planning practices and promoting the development of smart, resilient cities.

1.2. RESEARCH PROBLEM AND OBJECTIVES

1.2.1. RESEARCH QUESTION

After the background analysis, the research problem is articulated through the following research question "How can integrating Blue-Green Infrastructure (BGI) and its digital twins within Urban Information Modeling (UIM) facilitate sustainable urban planning practices and contribute to the development of Smart Resilient Cities?"

To achieve a comprehensive understanding of this research question, it is deconstructed and analyzed by using the framework of the four cardinal 'W' questions: What, Where, When, and Why.



This approach has been designed to provide an in-depth comprehension of the intricate facets embedded within the research inquiry, thereby establishing a study groundwork for further analysis.

1.2.2. AIM OF THE THESIS

The primary aim of the thesis is to conduct an extensive exploration into the potential synergies existing among Digital Twin (DT), Blue-Green Infrastructure (BGI), and Urban Information Modeling (UIM), focusing on the technologies to support sustainable urban planning. Through a rigorous literature review and pilot study analysis, the study aims to identify and analyze the best practices for integrating BGI and its digital twins within the UIM environment. By delving into the applications of these technologies, the study aims to enhance urban resilience, mitigate environmental risks, and promote the development of smart resilient cities. Moreover, through comprehensive analysis, this thesis aims to provide insights and actionable recommendations to facilitate decision-making processes for urban planners, designers, policymakers, and stakeholders, thereby fostering the creation of sustainable urban settings.

1.2.3. RESEARCH OBJECTIVES

Aligned with the research question outlined above, the following research objectives are formulated to address the research problem systematically:

- To conduct a thorough review of existing literature to identify the potential synergies among Digital Twin (DT), Blue-Green Infrastructure (BGI), and Urban Information Modeling (UIM) in supporting sustainable urban planning initiatives.
- Investigating the pilot study to analyze the practical applications of integrating BGI within UIM and identify challenges and opportunities for the integration procedure.
- Assessing the effectiveness of integrated digital twins of BGI within UIM in improving informed decision-making processes and outcomes, including their impact on urban resilience, mitigating environmental risks, and promoting equitable urban growth.
- To develop a comprehensive framework outlining the potential approaches for integrating BGI models and its digital twins within the UIM environment to optimize sustainable urban planning practices.
- Providing actionable insights and future research directions to empower urban planners, policymakers, and diverse stakeholders in effectively implementing and leveraging the integration of BGI and its digital twins within UIM for the development of smart and resilient cities.

These objectives guide the research design and framework towards the exploration of topics related to the integration of Blue-Green Infrastructure (BGI) and its digital twins within the Urban Information Modelling (UIM) environment. The goal of the study is to identify possible synergies and existing challenges between these technologies to support sustainable urban planning practices and foster the development of smart, resilient cities.

1.3. SIGNIFICANCE OF THE STUDY

i. Bridging the research gap:

The research field of urban planning is constantly evolving, with new research continually enhancing its practices. The concept of digital model and digital twin have emerged as promising tools, yet the integration of Blue-Green Infrastructure (BGI) within this holistic framework remains underexplored. This research aims to bridge this gap by demonstrating the process of integrating BGI into Urban Information

Modeling (UIM) and showcasing its potential benefits for sustainable urban development. By addressing this research gap, this thesis contributes to the advancement of knowledge and provides guidance for incorporating BGI into future urban planning initiatives.

ii. Practical implications for urban professionals:

Through this research, practical implications for urban professionals can be identified, enabling them to utilize digital twin technology to effectively address urban challenges and achieve sustainable development goals. To ensure the successful development of the digital twin city, fostering a collaborative dialogue among all relevant stakeholders, such as academics, industry leaders, researchers, and application specialists, is essential. This collaboration will facilitate a shared understanding of the concept and the identification of best practices (Digital Twin Cities: Framework and Global Practices, 2022).

iii. Contribution to sustainable development:

Connected planning solutions focusing on digital twin (DT) should adopt a socio-technical approach, considering both social and technological aspects (Digital Twin Cities: Framework and Global Practices, 2022). This ensures multiple benefits ranging from decision-making to optimized economic outcomes, eventually contributing to sustainability, and fostering resilience for both the people and the environment. The urgency of this approach is outlined by the escalating global average annual losses from weather-related disasters in the built environment, currently estimated at USD 314 billion and projected to reach USD 415 billion by 2030 (UNISDR, 2015). This research, therefore, contributes to sustainable development by exploring the potential of BGI and its digital twins in UIM to mitigate these risks, protect urban assets, and create more resilient cities.

iv. Contribution to BGI integration technique:

Within the scope of this thesis, a comprehensive investigation of BGI models, their properties, data formats, and simulation techniques has been undertaken. This in-depth exploration aims to generate insights and approaches, simplifying the integration process and creating new directions for future study. By providing a detailed analysis and practical examples, this study can serve as a foundation for other researchers to explore alternative methods and further advance the integration of BGI into urban planning and modeling practices.

v. Global applicability:

The research topic presented in this thesis is not limited to a specific geographic location or setting. The proposed framework for integrating Blue-Green Infrastructure (BGI) and its digital twins within Urban Information Modeling (UIM) can be applied globally to address urban challenges. Not only does this research have consequences for urban planning, but it also impacts hydrology, sustainable studies, ecosystem management, biodiversity protection, and more. The applications of green and blue infrastructure, such as carbon-absorbing green spaces, energy-efficient buildings, and sustainable urban solutions, offer a global approach to mitigating environmental risks including climate change and creating more resilient urban environments.

1.4. STRUCTURE OF THE THESIS

The thesis is comprised of six main chapters, each of which is carefully structured with subchapters and further subdivisions where it is essential. The planned structure ensures that every chapter fulfills a specific function in clarifying how Blue-Green Infrastructure (BGI) and its digital twins are integrated within the Urban Information Modeling (UIM) for creating smart and resilient cities through sustainable urban planning.

Chapter 1 provides a background and context of the recent scenario stating the ongoing environmental challenges, emphasizing issues such as climate change, energy consumption, and their potential implications for the urban environment. It articulates the research problem, identifies the existing research gap, and formulates research questions and objectives.

Chapter 2 provides a theoretical background on the key topics of this research. First, the concept of digital twins and its benefits in urban planning has been discussed. Then the principles and typologies of BGI in urban planning are elaborated with its benefits. After that, the current practices regarding the integration of BGI in urban planning have been identified along with the alignment of sustainable development goals and later, the role of UIM and the associated challenges of integrating DT in UIM has been defined.

Chapter 3 defines the research methods to investigate the integration of BGI within UIM for sustainable urban planning. It elaborates on the concept behind the research framework, explains the detailed workflow along with sequential steps of the whole research process, and concludes with the overall data collection, analysis, and limitation of research.

Chapter 4 delves into a detailed data application using the selected pilot study area, and implementation of BGI including modeling and simulation techniques followed by the research design. It then presents and analyzes the simulation outcomes, showing results for various environmental parameters, and concludes with the integration of the outcomes into the UIM environment.

Chapter 5 critically evaluates the research findings compared to the existing knowledge, providing insights into application challenges and opportunities, discussing the BGI maintenance after the implementation phase, and suggesting future research directions that can facilitate urban planning practices.

Chapter 6 encompasses the summary derived from the research journey, culminating with a definitive response to the research question. It also reflects on the implications of the study within the realm of sustainable urban planning as well as enhancing the development of smart resilient cities.

This strategic arrangement facilitates a detailed comprehension of the implications of BGI for urban resilience and sustainability by methodically guiding through an in-depth study of the multifaceted dimensions inherent in the implementation of BGI and its DT within UIM.

2

LITERATURE REVIEW

2.1.OVERVIEW OF DIGITAL TWINS IN URBAN PLANNING

2.1.1. DEFINITION AND CONCEPT

A digital twin is a virtual representation of a physical entity or process, continuously updated with real-time data. It can be defined as a virtual representation of a physical system, complete with its surroundings and functions, that is updated in real time via data exchanges between the virtual and physical systems (VanDerHorn & Mahadevan, 2021).

In other words, a digital twin is a digital representation of a specific physical entity or process, connected through data that enables synchronized convergence between the physical and digital states. It possesses capabilities for connection, integration, analysis, simulation, visualization, and optimization, offering a comprehensive view throughout the entire lifecycle of the physical entity or process (ISO/IEC 30173, 2023).

The concept of the digital twin encompasses various elements, including digital representation, connection, integration, computation, real-time 3D visualization, prediction, and decision-making. Essentially, it refers to a digital replica of a physical object, with synchronized data flow between the virtual and physical versions (Figure 4). This synchronization enables real-time simulations, optimizations, and visualizations to occur seamlessly (Sepasgozar, 2022).

In the field of urban planning, the digital twin has the potential ability to visualize and forecast the impacts of planning decisions. The digital twin itself can be considered as an infrastructure for virtual modeling and data management.

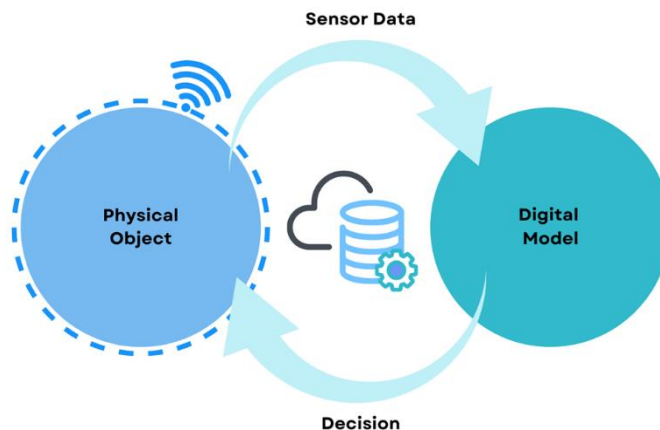


Fig. 4– Digital Twin Concept; Source: Author

2.1.2. APPLICATIONS AND BENEFITS

The concept of digital twins is expanding rapidly in the planning sector, along with other diverse fields including construction, manufacturing, and product development. The major advantage of digital twins is the application of potential future scenarios to analyze the impact without causing any change to the existing environment, thereby avoiding costs and resources.

The introduction of Digital Twin Cities (DTC) intends to transform regulatory frameworks and governance structures. DTC is a ground-breaking approach to urban development. This new method is gaining progress rapidly across the world, with major cities leading the way on projects to use digital twinning to foster continuous urban development and transformation (T. Deng et al., 2021).

A Digital Twin City (DTC) is an advanced 3D city model enhanced by integrating city information and data sources. This is achieved using technologies like surveying and mapping, BIM, IoT, 5G, blockchain, collaborative computing, and simulation. Improving policy decisions, urban planning, and city management are the main goals of DTCs (Michalik et al., 2022).

Digital Twin City (DTC) (Mohammadi & Taylor, 2017 and T. Deng et al., 2021), City Digital Twin (CDT) (Shahat et al., 2021), Urban Digital Twin (UDT) (Dembski et al., 2020), Smart City Digital Twins (SCDT) (Mohammadi & Taylor, 2017 and Abdeen & Sepasgozar, 2022), and the Digital Twin Smart Cities Model (DTSCM) (White et al., 2021) are the same concepts with different terminologies in the academic literature. By using digital twin technology, cities are expected to save a large amount of money which is estimated at 280 billion dollars by 2030. This could be possible with more effective urban planning and comprehensive asset maintenance (Urban Planning and Digital Twins, 2021).

2.1.3. CHALLENGES AND LIMITATIONS

There is a difference between the theoretical potential and real-world uses of Digital Twins (DTs) (Kar et al., 2019). The primary challenges as well as concerning matters related to the implementation of an Urban Digital Twin (UDT) are outlined with eight critical categories of challenges which are (i) understanding of data and interoperability; (ii) infrastructure, including computation, storage, and network capabilities; (iii) data collection and control; (iv) data accuracy and consistency assurance; (v) modeling, simulation, and decision-making support; (vi) visualizing data and presenting information; (vii) human and financial resources; and (viii) addressing organizational, governance, and social issues (Weil et al., 2023). These areas are extensively discussed in existing literature, with particular emphasis on issues with data and model understanding, incomplete data, data quality, and modeling accuracy.

Summing up, the challenges could be categorized into three main domains, which are i) fragmented comprehension, ii) preliminary technology, and iii) uncertain business plans (Digital Twin Cities: Framework and Global Practices, 2022).

The limitations of digital twins (DT) are primarily rooted in the lack of involvement and cooperation among the various stakeholders necessary for their effective application. This lack of coordinated effort hampers the seamless integration and utilization of DT technologies, leading to inefficiencies and suboptimal outcomes. Additionally, these limitations are further compounded by the absence of an established governance framework for the mapping and exploration of DT (Digital Twin Cities: Framework and Global Practices, 2022). Without clear guidelines and standardized procedures, the development and application of DT remain fragmented and inconsistent, which limits their potential benefits.

2.2. BLUE-GREEN INFRASTRUCTURE (BGI) IN URBAN PLANNING

2.2.1. DEFINITION AND PRINCIPLES

According to the European Commission, BGI is defined as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (JNCC et al., 2019).

Alternatively, considering the broader scope of functions and elements, BGI can be defined as a multifunctional infrastructure that conducts various ecological, social, and economic functions (Pauleit et al., 2011).

Integrating BGI into the discussions of climate change, water management, urban heat island mitigation, regeneration, biodiversity, or health and wellbeing, a heightened level of debate emerges, particularly around its technical specifications, such as BGI in stormwater management (NYC Environmental Protection, 2010). This contrasts with more socio-cultural perspectives on landscape quality (Waldheim, 2016). Therefore, it's essential to place BGI within a broader framework of environmental concepts and approaches to understand how these terms interrelate, rather than focusing solely on defining or delivering BGI in isolation (Mell & Scott, 2023).

The design principle prioritizes BGI that not only aligns with the local context but also offers multiple advantages appreciated by the community and requires minimal maintenance while the procedure principle implies that the creation of BGI should be a cooperative, efficient, and sustainable process, considering the viewpoints of all community members (when provided) to produce a co-designed BGI (E. O'Donnell et al., 2020).

The following 12 principles adapted from (Mell & Scott, 2023) define the characteristics and value of effective Blue-Green Infrastructure (BGI) in shaping the built environment through policy and practice.

- Incorporate essential infrastructure for cities and natural areas into initial design plans
- Extend across rural, suburban, and urban areas without boundaries
- Create multifunctional spaces that benefit people, nature, society, and the economy
- Improve connectivity between people, places, and nature through pathways and corridors
- Establish a managed network of green features supporting diverse activities
- Integrate water resources as fundamental components, both conceptually and practically
- Provide economic, social, and ecological benefits through investment and maintenance
- Promote integration of socioeconomic and environmental policies and practices
- Operate across various spatial and temporal scales, adapting to change
- Evolve with the landscape and changing socio-economic needs
- Ensure accessibility and inclusivity for everyone
- Implement active, long-term management for sustained benefits and placekeeping

2.2.2. TYPOLOGIES OF BGI

Increased erosion and more frequent, severe flooding occurrences are the results of urbanization, reduced forest areas, and inadequate agricultural practices. The authorities of Belgrade city (the Capital of Serbia) have outlined an innovative approach to land utilization and urban planning. This strategy based on the restoration of the blue-green corridors aims to reduce the hazards associated with severe erosion and flash floods. It also supports the creation of new recreational spaces, the conservation of biodiversity, and the reduction of the "heat island" effect (Ristić et al., 2013).

Table 2 outlines the types of BGI, primarily adapted from (Krauze & Wagner, 2019). The types are being arranged based on the categories and types of approaches adapted from (Kopp et al., 2021).

Table 2 – Types of BGI

Categories of Approaches	Types of Approaches	Types of BGI	Reference
Hydrological	Stormwater management	_Infiltration Systems (Infiltration basins, trenches, tree trenches) _Hydraulic Detention Systems _Green Roofs _Bioswales/Vegetative Swales _Stormwater Retention Ponds/Detention Basins _Permeable Areas (Paving)	(Fletcher et al., 2015)
	Hydrological process & stormwater management	_Infiltration Systems _Rain Gardens/Bioretenction Cells _Stormwater Wetlands _Permeable Areas (Paving) _Swales/Vegetative Swales/Bioswales	(Stovin et al., 2012)
Integrated	Ecosystems, ecosystem services & amenity	_Green Spaces (Existing, Newbuilt, Regenerated) _Green Roofs _Green Walls _Rain Gardens/Bioretenction Cells _Stormwater Wetlands _Vegetated Buffer Strips _River and Stream Restoration _Street Trees _Urban Forests/Parks _Biogeochemical Barriers	(Tzoulas et al., 2007)
	Land cover and amenity	_Green Spaces (Existing, Newbuilt, Regenerated) _Green Roofs _Green Walls _Water/Rain Gardens _Stormwater Wetlands _Street Trees	(Consumer Scotland, 2023)
Structural	Green networks	_Connectivity of Green Spaces in Cities (Blue-Green Networks) _Nature 2000 _Landscape Integrity _River and Stream Restoration	(Benedict & McMahon, 2006)
	Water bio-corridors	_River and Stream Restoration _Stormwater Wetlands _Vegetated Buffer Strips	(Hamel & Tan, 2022)

The types of BGI in Table 3, are being analyzed based on the spatial level and spatial context adapted from (Mell & Scott, 2023, Krishnan et al., 2019 and Cheshmehzangi et al., 2021).

Table 3– Types of BGI depending on spatial analysis

Spatial Level	Spatial Context	Types of BGI
Micro	Building, Plot, Site, Urban block	Green walls, Green roofs, Rain gardens, Bioswales/Vegetated swales, Permeable paving (ex: driveways)
Meso	Street, Neighbourhood, Community, Ward	Street trees, Pocket parks, Amenity green spaces, Play areas, Urban Agriculture, Urban woodland, Sustainable drainage systems (SuDS)-smaller systems, Green cycle routes
Macro	City, District, Region, Watershed, Country	Urban regional parks, Sustainable drainage systems-larger systems (ex: wetlands), Formal green belts, River corridors, Riverfronts, Lakes, Ponds, Urban Forest, Green cycle routes (city-wide networks), Infrastructure greening (roadside/highway greening)

2.2.3. BENEFITS AND CHALLENGES

A key feature of blue-green infrastructure is its multifunctionality, allowing it to perform multiple tasks and offer various benefits within a single space. BGI provides several benefits, such as enhancing water quality, reducing flood risk while cutting infrastructure costs, and creating additional spaces for community use and wildlife habitat (Bedla & Halecki, 2021). The benefits of blue-green infrastructure (BGI) extend beyond flood risk management and influence other aspects including climate change adaptation, urban regeneration, and enhancing public health and wellbeing (O'Donnell et al., 2017).

The fundamental benefit of BGI is urban environment management. According to (Siehr et al., 2022), the additional benefits of this primary benefit include the following:

- Reducing disaster risk (managing stormwater, flooding, etc.)
- Climate change adaptations (heat island effect, sea level rise, etc.)
- Maintaining biodiversity
- Improving air quality
- Economic enhancement (attracting investment, increasing property value through tourism, etc.)
- Public health and wellness (social gatherings, cultural activities, noise reduction, etc.)

Selecting different BGI measures at the same time is more effective in terms of creating impact. This strategy was successfully adopted in the case of green roofs in Germany (Burszta-Adamiak & Fialkiewicz, 2019).

BGI encompasses green spaces as well as natural and artificial water features, forming a network within urban areas that provides environmental, economic, and social benefits (Brears, 2018). Table 4 shows the most likely deliverable benefits of Blue-Green Infrastructure at micro, meso, and macro spatial levels.

Table 4– Benefits of BGI; Source: Adapted from (Barker et al., 2019)

Spatial Level	Micro	Meso	Macro
Benefits			
Environmental	Improved thermal comfort, Improved air quality, Reduced flood risk, Climate change adaptation, Increased biodiversity, Reduced energy use	Reduced urban heat island, Improved air quality, Improved water quality, Reduced flood risk, Increased habitat area, Increased populations of protected species, Facilitation of species movement	Reduced urban heat island, Improved macro-scale air quality (urban), Facilitation of species movement, Increased biodiversity, Climate change mitigation, and adaptation
Economic	Increased land and property values, Enhanced quality of place, Improved recreation and leisure offers, Provision of products from the land/water, Reduced flood risk, Reduced health and well-being expenditure, Climate change mitigation, and adaptation	Improved recreation and leisure offers, Reduced health and well-being expenditure, Reduced flood risk	Provision of products from the land/water, Reduced flood risk, Improved recreation and leisure offers, Climate change mitigation, and adaptation

Social	Improved aesthetics,	Provision of access to and enjoyment of nature,	Provision of products from the land/water,
	Improved community resilience to environmental/climate change,	Provision of sport and recreational opportunities,	Provision of sport and recreational opportunities,
	Improved social interaction and community cohesion,	Enhanced physical health,	Enhanced physical health,
	Enhanced environmental awareness,	Enhanced mental health and well-being,	Enhanced mental health and well-being,
	Enhanced physical health,	Improved community resilience to environmental/climate change,	Improved community resilience to environmental/climate change,
	Enhanced mental health and well-being,	Provision of products from the land/water	Amelioration of air pollution,
	Provision of access to and enjoyment of nature,		Enhanced environmental awareness
	Provision of products from the land/water,		
	Amelioration of air pollution		

Challenges or barriers to BGI adoption can generally be classified into two main categories: biophysical and socio-political (Thorne et al., 2018). Covering these categories, the barriers to BGI (Almaaitah et al., 2021) are the following:

- Lack of multilevel coordination
- Budget constraints
- Lack of proper funding schemes
- Absence of risk reduction frameworks
- Uncertainties regarding hydrologic and ecologic performance
- Existing maintenance practices
- Reluctance to support new practices
- Social and institutional barriers

2.3. INTEGRATION OF BGI IN URBAN PLANNING

2.3.1. IMPORTANCE AND RATIONALE

Sustainable urban planning incorporates blue-green infrastructure (BGI) and ecosystems to generate environmental benefits and enhance the quality of life (Thammadi et al., 2022). Many cities are exploring blue-green infrastructure (BGI) solutions that increase climate resilience and restore ecological balance in the context of climate change and degradation of the environment (Ghofrani et al., 2020). Collaborative research across disciplines and engagement with stakeholders can facilitate strategic planning and effective implementation of Blue-Green Systems in urban areas (Probst et al., 2022).

Three essential aspects of information handling need to be managed to build a structure for data flow: data storage, data analysis, and visualization, and data maintenance (Sörensen et al., 2021). Climate models need to incorporate specific dynamic and thermal parameterizations that are dedicated to the transfer of water and energy between the atmosphere and urban surfaces. This is crucial for accounting for the interactions between a city's surface and its atmospheric conditions (Hamdi et al., 2020).

The following is the list of categories of data required for the implementation of BGI in planning:

Table 5– List of categories of required data; Source: Adapted from (Sörensen et al., 2021)

Data Category	Example
Cadastral	Property ownership, zoning information, land cover
Technical	Utility lines (electricity, water, gas, sewage, etc)
Geological	Soil layers, mineral resources, stability
Biological	Biodiversity hotspots, wildlife migration corridors
Environmental	Environmental monitoring, groundwater
Risks	Wildfire risk zones, flood hazard mapping
Administrative	Protected areas, infrastructure development plans
Social	Population demographics, recreational and historical buildings
Meteorological	Temperature, humidity, precipitation, wind speed

Integrating BGI in urban planning has the following several challenges, according to (E. C. O'Donnell et al., 2017 & E. C. O'Donnell et al., 2020).

- Regulatory and governance difficulties
- Maintenance and adaptation issues
- Financial expenses
- Unwilling to support new approaches
- Community perceptions of BGI
- Uncertainties related to its hydrologic performance

2.3.2. STRATEGIES AND BEST PRACTICES

The Digital Surface Model (DSM) layer is instrumental in differentiating various infrastructures including blue-green infrastructures. Using Unmanned Aerial Vehicle (UAV) images to categorize urban infrastructure into blue, green, and even gray categories is a feasible approach. Machine learning algorithm-based infrastructure classification is effective and could be useful in developing models for urban stormwater management and eventually in sustainable urban planning (Jia et al., 2022).

To overcome the BGI implementation challenges, the following strategies from (E. C. O'Donnell et al., 2017) can be adopted:

- Better data
- Planning guidelines
- Industry rules and regulations
- BGI considering the microclimate

- Low maintenance of BGI
- Community involvement
- Identification of potential beneficiaries
- Support of Stakeholders or key decision-makers
- Multifunctionality or multiple co-benefits

2.3.3. CONNECTION WITH SUSTAINABLE DEVELOPMENT GOALS (SDGs)

Most municipal employees acknowledged BGI as an essential tool. The Department of Parks and Green Spaces, alongside the Department responsible for urban drainage, emerged as the two primary actors. This core group is further supported by the urban planning and environment departments. Although the transport department has the potential to be a significant actor, it is still not as involved as it could be. On the other hand, the real estate and housing sectors were found to be the least supportive or even resistant to BGI initiatives (Winker et al., 2022).

BGI plays a vital role in various aspects of sustainable urban growth. The process of designing and planning with BGI requires a collaborative and interdisciplinary approach that aligns with the goals of sustainable development (Kopp et al., 2021).

Table 6– BGI fields and their benefits to relevant SDGs; Source: Adopted from (Kopp et al., 2021)

SDG	Urban Water Management (SUDS, WSUD)	Urban Planning (sustainable cities, eco-cities, resilient cities)	Ecosystem Management (green networks, NBS)	Hydrology (Ecohydrology, LID)
3	●	●	●	
6	●	●		●
7		●		
8		●		
9	●	●	●	
11	●	●	●	●
12	●	●		
13	●	●	●	●
14	●		●	●
15	●		●	●
17	●	●		

In Table 6, SDGs: 3 Good Health and Well-being; 6 Clean Water and Sanitation; 7 Affordable and Clean Energy; 8 Decent Work and Economic Growth; 9 Industry, Innovation and Infrastructure; 11 Sustainable Cities and Communities; 12 Responsible Consumption and Production; 13 Climate Action; 14 Life Below Water; 15 Life on Land; 17 Partnerships for the Goals

2.4.URBAN INFORMATION MODELLING (UIM) AND URBAN DIGITAL TWINS (UDT)

2.4.1. ROLE OF UIM AND UDT IN URBAN PLANNING

UIM (Urban Information Modelling) and CIM (City Information Modelling) are considered 'Identical Concepts' (Zhang, 2024, Schaufler & Schwimmer, 2020, International Electrotechnical Commission, 2021, Thompson et al., 2016, & Hamilton et al., 2005).

The necessity for evidence-based, informed, cooperative, and participatory urban planning and decision-making, characteristic of Smart Cities, is driving the digitalization of the urban development process. This transformation is facilitated by innovations in information technology, such as 3D city models, Digital Twins, Geographic Information Systems (GIS), Urban Analytics and Informatics, and Planning Support Systems (PSS). Within this framework, the concept of City Information Modelling (CIM) has emerged, integrating these technological advancements to enhance urban planning and management (Gil, 2020a).

Urban Information Modelling (UIM) or City Information Modelling (CIM) is a digital representation of the urban environments with the integration of various data sources, analytical tools, and technologies to optimize urban planning, and urban management and support the decision-making process. While BIM reflects the digital representation of a building's physical and functional characteristics, CIM represents the physical, functional, and spatial aspects of the city or urban area. CIM integrates data from buildings, infrastructure, transportation, and the environment, offering a comprehensive, dynamic view of the city. This facilitates decision-making, urban planning, urban design, and management (LED-UFC).

A CIM (City Information Modeling) is a data-driven ecosystem comprising integrated IT applications designed to fulfill the needs of all stakeholders involved in urban planning within a smart city. It consists of tools for urban analysis, data processing, design, modeling, simulation, and visualization that are interoperable and frequently open-source across different knowledge domains. These tools are interconnected through shared ontologies, forming a semantically rich, integrated urban model based on open standards. This model operates within a multiscale and multitemporal database, incorporating a wide range of large open data sources that represent the entire spectrum of urban features, systems, and processes (Gil, 2020b).

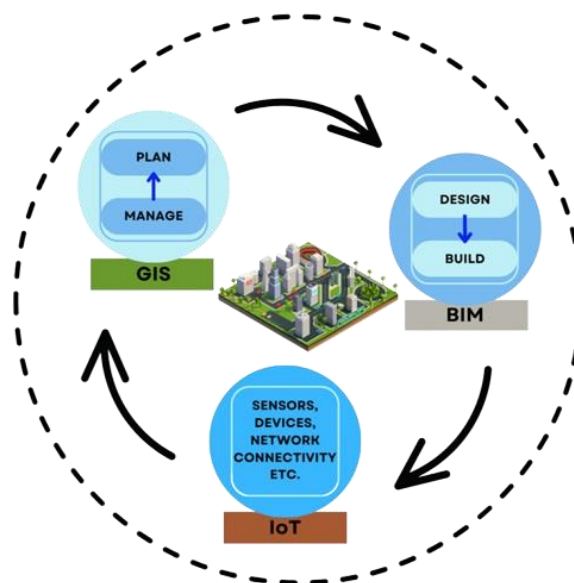


Fig. 5– Urban Information Modelling (UIM) Concept; Source: Author

CIM (City Information Modeling) explores the specific sectors and entities that make up a city and examines how they interact with one another. CIM is the process of utilizing technology in an interactive and interoperable way to support planning and decision-making for smart cities while going beyond more than just the data and tools. CIM can be defined as a smart city integration system, combining BIM, GIS, and IoT technologies to create a digital replica of physical cities (Figure 5). This sophisticated, near-real-time digital urban model, known as CIM, provides a comprehensive foundation for the smart planning, construction, management, and operation of urban environments (International Electrotechnical Commission, 2021).

The digital twin extends beyond visualization to enable interaction, simulating and predicting outcomes based on digital behavior. This concept has been adapted for urban environments, aiming to reform city planning, construction, and management to improve livability, inclusivity, safety, resilience, and sustainability. Due to the complexity of urban environments, an Urban Digital Twin (UDT) comprises multiple digital twins across sectors like energy, buildings, and transportation, utilizing relevant modeling tools. Developing a UDT from a systems thinking perspective necessitates the use of City Information Modeling (CIM), which serves as a foundational model of the built environment for scenario modeling and monitoring (International Electrotechnical Commission, 2021).

DTs applied to manufacturing, construction, and maintenance are not similar to DTs used in cities or City DTs (Lehtola et al., 2022). It is necessary to have an accurate, inclusive, and up-to-date spatial data framework including spatial matching between different scales, datasets, and data formats for an urban digital twin or City DT (International Electrotechnical Commission, 2021). The most similar to DTs in the building sector is Building Information Modeling (BIM) (M. Deng et al., 2021). However, a city DT incorporates not only the features of a computer model but also the way in which daily city services are organized to carry out all planning functions within a single digital model. 3D models utilized for Digital Twins (DTs) are generally derived from point clouds or images, which serve as the foundational data. Whereas Point clouds, generated by sensor systems, are the initial raw outputs, these 3D models are the final products for GIS-based or BIM-based DTs, frequently used for visualization purposes (Lehtola et al., 2022). City DTs integrate a vast amount of information, than the earlier DTs. Thus, city DTs have evolved as a natural progression from two existing ecosystems in 3D modeling: Building Information Modeling (BIM) and Geo-Information Systems (GIS).

Table 7– Used Algorithms and Software for the Development of 3D City Models and Urban DTs;
Source: Adapted from (Boccardo et al., 2024)

Development of 3D City Model			
Stage	Method/Algorithm/ Software	Medium/Data Source	Function
Data Acquisition and Processing	Data Collection Method	Sensors and IoT Devices	-Collecting data on traffic patterns, weather conditions, energy consumption, etc.
		Remote Sensing Technologies; ex: -Satellite imagery -Aerial photography (using drones)	-For capturing large- scale urban landscapes

		GIS	-Geospatial data collection for mapping and analyzing urban environments
	Data Processing Method	Data cleaning and integration	-Remove inaccuracies -Resolve inconsistencies -Combine data from different sources into a coherent format
	Advanced-Data Analysis in interpreting data -Statistical analysis -Predictive modeling -Machine learning algorithms	-	-Extracting insights and patterns from the data
Modeling Methodologies	Geometric and Textural Modeling	Techniques: using photogrammetry for real-world textures	-Algorithms for 3D geometric representations of urban features (ex: buildings, roads, natural elements) -Real-world Textures and Appearances
	Spatial Analysis Algorithms	-	-Spatial relationships and patterns for understanding urban dynamics (ex: land use patterns and population distribution)
	Simulation and Forecasting Algorithms	Techniques: agent-based modeling or computational fluid dynamics	-Urban process simulation (ex: traffic flow, environmental changes) -Predicting future scenarios
Required Tools and Software	CAD and BIM Software	-AutoCAD 2024 -Revit 2022	-Modeling of individual buildings and infrastructure

	GIS Software	-ESRI ArcGIS Pro -QGIS (v. 3.34)	-Integrating spatial data into urban models
	Specifically designed Urban Modeling Software	-CityEngine 2023.1 -UrbanFootprint 1.5	-Creating large-scale urban models -Simulating urban layouts, land use, and zoning scenarios
	Data Analysis and Visualization Tools	-Tableau -Power BI	-Interpreting complex urban data and presenting it in an accessible format
Development of Urban DTs			
Stage	Method/Algorithm/Software	Medium/Data Source	Function
Real-time Simulation and Visualization	Data Sharing Platforms	-Cesium -MapStore	-Providing data-sharing functionalities, with basic measurement and visualization functions
	Game Engines Software	-Twin Motion -Unreal Engine -Unity	-Providing realistic graphics and lighting that replicate real-world conditions in a virtual environment
Integration of IoT (Internet of Things) and AI (Artificial Intelligence) in Enhancing DT Applications	Data Collection, Transmission, and Monitoring	IoT Devices	-Real-time data collection -Connectivity and interactivity within the DT
	AI Algorithms	-	-Data processing and analysis -Predictive modeling (forecasting future urban scenarios which helps long-term urban planning) -Facilitating informed decision-making -Continuous adaptation and improvement of models

2.4.2. INTEGRATION OF URBAN DIGITAL TWINS WITH UIM

A sustainable urban ecological environment, livable urban living places, and more efficient urban operation are the three visions that the digital twin city aspires to. Digital twin technology is used to intelligently analyze complicated scenarios for urban planning, including resource management, infrastructure optimization, enhancing decision-making processes, and creating resilient and adaptive urban systems (Digital Twin Cities: Framework and Global Practices, 2022). CIM combines BIM methodology with GIS to create a model that compiles and arranges all information into a single database, serving as a foundation that is essential for managing smart cities. Generally, CIM consists of a 3D urban information complex that integrates city data from different temporal and spatial dimensions. It is built based on GIS, BIM, and IoT technologies.

City Information Modeling (CIM) expands the concept of Building Information Modeling (BIM) to an urban scale, by managing a 3D model using a data-centric approach. This integration provides a comprehensive view of the city, facilitating real-time collaboration among professionals on a unified data source, thereby improving city planning, development, and maintenance. CIM combines the visualization and analysis capabilities of BIM with the spatial-temporal localization of Geographic Information Systems (GIS), referencing all accessible urban data. Solutions like ACCA software's usBIM.geotwin exemplifies this integration by combining GIS data with openBIM IFC models to create and manage geospatial Digital Twins (BibLus Editorial Team, 2024).

The foundational platform of CIM displays information visually by integrating comprehensive 3D models and asset data from BIM, such as addresses, population statistics, housing, units, facilities, and more. BIM facilitates the development of 3D models and makes it easier to integrate temporal and spatial data about certain city points. By combining these discrete points, GIS generates an overall view of the city that illustrates the interaction between the physical environment and structures. In addition, by integrating models with data from sensors and other IoT devices, CIM is developing to continuously contribute to city asset management. The Internet of Things (IoT) makes it possible to continuously gather data about the built environment, highlighting the connections that exist between people, machines, and objects in the city at any given time and location (International Electrotechnical Commission, 2021).

A list of common GIS file formats and the Software they are compatible with is shown in Table 8, adapted from (Carleton University Library, 2024)

Table 8– GIS file formats and their supporting software

File Format	File Extension(s)	Supported Software
AutoCAD Drawings	.dwg, .dxf	ArcGIS Pro, QGIS, Global Mapper
Digital Elevation Models	.dem, .flt, .csv, .tif, .txt, .hgt	Global Mapper, ArcGIS Desktop/ArcMap, ArcGIS Pro, QGIS, AutoCAD Map 3D (with extension)
Esri File Geodatabase	.gdb	ArcGIS Pro, ArcMap, ArcGIS Online
Esri Layer File	.lyr	ArcGIS Desktop (ArcMap, ArcCatalog, ArcGIS Pro)

Shapefile	.shp	ArcGIS Pro, ArcGIS Online, ArcMap, Global Mapper, QGIS
Geography Markup Language	.gml	Global Mapper, ArcGIS Pro, and ArcMap (with Data Interoperability extension)
GeoJSON	.json, .geojson	QGIS, Global Mapper, ArcGIS Online, ArcGIS Pro (requires conversion)
GeoPackage	.gpkg	QGIS, ArcGIS Pro, ArcGIS Online, Global Mapper
KML - Keyhole Markup Language	.kml, .kmz	Global Mapper, QGIS, ArcGIS Pro (with limitation), ArcGIS Online (view-only)
LiDAR	.las, .laz, .zlas	Global Mapper, ArcMap, ArcGIS Pro
Esri Layer Package	.lpx, .lpxx	ArcGIS Pro, ArcGIS Desktop/ArcMap, Global Mapper (.lpx), 7zip, Archive Utility (Mac)

CIM/UIM is a vital tool for planning Smart Cities. Currently, the cities of Singapore, Helsinki, London, and Rotterdam are utilizing and developing Urban or City Digital Twins. The integration of BIM and GIS technologies allows for the development of a semantically enriched City Information Model, providing a structured framework for organizing urban data (X. Xu et al., 2014). The integration of BIM (Building Information Modeling) and GIS (Geographic Information Systems) forms the basis for building and managing smart cities. In short, BIM+GIS=Smart City, (Andrews, 2018).

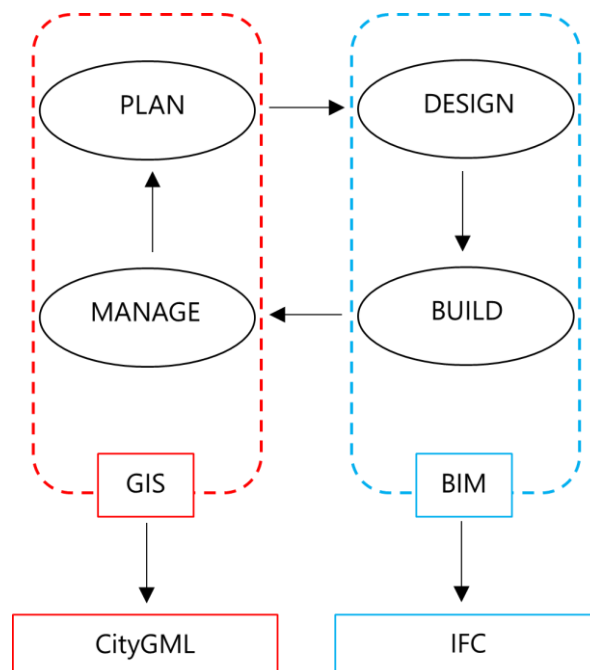


Fig. 6– Connectivity of GIS and BIM;
Source: Adapted from(Andrews,2018 & buildingSMART USA,2021)

Industry Foundation Classes (IFC) is a standardized digital representation of the built environment, encompassing buildings and infrastructure. It is an open, international standard (ISO 16739-1:2018) that is vendor-neutral and compatible with various hardware, software, and interfaces. The IFC schema, developed by buildingSMART International, promotes openBIM® by logically codifying the identity, characteristics, and relationships of objects, abstract concepts, processes, and people within the built environment (buildingSMART International, 2024).

CityGML is an open standard that defines a conceptual model and exchange format for virtual 3D city models. It enables the integration of diverse urban geospatial data, facilitating applications for Smart Cities and Urban Digital Twins in areas such as urban planning, Building Information Modeling (BIM), disaster management, tourism, navigation, facility management, and simulations of energy, traffic, and the environment (Open Geospatial Consortium, 2024).

CityGML enables the representation of building models in five increasing levels of detail (LODs), from LOD0 to LOD4, to manage complexity. As shown in Figure 7, higher LODs provide more detailed and accurate representations, allowing users to choose the appropriate level of detail for their specific needs.

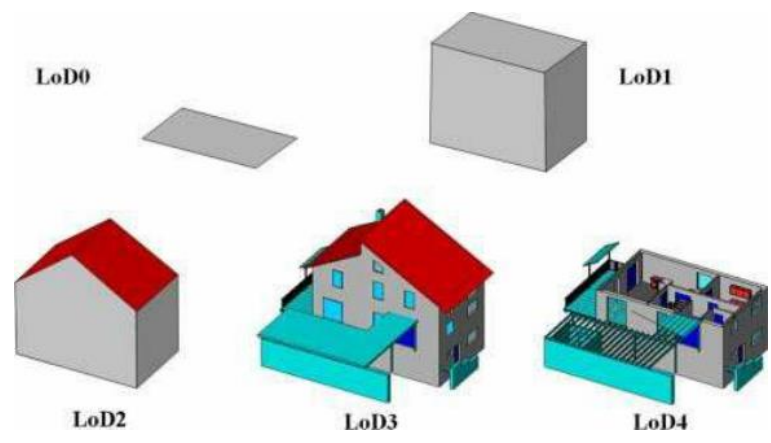


Fig. 7– Illustration of LOD Concept in CityGML;
Source: (Akmalia et al., 2014)

Table 9– Definition of LODs in CityGML; Source: Adapted from (Kolbe, 2009)

LOD0	LOD1	LOD2	LOD3	LOD4
Two-and-a-half-dimensional digital terrain model (DTM)	Blocks model	Roof structures and larger building installations like balconies and stairs	Architectural models with detailed wall and roof structures, doors, windows and bays	LOD3 model with interior structures like rooms, stairs, and furniture

Table 10– Comparison between CityGML and IFC; Source: Adapted from (Weil et al., 2023)

Format	CityGML	IFC
Maintainer/standard organization	Open Geospatial Consortium (OGC)	buildingSMART
Technology/process	GIS	BIM
Purpose	Representation, storage, and exchange of virtual 3D city models.	Data model and exchange format for building and infrastructure data.
Focus	Cities objects: Buildings, Roads, Bridges, Vegetation, Water bodies, Transportation, Land use, Relief, etc.	Building & AEC (system, components), surrounding site.
Software provider	ESRI	Autodesk
Semantic	Yes	Yes
Spatial (Geometry)	Yes	Yes
3D Geometry	Yes	Yes
Conceptual Model	Conceptual Model Standard ("OGC City Geography Markup Language (CityGML) Part 1: Conceptual Model Standard,").	Specification of the IFC standard

Several commercial software systems and free tools or services that provide support to CityGML are shown in Table 11 and Table 12.

Table 11– Supported Commercial Software Systems; Source: Adapted from (CityGML Wiki, 2020)

Software/Tool	Developer/Company	Key Features
CityEditor	3DIS GmbH	Import, edit, export, and present CityGML models using SketchUp
3D-MAP	3DIS GmbH	Web-based platform for managing, processing, and visualizing 3D city models
Bentley Map	Bentley Systems	Advanced 3D GIS tool with CityGML support
BS Contact Geo	Bitmanagement	3D visualization of GIS and geodata with CityGML support
CityGRID	UVM Systems	Manage and edit 3D city models
CodeSynthesis XSD	Code Synthesis	Open-source XML data binding compiler for C++ with CityGML support

FME	Safe Software	Provides CityGML reading and writing capabilities
FME Technology	con terra GmbH	CityGML Reading and Writing capabilities within FME
Galdos INscape CityGML Server	Galdos Systems Inc.	Web Feature Service-Transactional (WFS-T) is fully compliant with CityGML and supports user-defined extensions
Galdos INdicio CityGML Registry	Galdos Systems Inc.	Manages code lists and schema components for CityGML
Galdos CityGML INspector	Galdos Systems Inc.	Advanced visual inspection and quality assurance for CityGML data
PlexMap	GEOPLEX	A browser-based platform for storing, processing, and visualizing CityGML data
VC Suite	Virtual City Systems	Modular solution for storage, management, distribution, and visualization of CityGML data

Table 12– Supported Free Tools and Services; Source: Adapted from (CityGML Wiki, 2024)

Software/Tool	Developer/Company/ Institution	Key Features
tridicon(R) CityDiscoverer light	3DCon GmbH (part of Hexagon)	Viewer for CityGML data
eveBIM	CSTB	Multi-scale viewer for CityGML, IFC, BCF, and GIS files with various plugins
GEORES for Sketchup	GEORES	Free and open-source SketchUp plugin to export CityGML data
KITModelViewer (FZKViewer)	Karlsruhe Institute of Technology, Institute for Applied Computer Science	Viewer for CityGML, IFC, gbXML, LandXML, CIM (IEC), and point clouds data
Liquid XML Editor	Liquid Technologies Ltd.	Free graphical XML schema editor, intelligence XML editor, and validator
BIMserver	Open source BIMserver	Open-source building information model server with CityGML export and visualization in 03D
GML Viewer	Snowflake Software	Generic 2D GML viewer capable of viewing CityGML
TerrainView	ViewTec	Free (for non-profit use) 3D viewer with CityGML support
3D City Database	Technical University of Munich, Chair of Geoinformatics	Free 3D geo database for storing and managing virtual 3D city models, includes web client based on Cesium

QS-City 3D	University of Applied Science, Stuttgart	Free online service and downloadable software for checking CityGML data
Aristoteles	University of Bonn, Institute for Cartography and Geoinformation	Open-source viewer for CityGML data
citygml4j	virtualcitySYSTEMS	Open-source Java class library and API for processing 3D city models in CityGML

The goal of both city information modeling (CIM) and urban digital twins (UDT) is to facilitate urban planning for proper city management by using data and smart technologies. It is needed to investigate how to enhance Industry Foundation Classes (IFC) and CityGML data models to fulfill the requirements of CIM/UDT (International Electrotechnical Commission, 2021).

There are various CIM platforms developed by different companies. The following are some of these platforms:

Table 13 – CIM/UIM Platforms; Source: Author

CIM Platform	Focus	Features	Example of Supporting Software	Reference
Esri ArcGIS CityEngine 	3D City Modelling, Visualization, Integration of GIS Data	_Advanced 3D Modelling Tool _Rule-based Design _Simulation features _Integration with other Esri products	1. ArcGIS Pro (for GIS data integration and analysis)  2. ArcGIS Urban (for urban planning, zoning, and stakeholder engagement) 	(Esri)
Bentley OpenCities Planner 	Urban Planning and Design, Collaboration, BIM, and GIS Integration	_Interactive 3D Visualization _Stakeholder Engagement Tools (feedback collection through polls, surveys, and pins) _Cloud-based Collaboration _Create, Visualize, and Analyze Scenarios	1. MicroStation (for advanced 3D modeling)  2. Reality Modeling WorkSuite (for reality modeling) 	(Bentley Systems)

Table 14– Supported File Formats by Esri CityEngine; Source: (Esri)

Import Format	Export Format
Import by drag and drop; Import by dialog	3D format
DAE (COLLADA)	ABC (Alembic)
DWG (Autodesk)	DAE (COLLADA)
DXF (AutoCAD)	DATASMITH (Unreal and Twinmotion)
FBX (Autodesk)	DWG (Autodesk)
FGDB (Esri File Geodatabase)	FBX (Autodesk)
glTF (Khronos Group)	glTF (Khronos Group)
IFC (buildingSMART)	IFC (buildingSMART)
KMZ/KML (Keyhole Markup Language)	OBJ (Wavefront)
OBJ (Wavefront)	USD (Universal Scene Description)
OSM (Open Street Map)	VOB (e-on VUE)
SHP (Esri Shapefile)	3D GIS format
USD (Universal Scene Description)	FileGDB (Esri File Geodatabase)
Image File	KMZ/KML (Keyhole Markup Language)
	ArcGIS Online format
	MSPK (Mobile Scene Package)
	SLPK (Esri Scene Layer Package)
	3VR (360 VR Experience)
	Material format
	CGA Material
	Custom export format
	Python (script-based export)

2.4.3. APPLICATIONS AND CHALLENGES

Based on BIM-GIS integration according to (Zhang, 2024), the applications of CIM include the following but are not limited to these.

- Urban planning
- Urban facility management
- Urban flood hazard assessment
- Route and evacuation planning
- Underground space development
- Underground utility management
- Building energy analysis and management

There are many challenges in the way of implementing a digital twin-based smart city, the most significant of which is the vertical nature of city administration. Various municipal agencies use proprietary software and data models to create their own digital twins after collecting data in distinct, frequently incompatible formats. To solve this issue, a city's digital twin needs an open platform that enables co-building, co-sharing, and co-governance (International Electrotechnical Commission, 2021).

Major challenges for including DT in cities or urban areas include the following:

- Data Collection (Cost and Complex System)
- Model Accuracy (Quality and Completeness of Data)
- Interoperability (DT need to exchange Data)

Integrating both outdoor and indoor information into a unified City Information Model (CIM), a crucial component of DTs, also presents a significant challenge (X. Xu et al., 2014). CIM, as an emerging technique, faces technical and management issues including data accuracy, limited automation, and collaborative design across diverse stakeholders (Z. Xu et al., 2021). Moreover, data exchange formats, a lack of dynamic data, and effective data management pose further challenges to CIM implementation (Schaufler & Schwimmer, 2020).

3

METHODOLOGY

3.1. RESEARCH DESIGN

This research adopts an action research approach to answer the research questions. The research design is mainly exploratory and explanatory, aiming to identify the potential synergies among digital twins, Blue-Green Infrastructure (BGI), and Urban Information Modeling (UIM). It follows a mixed-methods design, which combines a comprehensive review of existing studies with an analysis of a pilot study.

A flowchart is presented below to illustrate the research methodology (see Figure 8). The research begins with a thorough analysis of the literature and ends with recommendations for urban professionals. Each stage of the research process is designed to address specific research objectives, concluding with a better understanding of how integrating BGI can enhance urban resilience and sustainability.

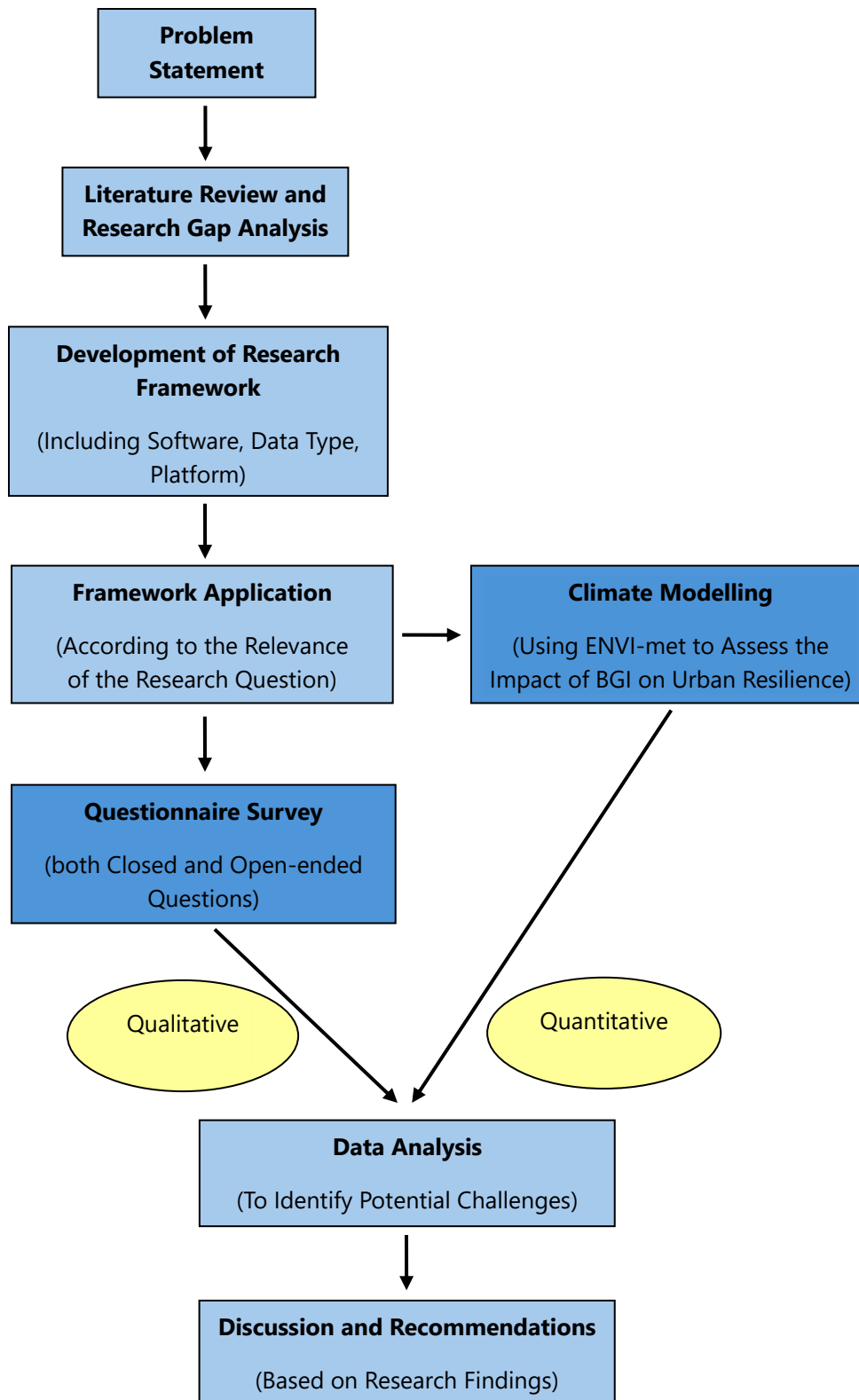


Fig. 8– Research Methodology; Source: Author

3.2. RESEARCH FRAMEWORK

Based on the knowledge synthesized from the literature review, Figure 9 presents a simplified conceptual diagram illustrating the integration of data into the Urban Information Modeling (UIM) environment. This diagram serves as the foundation for the development of the 3D BGI model integration framework proposed in this research.

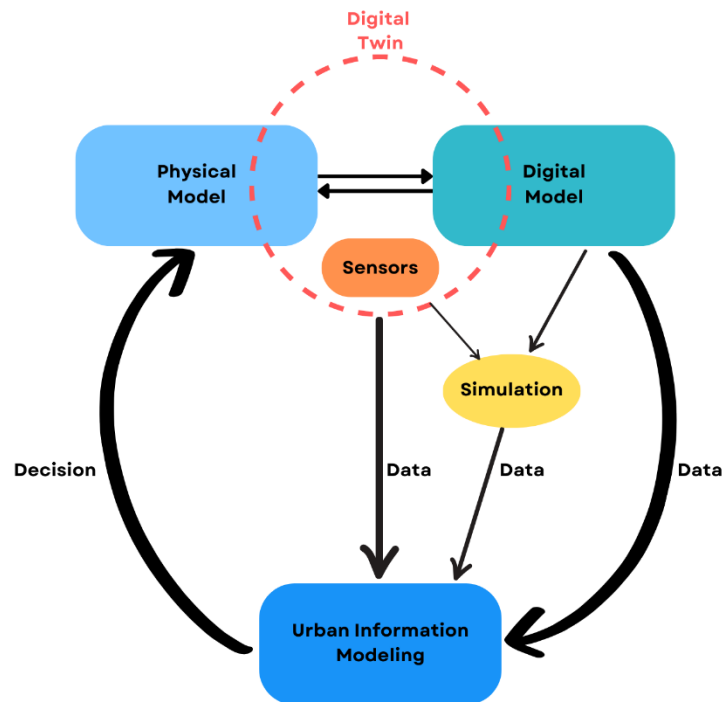


Fig. 9– Conceptual Diagram of Data Integration into UIM; Source: Author

3.2.1. FRAMEWORK FOR INTEGRATING BGI INTO UIM

Step 1: Modelling of BGI

3D models of different types of BGI (Green wall, Green roof, Bioswale, Tree, etc.) can be created using BIM software such as Autodesk Revit, Bentley Systems AECOSim Building Designer, Graphisoft ArchiCAD, etc. If available, the BIM models can also be downloaded from free BIM object libraries such as BIMObject.

Step 2: Export to IFC Format

After the creation of a 3D model of BGI elements in BIM software, it can be exported in the IFC (Industry Foundation Classes) format. IFC is an open standard for exchanging BIM data, representing building and infrastructure elements as volumetric models with associated semantic information, therefore it can be used for representing BGI elements as well. While IFC models can have varying levels of geometric complexity and utilize local coordinate systems in general, they are not limited to local coordinates. Georeferencing can be applied to align them with real-world coordinates (UTM or geographic coordinates).

Step 3: Conversion to CityGML

The IFC format which is commonly used for BIM volumetric models can be converted into the CityGML format using conversion software such as FME (Feature Manipulation Engine). FME facilitates the process by restructuring data models including geometry, attributes, coordinate systems, and projections.

In general, IFC to CityGML workflow, adapted from (Campanas & Hintz, 2013), involves the following steps:

- Reading the IFC file
- Compelling solid geometries to surfaces
- Resolving the relationship between elements
- Schema mapping IFC to corresponding CityGML feature types and fields
- Generating IDs, assigning appropriate LODs, and format attributes
- Constructing CityGML object
- Validating the resulting model
- Geo-referencing the model to a real-world coordinate system
- Writing the output CityGML file

The CityGML standard itself is divided into a core module and several thematic modules, including various aspects of urban environments such as the following.

- Appearance module
- Building module
- Bridge module
- Relief (Terrain) module
- CityFurniture module
- CityObjectGroup module
- Generics module
- LandUse module
- Transportation module
- Tunnel module
- Vegetation module
- WaterObject module

Annex A provides an overview of the feature types within the Vegetation and WaterObject modules in CityGML, detailing both non-spatial and spatial properties, their respective types, and the possible range of Levels of Detail (LOD) for each property (Open Geospatial Consortium, 2012). This comprehensive structure, encompassing a wide array of urban features with varying levels of detail, makes CityGML suitable for representing various Blue-Green Infrastructure (BGI) elements as well.

Step 4: Export to Shapefile Format

The CityGML model needs to be exported to Shapefile format, a widely supported GIS file type that enables further analysis and visualization in software like ArcGIS Pro and QGIS. Tools such as FME can be used to complete the conversion, allowing for customization of geometric simplification, attribute mapping, and feature extraction. Some details might be lost due to the limitations of the Shapefile format, but it allows seamless integration with climate modeling software such as ENVI-met.

Step 5: Import to ENVI-met

The generated shapefile, representing Blue-Green Infrastructure (BGI), can be imported into ENVI-met (Bruse & Fler, 1998), a microclimatic simulation software based on computational fluid dynamics (CFD). This integration allows for precise placement and representation of BGI elements within the model domain.

In ENVI-met, the modeling process is facilitated by the Monde and Spaces tools. The Monde tool enables the import of OpenStreetMap (OSM) data, which can be used to locate and define the pilot study area. Further refinement of the study area and the addition of BGI elements are done within Spaces. The Database Manager (DB Manager) provides the capability to add detailed specifications to the model, including building materials, vegetation types, and surface properties.

The boundary conditions are then set using ENVI-guide, which incorporates meteorological data relevant to the study area. The output is a (.SIMX) file, a comprehensive file format encompassing the 3D model, meteorological parameters, and additional simulation-specific details like duration and roughness values. Finally, the ENVI-core tool is used to run the simulation, generating results that can be analyzed and interpreted using the Leonardo tool.

Stage 6: Export and Integration of Results

Simulation results visualized in Leonardo can be exported as ASCII files, which can then be converted to raster datasets using GIS software such as ArcGIS Pro or ArcMap, or specialized conversion tools like FME. These raster datasets which are compatible with City Information Modeling (CIM) platforms such as ArcGIS CityEngine, can be integrated into the CIM/UIM environment.

The framework, shown in Figure 10, outlines the sequential steps involved in investigating the integration of the Blue-Green Infrastructure (BGI) model within Urban Information Modeling (UIM).

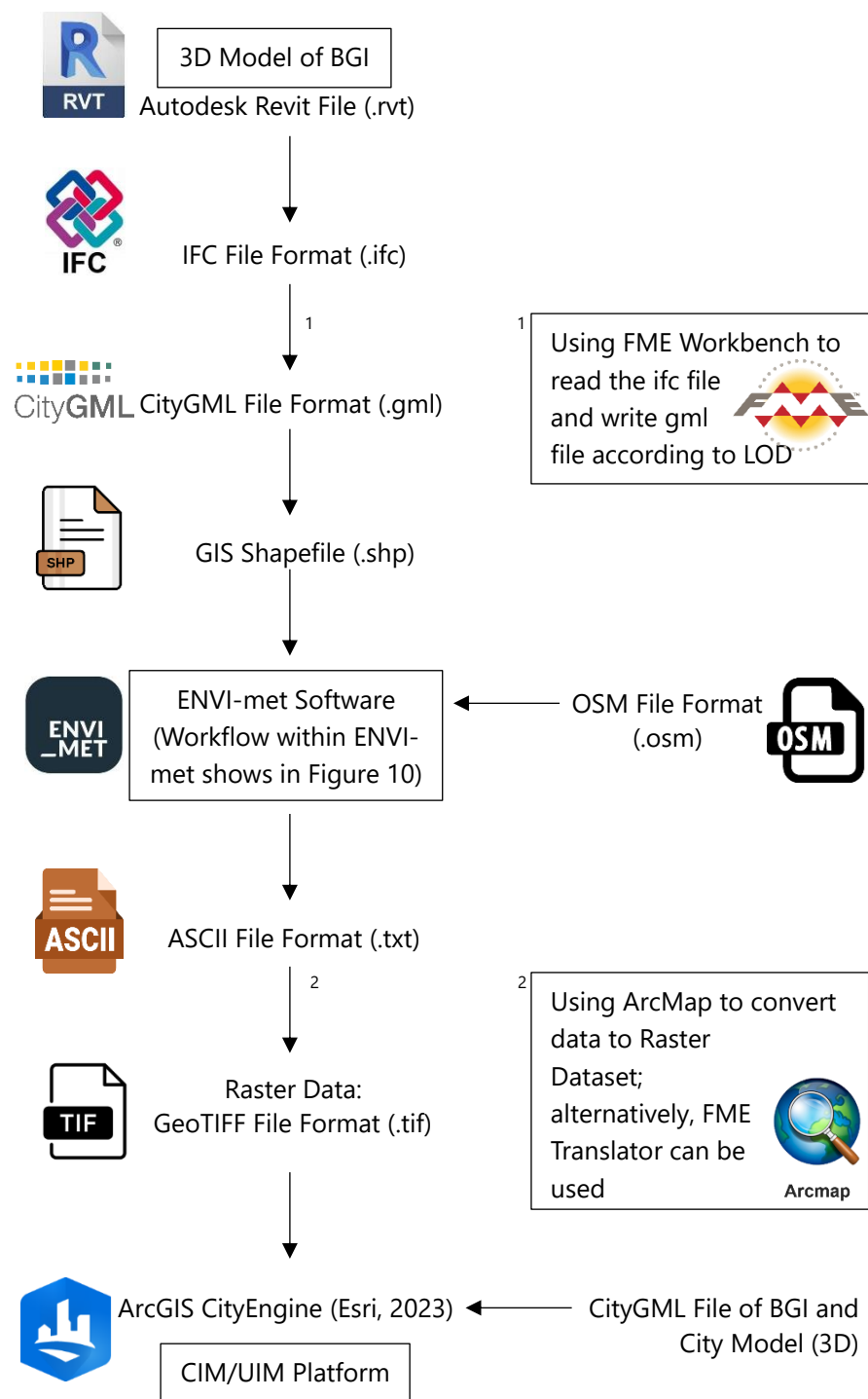


Fig. 10– Framework for Integrating 3D BGI Models into UIM; Source: Author

This integration enables the generation of maps, 3D visualizations, and analysis of microclimatic data alongside other urban factors within the context of the 3D city model. This can reveal how microclimatic conditions are distributed across the study area and how the microclimate affects the urban area at the city scale. By integrating BGI data into the UIM framework, a comprehensive evaluation of Blue-Green Infrastructure (BGI) performance can be conducted, contributing to sustainable urban planning decisions.

The workflow within the ENVI-met software is shown below.

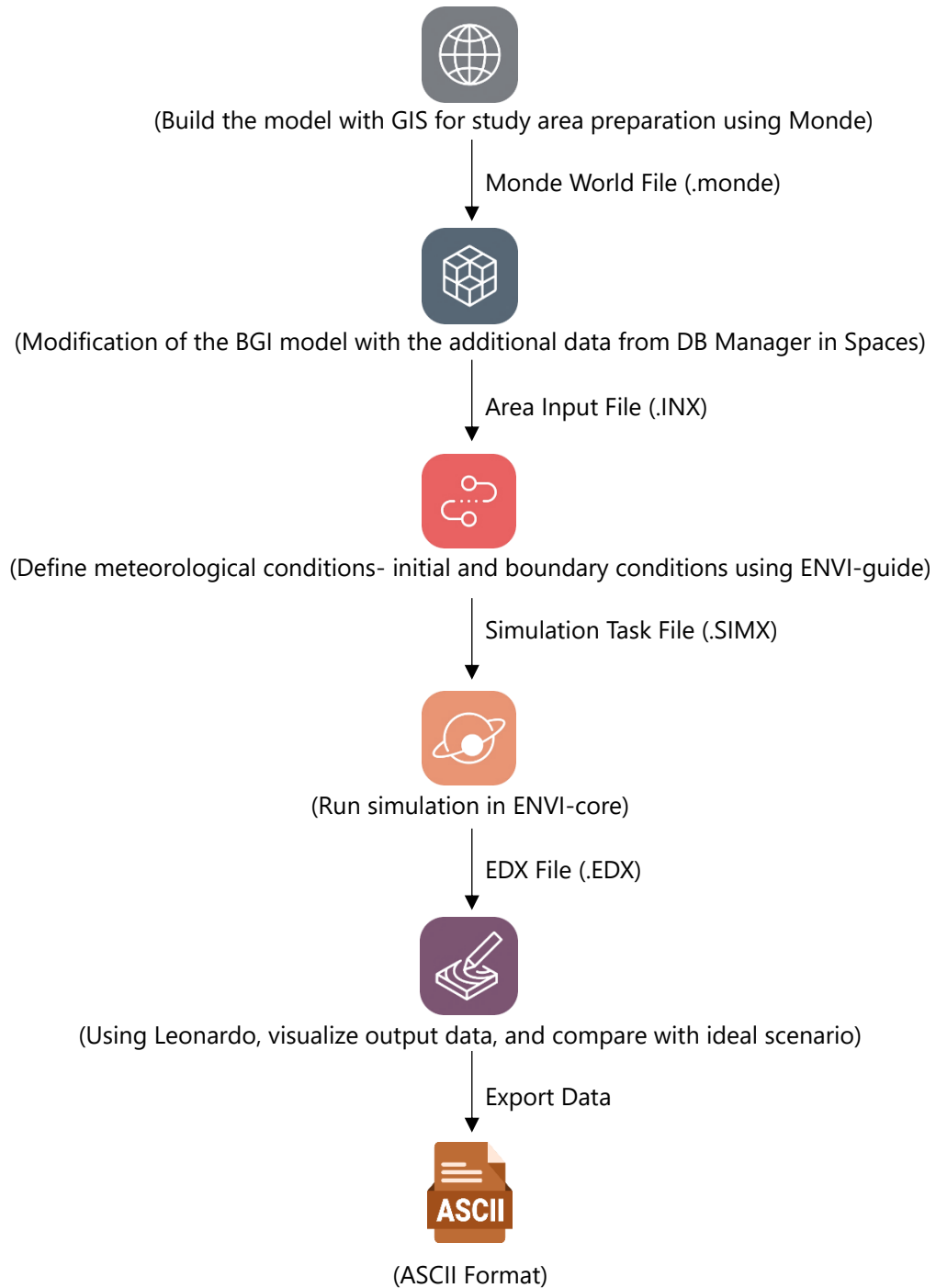


Fig. 11– Workflow within ENVI-met; Source: Author

3.2.2. SELECTION OF CLIMATE MODELING

The problem statement of this research focuses on environmental degradation and the increasing discomfort of living conditions worldwide. This study considers the environmental impacts in this context. The environmental impacts of Blue-Green Infrastructure (BGI) in urban planning can be demonstrated through the following various impacts shown in Table 15.

Table 15– Modelling of Environmental Impacts; Source: Author

Environmental Impacts	Modeling Technique	Examples of Software	Reference
Climate impacts	Climate modelling	MUKLIMO_3, ENVI-met, etc.	(Deutscher Wetterdienst -DWD), (ENVI-met GmbH)
Hydrological impacts	Hydrological modelling	QGIS, MODFLOW, PRMS, etc.	(QGIS), (USGS), (USGS)
Ecological impacts	Ecological/ecosystem modeling	Biome-BGC, EwE, GLOBIO, etc.	(NTSG), (Ecopath International Initiative), (Netherlands Environmental Assessment Agency)
Noise reduction	Noise propagation modeling	CadnaA, SoundPLAN, etc.	(DataKustik GmbH), (SoundPLAN GmbH)
Pollutant removal	Air quality modeling, Water quality modeling	AERMOD View, QUAL2K, etc.	(Lakes Environmental Software), (QUAL2K)

Climate impacts are directly associated with climate change and its effects such as the urban heat island effect and increased natural disasters. Considering these factors, climate modeling has been selected as the primary focus of this research. Among the software listed, ENVI-met is particularly suitable for this purpose, as it excels in working with 3D volumetric models, OpenStreetMap (OSM) data, and Shapefiles – formats that are essential to the development of the research framework. Therefore, ENVI-met has been identified to be the optimal choice for climate modeling in this research.

3.3. DATA COLLECTION METHODS

3.3.1. LITERATURE REVIEW

To conduct a comprehensive literature review, various platforms are utilized to access academic literature. These platforms include Web of Science (WoS), Scopus, ScienceDirect, Google Scholar, and ResearchGate.

WoS, Scopus, and ScienceDirect are preferred for their focus on scholarly articles from credible journals. Meanwhile, Google Scholar and ResearchGate provide a broader scope, encompassing diverse content such as books, conference proceedings, and preprints. The combined use of these platforms facilitates a thorough examination of existing literature, enabling the identification of relevant studies and insights for potential research.

3.3.2. QUESTIONNAIRE SURVEY

In this study, data collection was intended to involve using a structured questionnaire. A questionnaire was designed (see Annex B) which included both closed-ended (e.g., multiple choice, Likert scale) and open-ended questions. This approach allows for the comprehensive gathering of insights from professionals regarding their preferences for various aspects of Blue-Green Infrastructure (BGI), including types, scales, positions, and sizes within the selected urban area. By incorporating a mix of quantitative

and qualitative responses, the questionnaire was aimed to capture a diverse range of perspectives and preferences. Future research or practical implementation projects are highly encouraged to conduct similar surveys to gather insights from local people and professionals, ensuring community engagement and informed decision-making.

3.3.3. CLIMATE MODELLING

ENVI-met, a microclimate simulation software, has been used to gather data both before and after BGI implementation at the selected study area to simulate the microclimate effects of various BGI configurations, combining relevant weather data and site-specific parameters. Through ENVI-met various environmental parameters such as air temperature, humidity, wind speed, etc. have been simulated and analyzed.

3.4. DATA ANALYSIS

Data analysis in this mixed-methods action research focused on applying and refining the proposed framework for integrating BGI into UIM. The primary data sources included documenting the process of incorporating 3D BGI models into UIM, specifically addressing challenges and solutions related to data conversion and format compatibility across various software platforms. Additionally, ENVI-met simulations were conducted to compare scenarios with and without BGI, allowing for the evaluation of BGI's impact on microclimatic parameters. The analysis further identified potential challenges and limitations encountered during the application of the framework, providing valuable insights for future research and development in this field.

3.5. LIMITATIONS

The following are the potential limitations of the research:

- i. **Software Constraints:** The use of a student version of ENVI-met software limits the complexity of the simulations that can be conducted, potentially affecting the comprehensiveness of the microclimate modeling.
- ii. **Data Availability and Accuracy:** The accuracy and availability of data for climate modeling can pose significant challenges. Outdated weather data, incomplete vegetation database, and site-specific parameters may impact the accuracy of the simulation results.
- iii. **Integration Challenges:** Technical difficulties, such as incompatibilities between different software platforms and data formats, arise when integrating the BGI into the UIM environment.
- iv. **Technical Challenge:** Limited expertise in data conversion software posed a challenge in thoroughly checking object attributes and feature classes during the integration process.
- v. **Time Constraints:** The research timeline limits the option to conduct a questionnaire survey to assess the public's perception of BGI and its long-term impacts in practical applications. Additionally, this constraint restricted the exploration of alternative software options for evaluating data interoperability issues during the integration process.

By following this research framework and addressing these limitations, this research aims to contribute to the understanding of how integrating BGI within UIM can facilitate sustainable urban planning practices and contribute to the development of smart resilient cities.

4

FRAMEWORK APPLICATION

4.1. DESCRIPTION OF THE PILOT STUDY AREA

The area for the pilot study has been selected in the city of Giessen, Germany. Germany was an early adopter of BGI in Europe initiated by the European Union's Biodiversity Strategy (Hu et al., 2020). German planning regulations permit the incorporation of Blue-Green Infrastructure (*Deutsche Vereinigung Für Wasserwirtschaft Abwasser Und Abfall e.v.*, 2021 & *Abwasser Und Abfall e.v.*, 2021).

The study is focused on Giessen (see Figure 12). It is a town in the middle of Hessen, in central Germany. Covering an area of 72.56 square kilometers, Giessen had an estimated population of 83,628 as of June 2015 according to the population census.

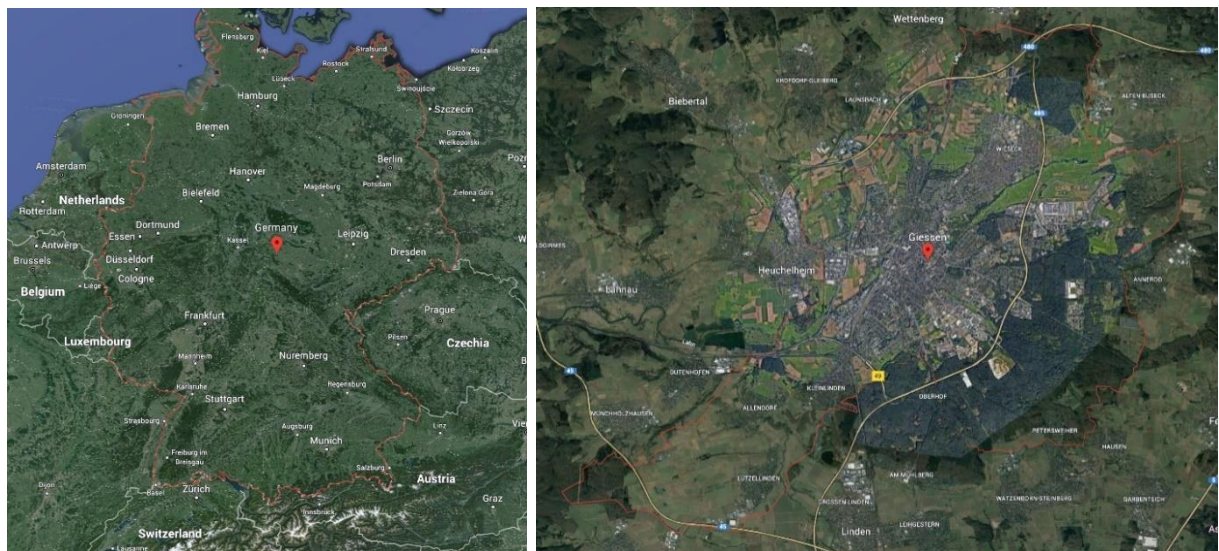


Fig. 12– Site Location; Source: Google Maps

The site for the thesis is situated in the university area of Giessen. This location (see Figure 13) was selected due to the necessity of intervention required for its physical layout and the current considerations for redevelopment in the area. Additionally, it is a public space under the university's jurisdiction, making it ideal for the implementation of Blue-Green Infrastructure without ownership issues. This site has the potential to become a valuable public space, providing health benefits and enhancing the quality of urban life for both students and nearby residents.

A SWOT analysis (see Table 16) has been conducted to gain a better understanding of the urban area.



Fig. 13– Pilot Study Area; Source: Google Maps

Table 16– SWOT Analysis of the site; Source: Author

Strength	Weakness	Opportunity	Threat
Existing Educational Land Use creates an environment where sustainable practices, of BGI, can be well-supported by the academic community.	The height of the buildings might cause challenges in integrating certain types of BGI due to structural limitations or higher costs.	The authority's current renovation considerations provide an opportunity to seamlessly incorporate new Blue-Green Infrastructure (BGI) initiatives into the plans, ensuring sustainable urban planning.	Increased temperatures and unpredictable weather conditions due to climate change could impact the maintenance of BGI.
The site's pedestrian-friendly design enhances the feasibility of implementing BGI, as there is less disruption from vehicular traffic.	Open circulation areas that experience high temperatures in summer can complicate the implementation of some green infrastructure solutions if not designed to withstand extreme heat.	The nearby Wieseck River and Lake of Schwanenteich Park offer opportunities for integrating water-based BGI solutions that can assist in managing stormwater and reducing heat.	–
BGI can improve the quality of urban life by providing green spaces that promote physical and mental well-being for both students and nearby residents.	–	–	–

The following are some detailed or close-up images of specific locations within the site area where Blue-Green Infrastructure (BGI) needs to be implemented.



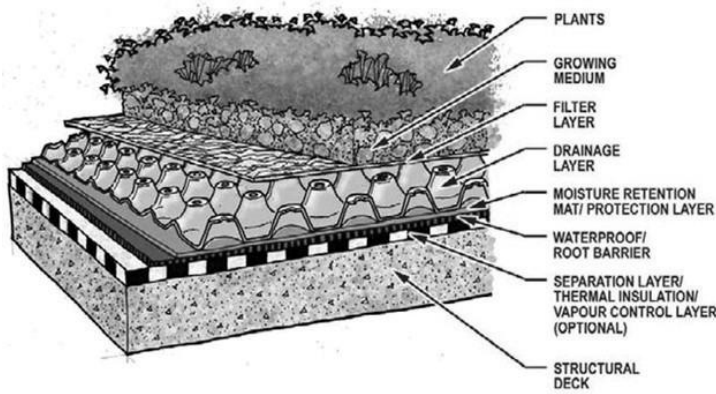
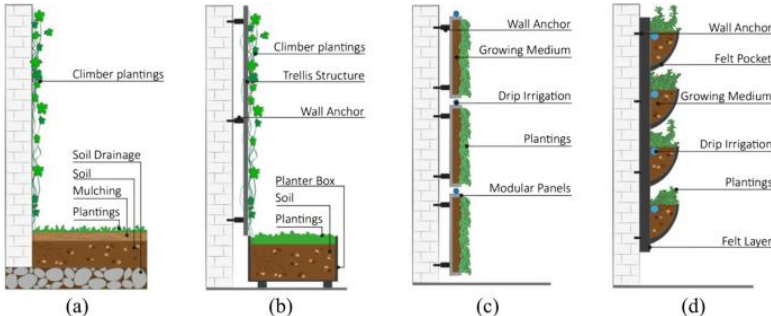
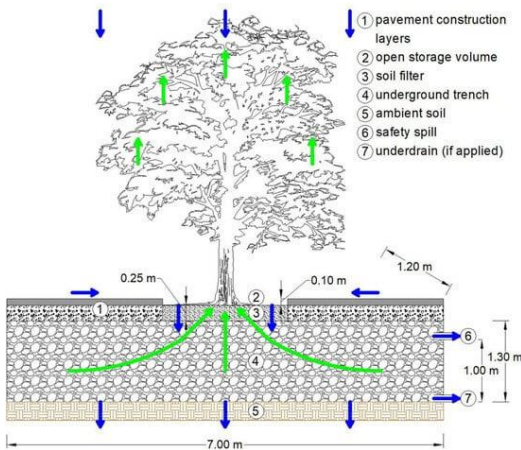
Fig. 14– Detailed Images within the Site Area; Source: Author

4.2. SELECTED BGI TYPE

Based on the field survey (observation method) and feasibility, selected BGI Types for implementation in specific locations of the site are listed below. Table 17 shows the selected BGI types and their examples for practical implementation.

For the modeling of the proposed BGI implemented scenario, ‘Street trees’ and ‘Green spaces’ are also considered along with these BGIs.

Table 17– Selected BGI for the Study Area; Source: Author

Selected BGI Type	Technical Details	Reference
Green Roofs		(Townshend, 2007)
Green Walls		(Ramadhan & Mahmoud, 2023)
Tree Trenches		(Novak et al., 2023)

Vegetated Swales

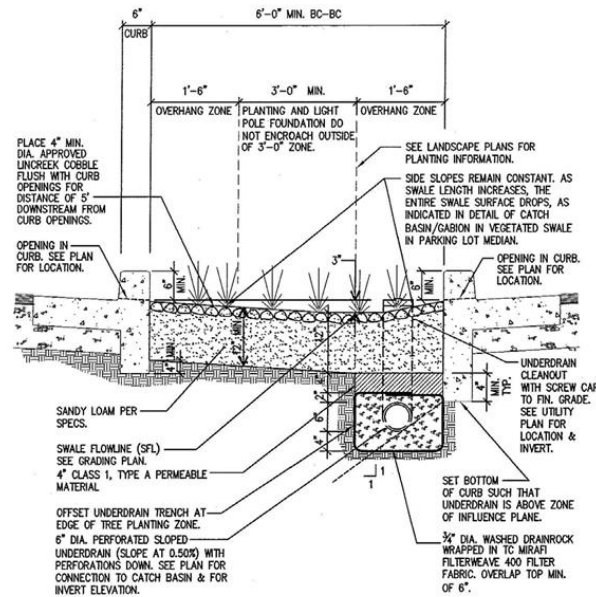
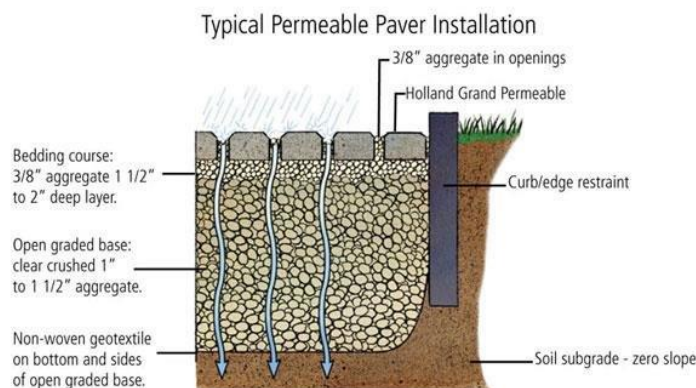


Figure 6-7: Vegetated Swale in Parking Lot Median at Beginning of Swale (Not to scale)

(Flowstobay, 2023)

Permeable Pavements



(Yau Seng Mah et al., 2016)

4.3. MODELING AND DATA CONVERSION

i. Autodesk Revit: Green wall, a BGI type, has been considered to implement the research framework. A 3D model of a Green wall, shown in Figure 15, has been downloaded from the source (NBS Enterprises Ltd., 2024). From its properties panel, it is visible that the Detail Level of the model is 'Fine'. Also, a Revit Family file (.rfa) of Tree has been downloaded from the source (BIMObject, 2024), shown in Figure 16. Here, the Detail Level is shown as 'Medium' which demonstrates that the Level of Detail (LOD) can vary depending on the model and intended use of the model. In the context of a 3D city model, the Level of Detail (LOD) of the BGI can be adjusted to LOD 1, 2, or higher depending on the specific requirements and visualization. In this application, the Revit file of the 'Green Wall' has been considered due to its level of detail for the research framework.

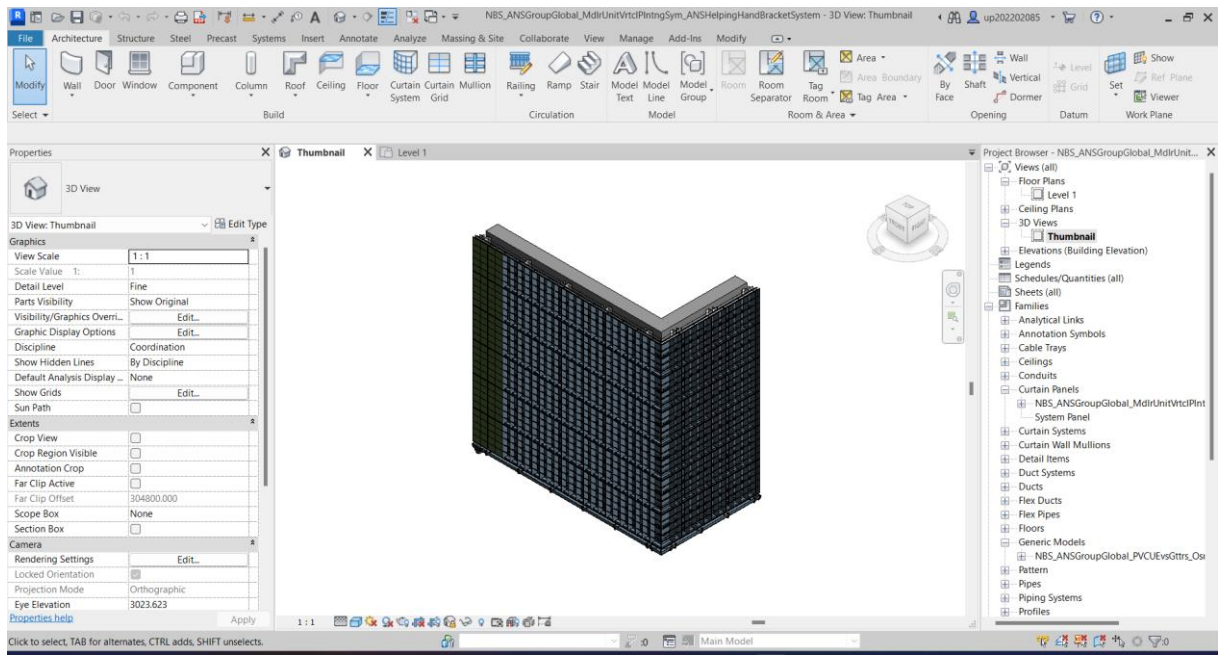


Fig. 15– 3D Model of Green Wall opened in Autodesk Revit; Source: Author

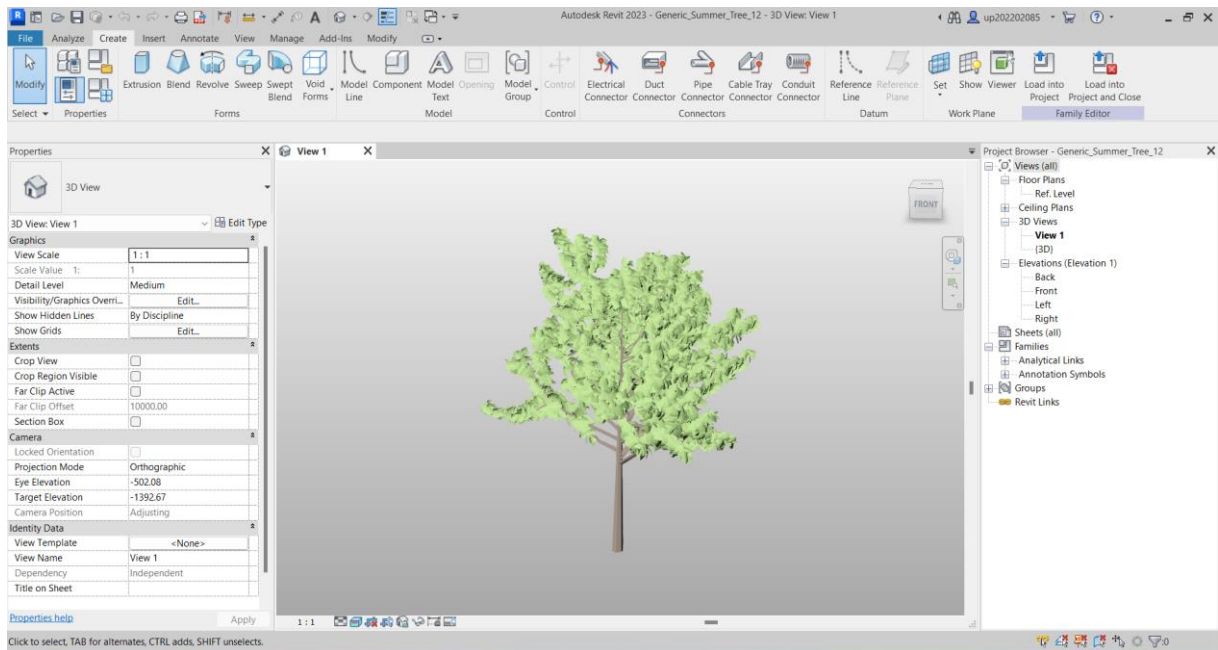


Fig. 16– Model of a tree; Source: Author

ii. FME: FME (Feature Manipulation Engine) is an 'all data' integration platform for supporting 14 different data types, including 3D, Geospatial and GIS Data, CAD and BIM, Business Systems and Intelligence, Big Data, Databases and Data warehouses, Real-time Events and Streams, Point Cloud/LiDAR, Markup Languages, Raster/Imagery, Sensor and IoT Devices, Augmented and Virtual Reality, Cognitive Systems (AI/ML), and Web Services (Safe Software, 2024).

Following the research design, the IFC file exported from Revit is opened in FME Workbench, as shown in Figure 17. This allows for the selection of specific parameters, enabling the extraction of only the

required data. If all parameters are kept, FME Workbench generates a comprehensive workflow, as shown in Figure 18, showcasing each feature type from the IFC file.

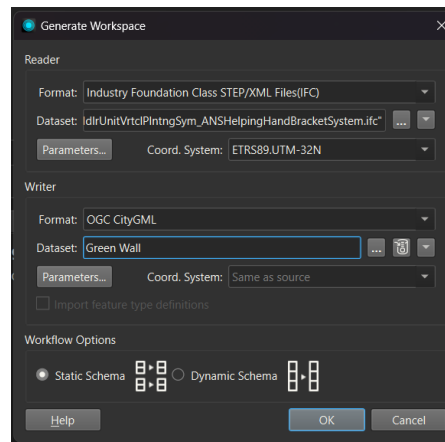


Fig. 17– Workspace Generate in FME Workbench; Source: Author

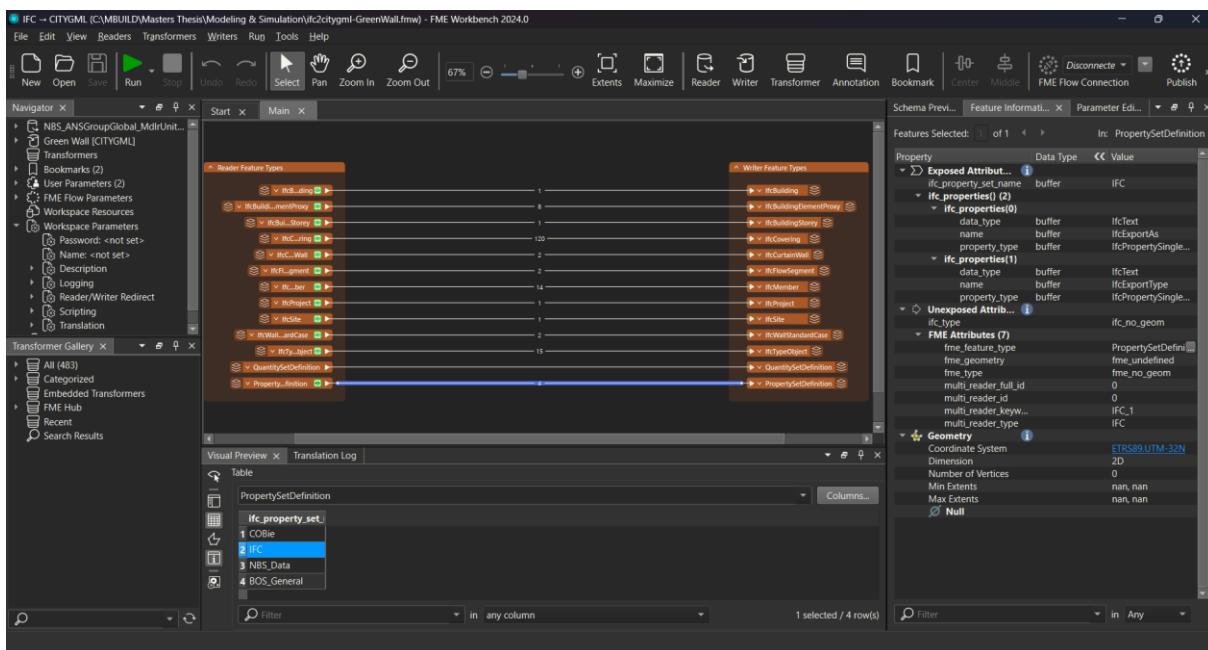


Fig. 18– Generated Workbench for ifc2citygml; Source: Author

Due to the limitation of required knowledge of reading the IFC file and then writing the CityGML file within FME Workbench, the simplified FME Quick Translator tool has been chosen for direct conversion of the Revit exported IFC Green Wall model into a Shapefile format, not from exporting the Shapefile from the CityGML.

The IFC file of the 3D Green wall model has been exported from Revit and it has been uploaded to the Free FME Quick Translator platform, as shown in Figures 19 and 20.

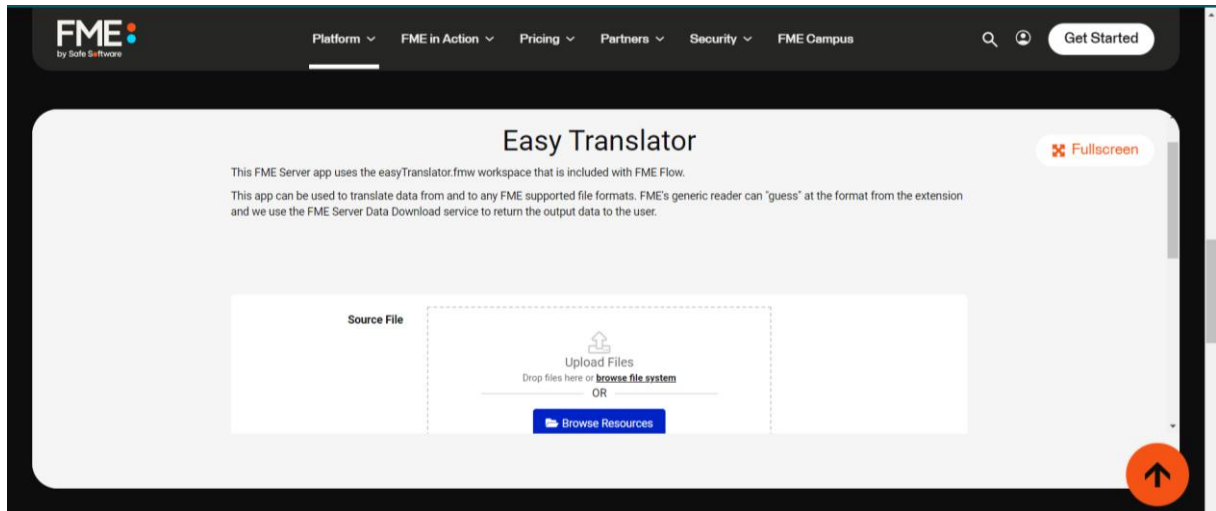


Fig. 19– FME Easy Translator Platform; Source: Author

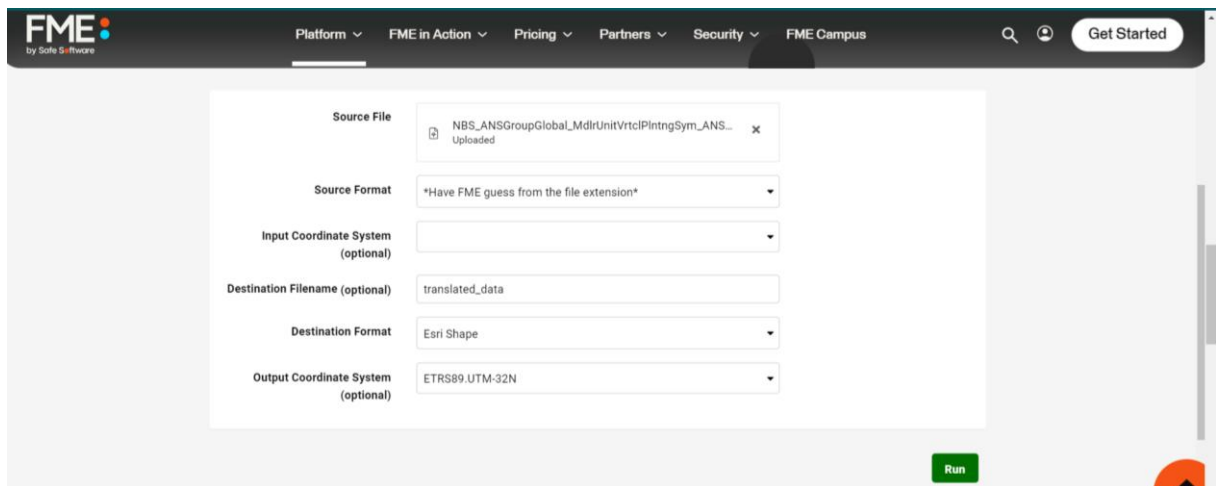


Fig. 20– Data Conversion Settings in FME; Source: Author

In the data conversion window, the destination file format has been set to Esri Shapefile and the coordinate system of the output file has been specified as ETRS89 UTM-32N, aligning it with the Study area's Coordinate System. The converted Shapefile can be downloaded easily after the conversion process as shown in Figure 21.

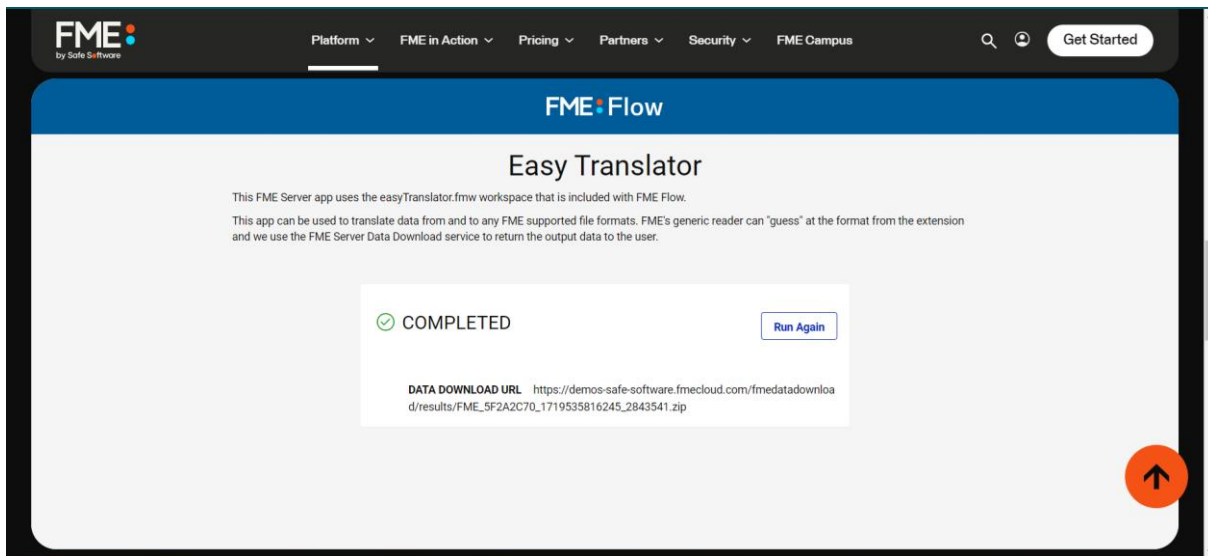


Fig. 21– Data Convert in FME Translator; Source: Author

iii. **ArcGIS:** The Green Wall Shapefile, converted from the IFC model, has been opened to check in ArcGIS Pro. Although the coordinate system was correct, as shown in Figure 22, the data is misplaced, showing in a different location not aligning with Giessen's location. To confirm this issue, the shapefile of existing trees having the correct coordinate system, has been opened and it has been positioned in the expected location as shown in Figure 23.

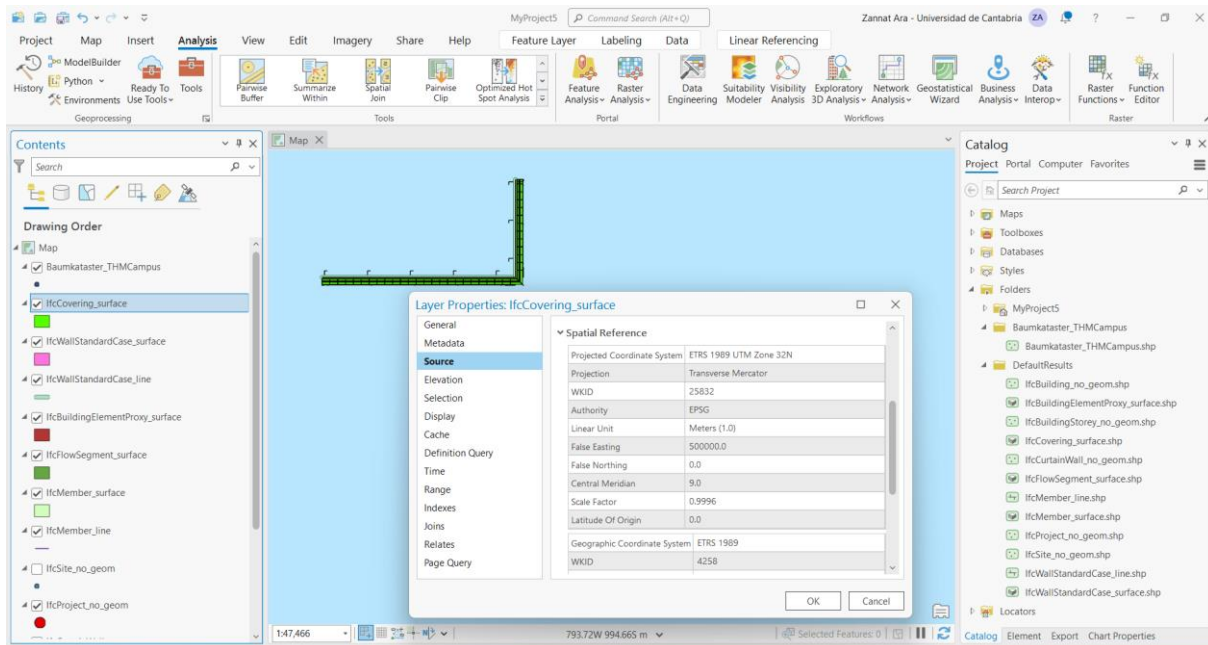


Fig. 22– Layer Properties of Green Wall; Source: Author

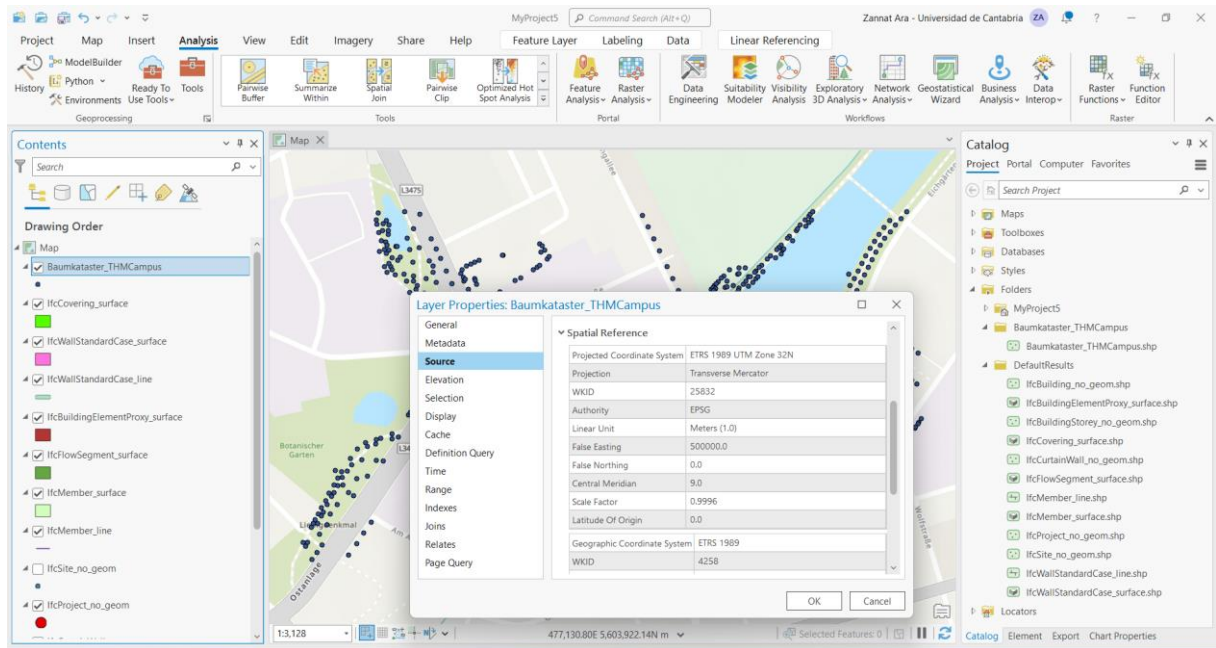


Fig. 23– Layer Properties of Trees; Source: Author

Despite using ArcGIS Pro tools such as 'Define Projection' and 'Feature Class' to correct the Green Wall Shapefile's Location, the positional inaccuracies remained, indicating a potential issue with the IFC model's georeferencing or the conversion process itself.

iv. ENVI-met: OpenStreetMap (OSM) data of Giessen, Germany has been imported into ENVI-met Monde. However, as defined by the rule, the water object is not present on the map (Figure 24). Although ENVI-met allows for the manual addition of water objects, the imported OSM data does not contain any information regarding water features in the area.

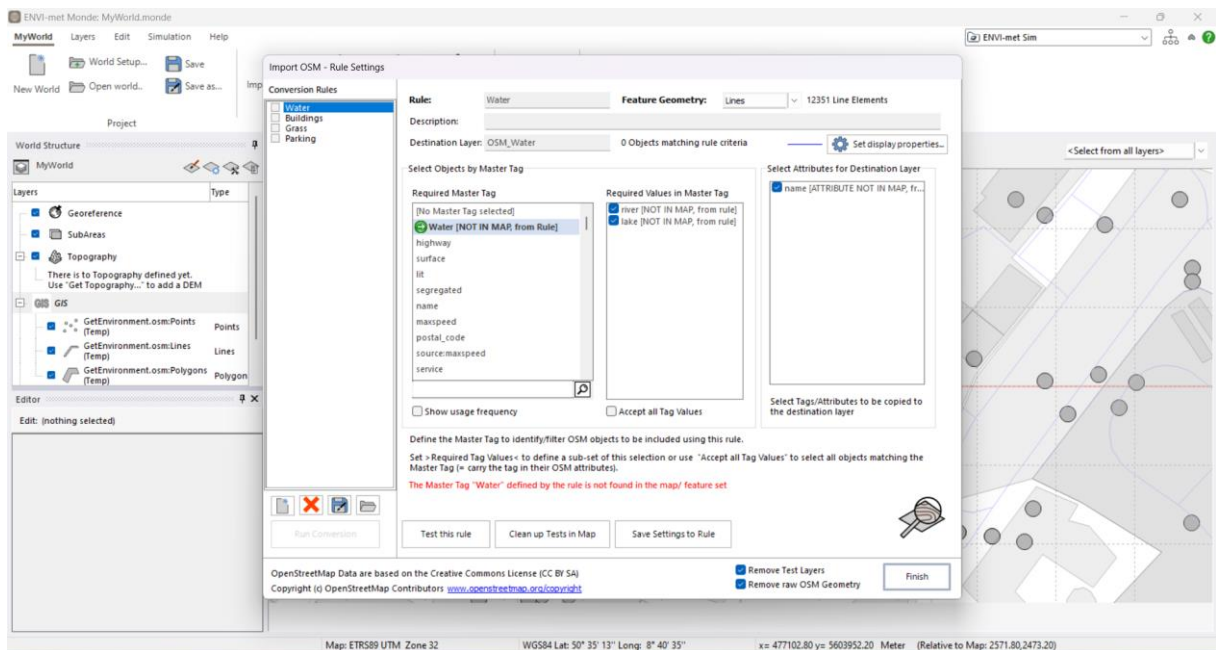


Fig. 24– The 'Water' object is not present by Defined Rule; Source: Author

The buildings are visualized using color from the display layer, with color assignment based on the selected attribute such as height. While the ENVI-met model within the study area contains a parking layer, there is no 'Grass' layer situated in the study area. In addition, the Student Version of ENVI-met has limited the ability to modify the attributes of the GIS layers, notably preventing adjustments to building heights as shown in Figure 25. However, ENVI-met tutorials and videos demonstrate that object attributes can be modified in the full version of the software (Figure 26).

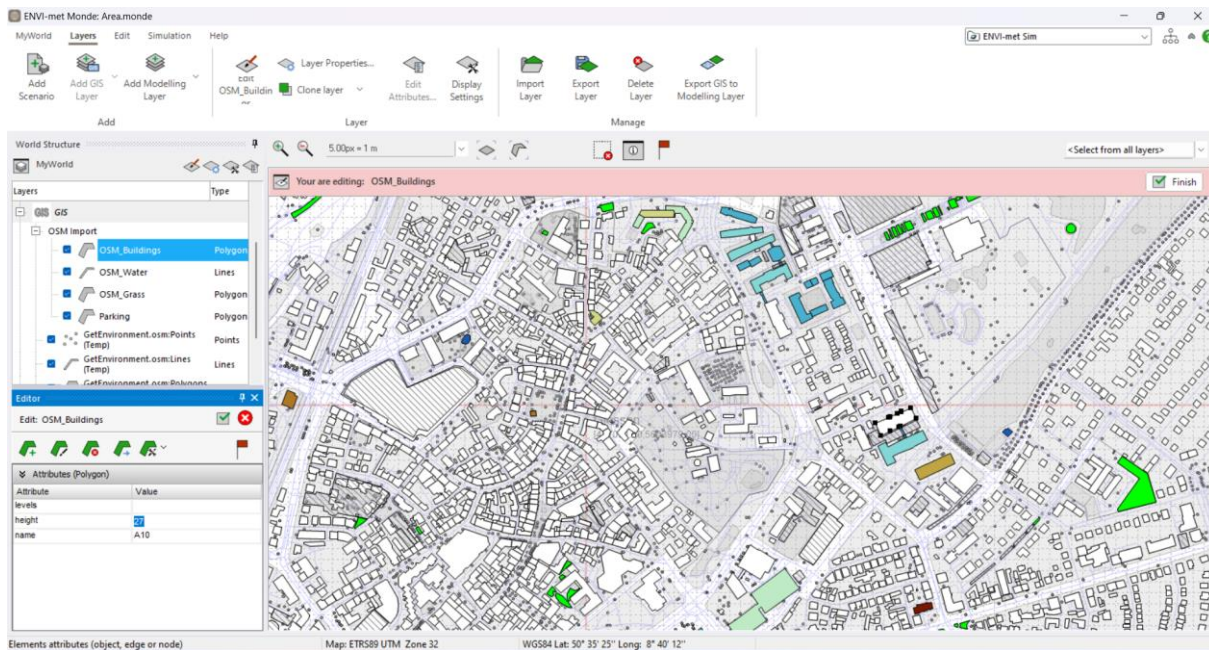


Fig. 25 – Importing OSM into Monde; Source: Author

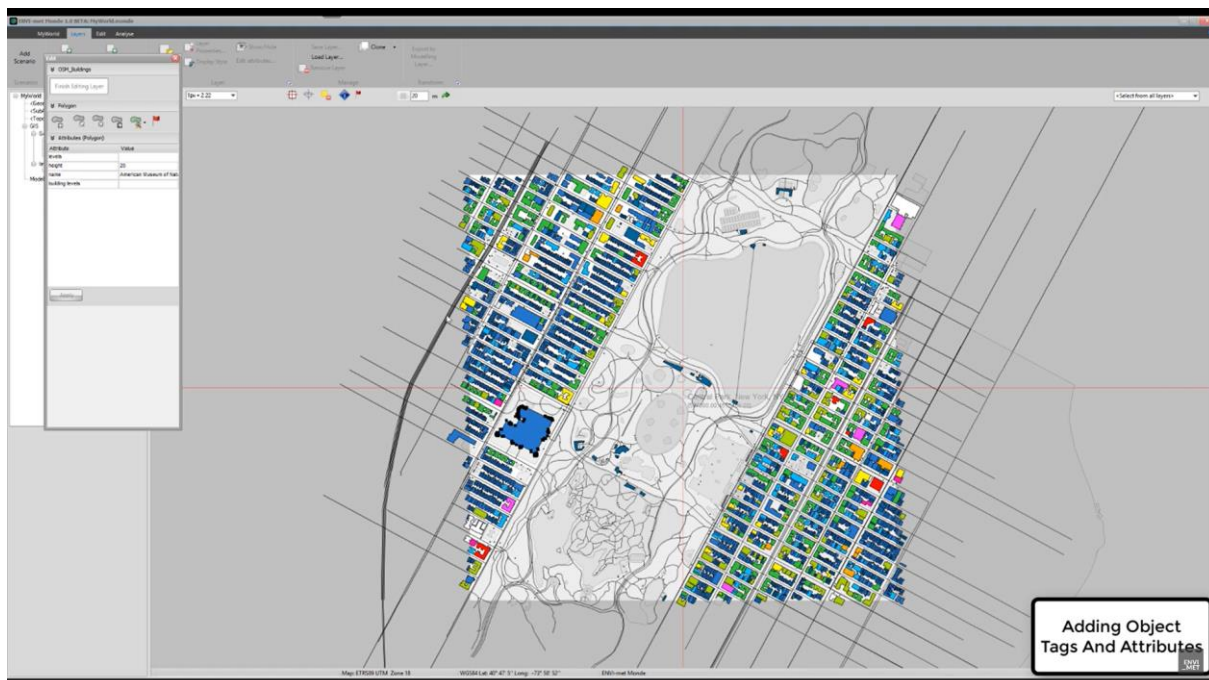


Fig. 26– Adding Object Attributes (height value); Source: (ENVI-met GmbH, 2019)

After importing the GIS layers (Buildings, Grass, Parking), they have been exported to the modeling layer within ENVI-met. The 'Assign Attributes' function has been used to assign specific values to each layer based on their attribute data. Figure 27 shows the process of assigning attributes to the 'Buildings' layer as an example.

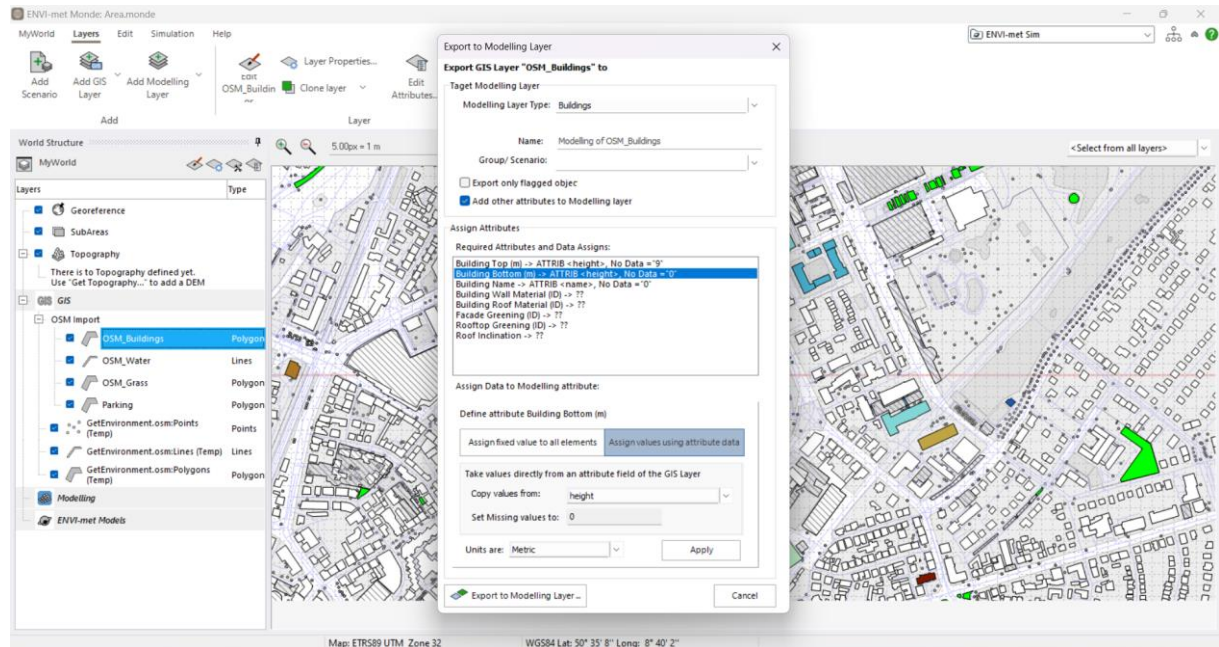


Fig. 27– Export to Modeling Layer using attribute data; Source: Author

Using the Database Manager, fixed values were assigned to attributes such as wall material and roof material for all elements, as shown in Figure 28. The 'Grass' layer is categorized under 'Simple Plants' within the Database Manager (Figure 29).

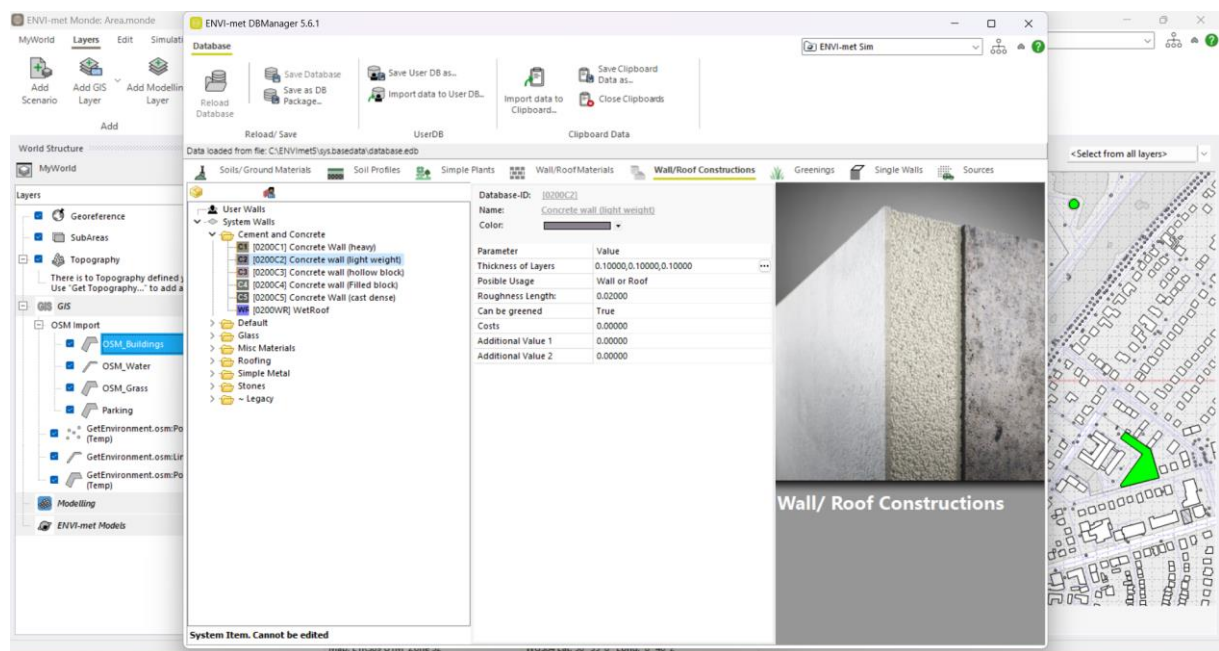


Fig. 28– Assigning attribute data using DBManager; Source: Author

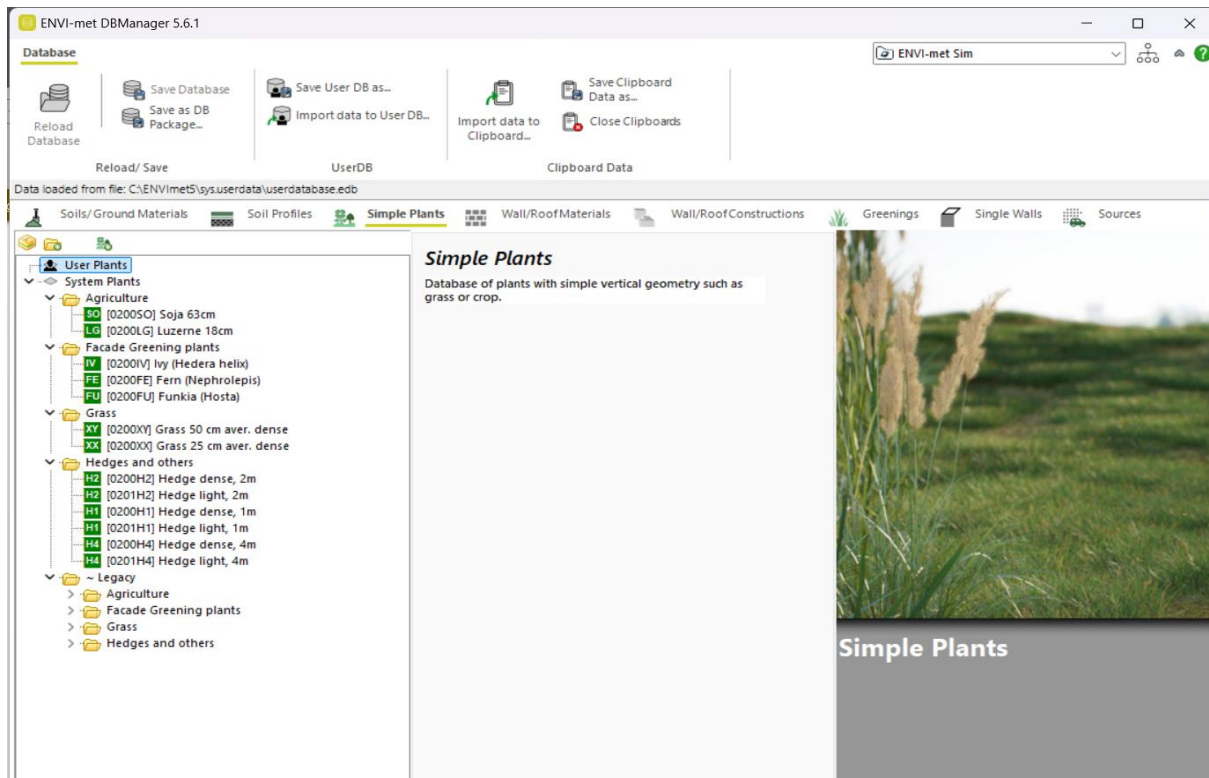


Fig. 29– Database named 'Simple Plants' while using Monde; Source: Author

After exporting the 'Buildings' layer to the modeling layer in ENVI-met, the building data is displayed in Figure 30. Similarly, the parking layer has been exported to the modeling layer after assigning a fixed value to the 'Surface Type' attribute (Figure 31). As the 'Grass' layer does not contain any feature within the study area, it has not been converted to the modeling layer.

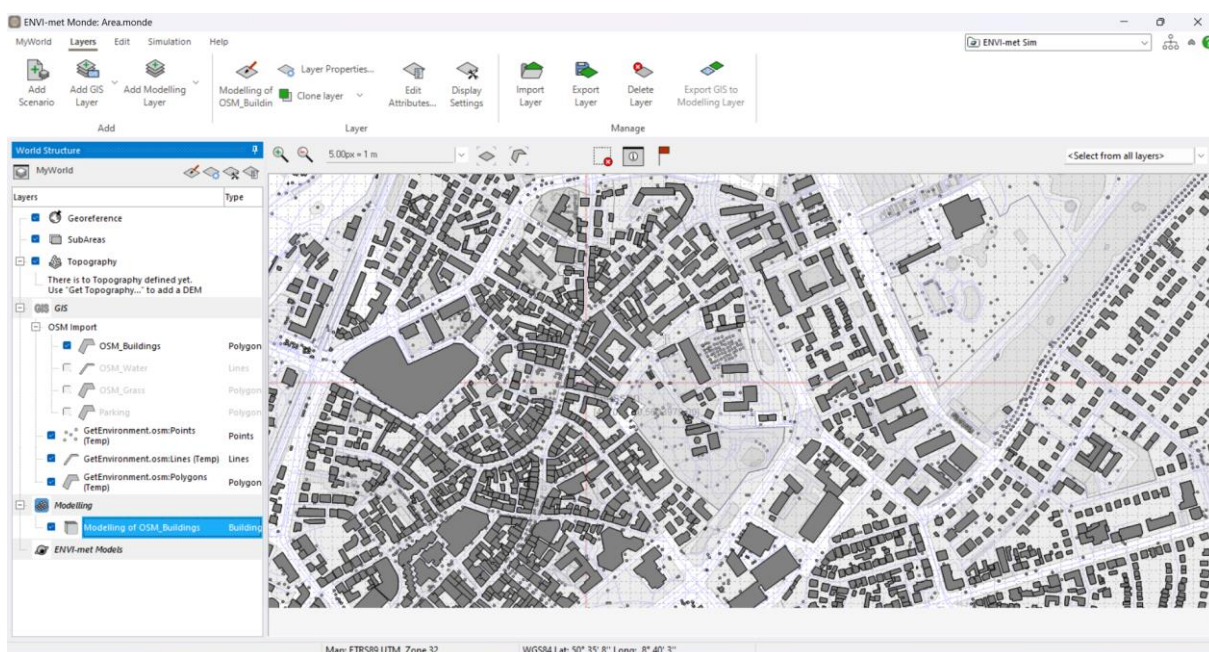


Fig. 30 – Modelling layer of Buildings; Source: Author

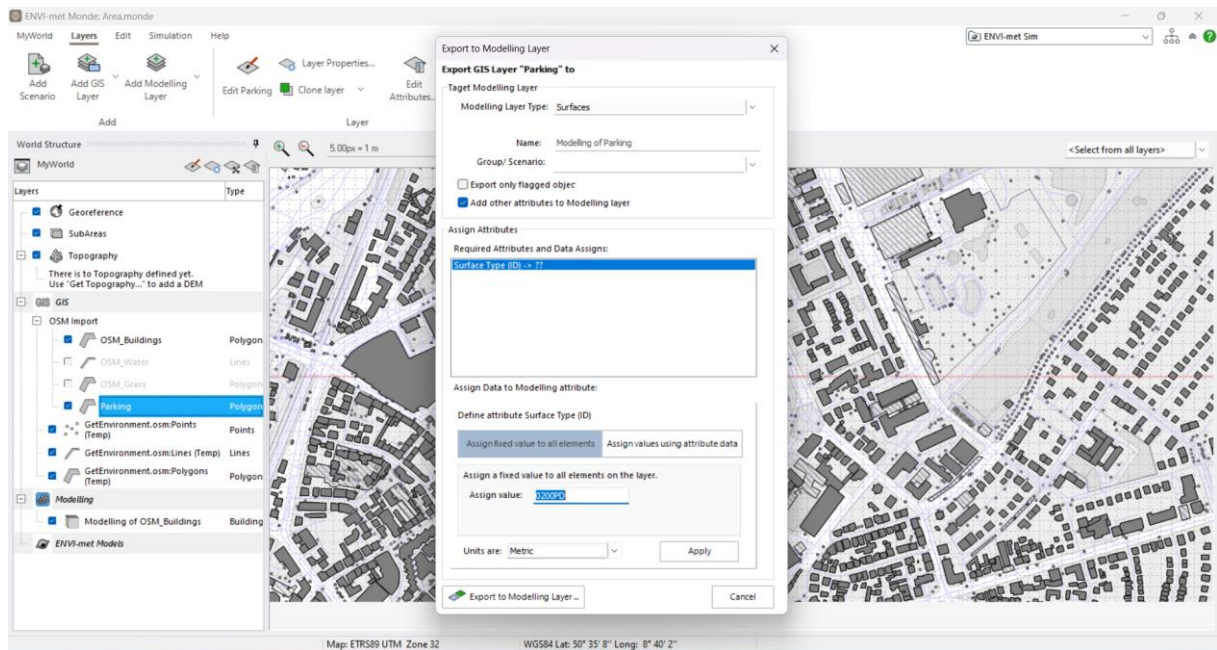


Fig. 31– Exporting the ‘Parking’ layer to the Modelling Layer; Source: Author

Following the previous steps, the Shapefile containing the existing trees within the study area has been imported into the GIS layer in ENVI-met Monde. The correct coordinate system is assigned to the Shapefile as shown in Figure 32, ensuring proper alignment with the rest of the model. The location of the trees is now accurately displayed on the map (Figure 33).

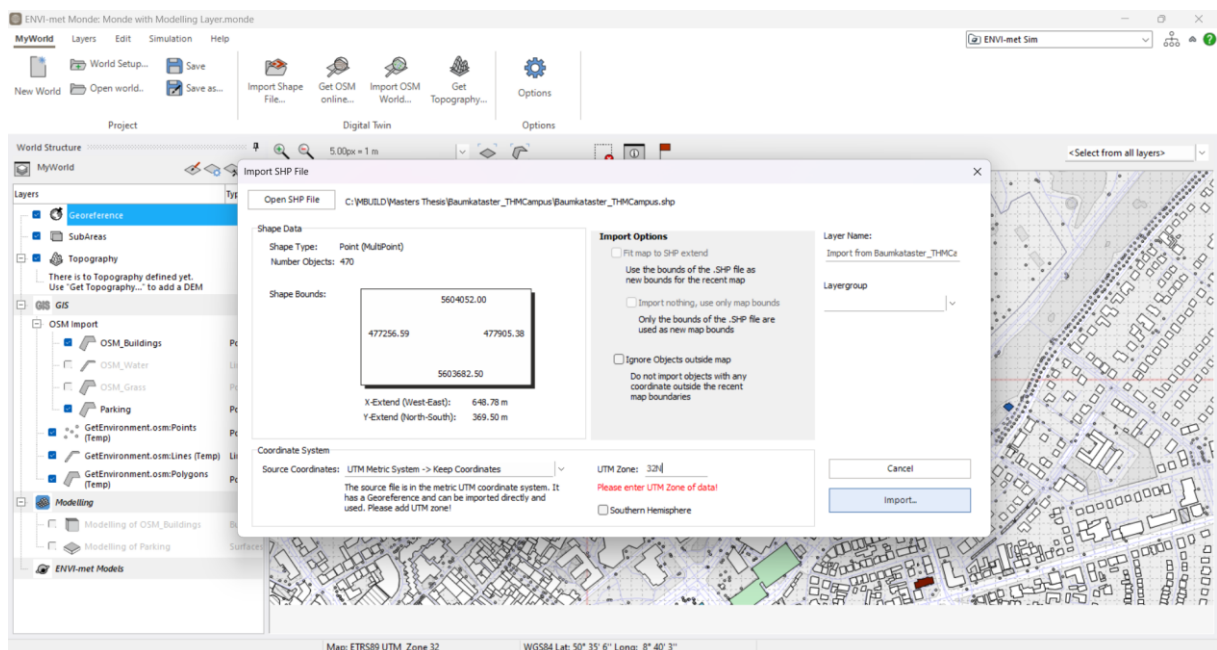


Fig. 32– Importing Shapefile to Monde; Source: Author

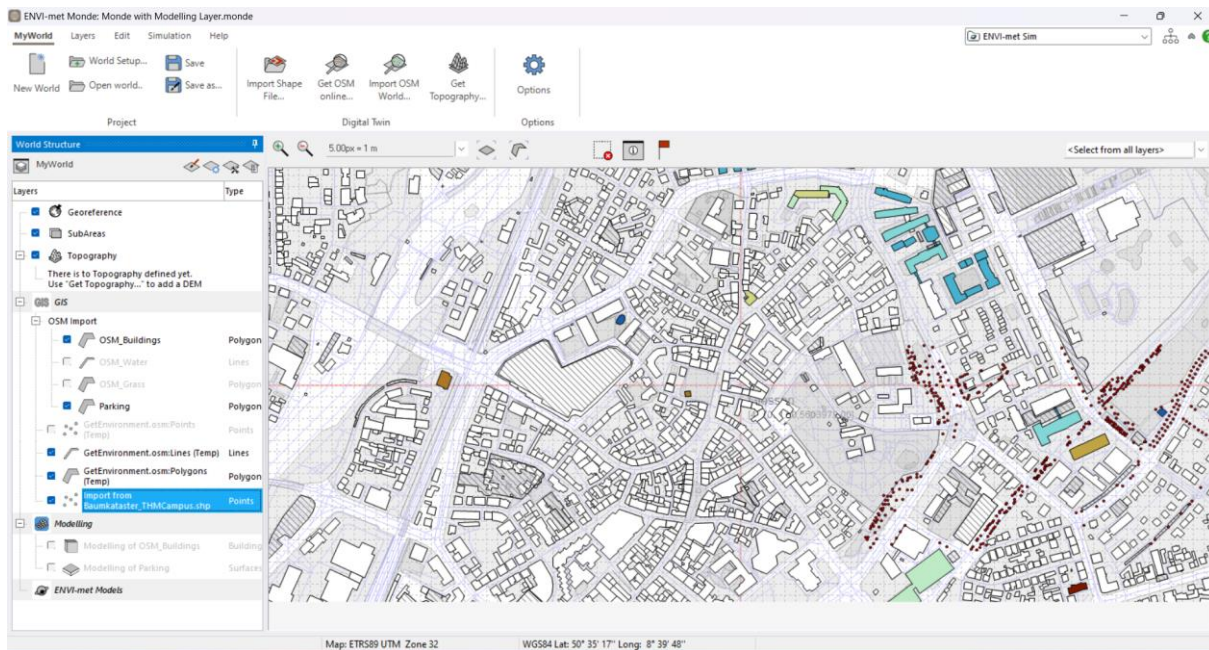


Fig. 33– Showing the location of Trees in the study area; Source: Author

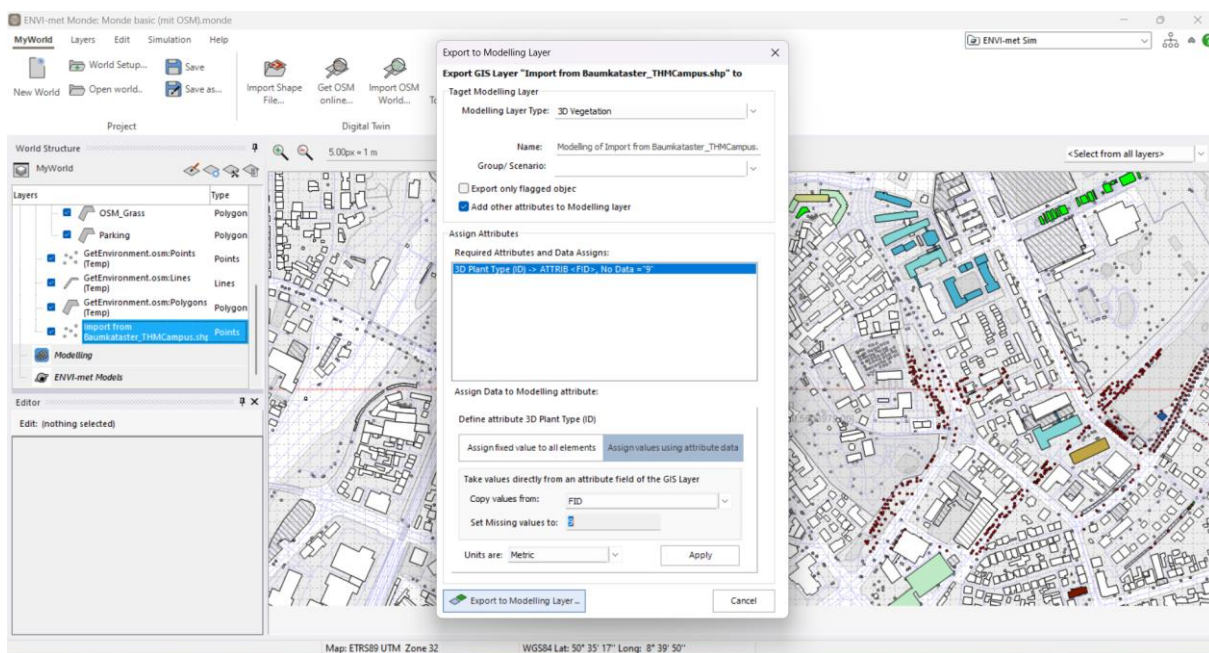


Fig. 34– Exporting 'Trees' to Modelling Layer; Source: Author

Values are manually assigned for the 'Tree' layer as there is no available 3D plant database in ENVI-met Monde from which specific tree species could be selected. Additionally, the tree data file only contained a single attribute with no values (Figure 34).

Afterward, a 'SubArea' named 'Site' has been created to delineate the study area, as shown in Figure 35. The model is then exported as an area input file using the 'Create ENVI-met Model' tool. The output settings, including horizontal and vertical resolution, as well as the number of Z grids, are defined as shown in Figure 36. This concludes the work within the ENVI-met Monde.

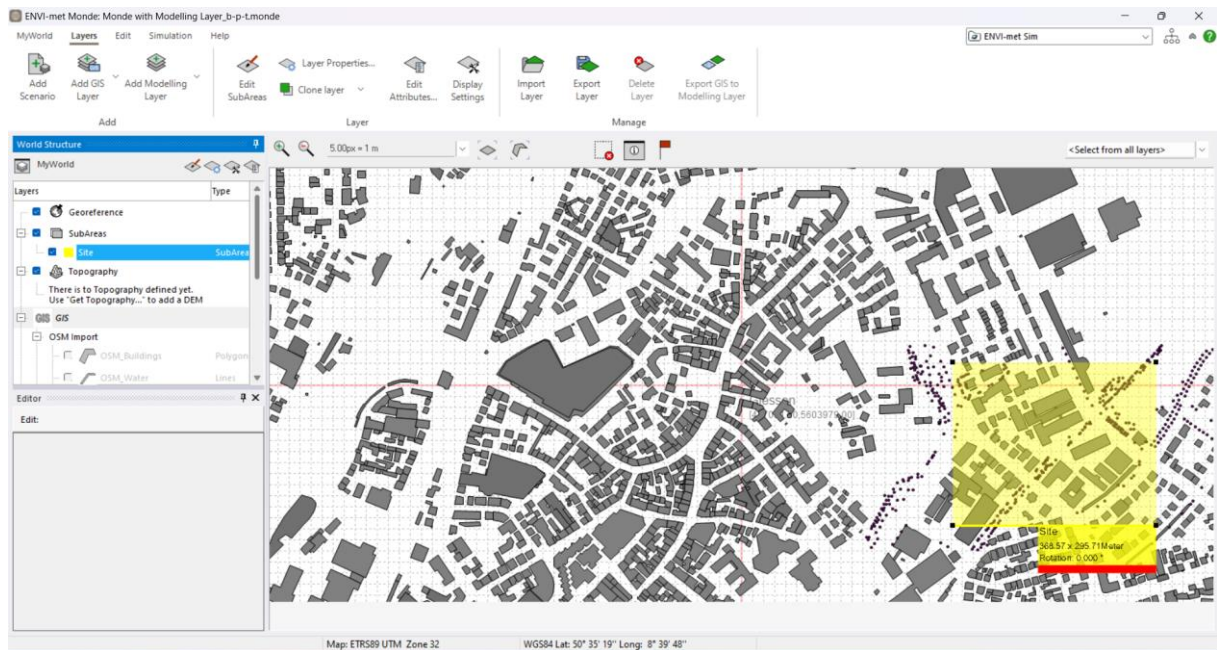


Fig. 35– Selection of 'SubAreas' named Site; Source: Author

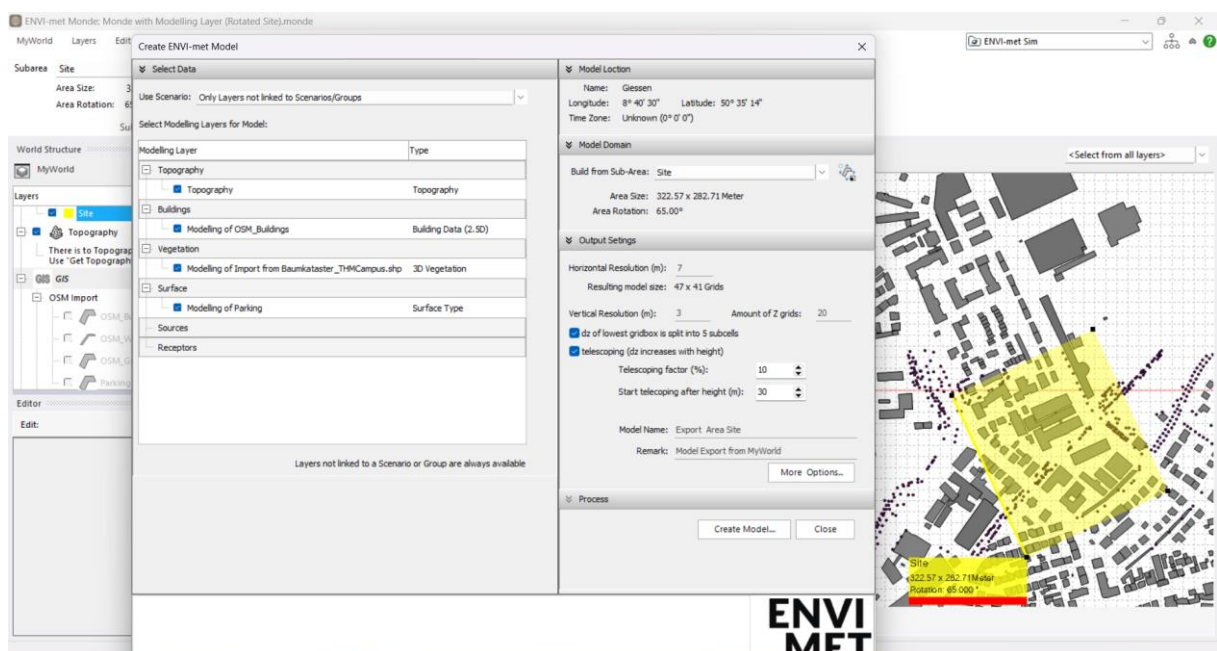


Fig. 36– Creating the ENVI-met Model (Area Input File); Source: Author

Upon opening the Area Input File in ENVI-met Spaces, the software automatically classifies the imported elements. Buildings are correctly identified, while the Parking layer is categorized under 'Soil and surface'. However, only two trees are recognized as Vegetation, with the rest of the elements also falling under the Soil and surface (Figures 37 and 38).

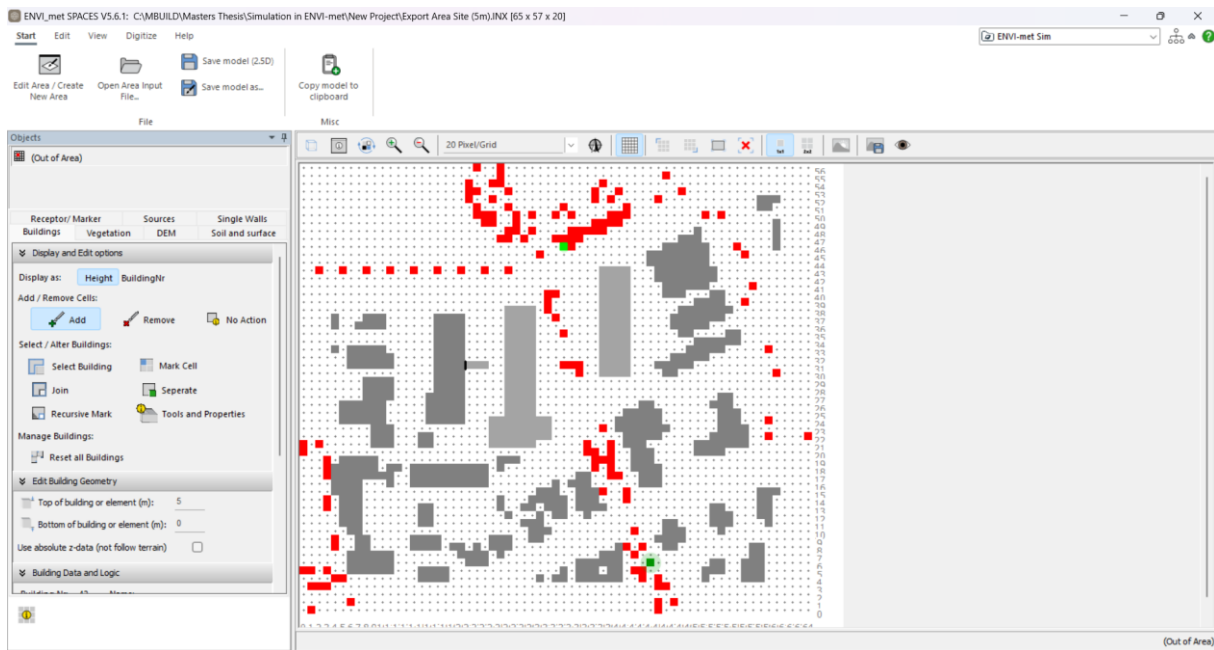


Fig. 37– Area Input File (.INX) opened in ENVI-met Spaces; Source: Author

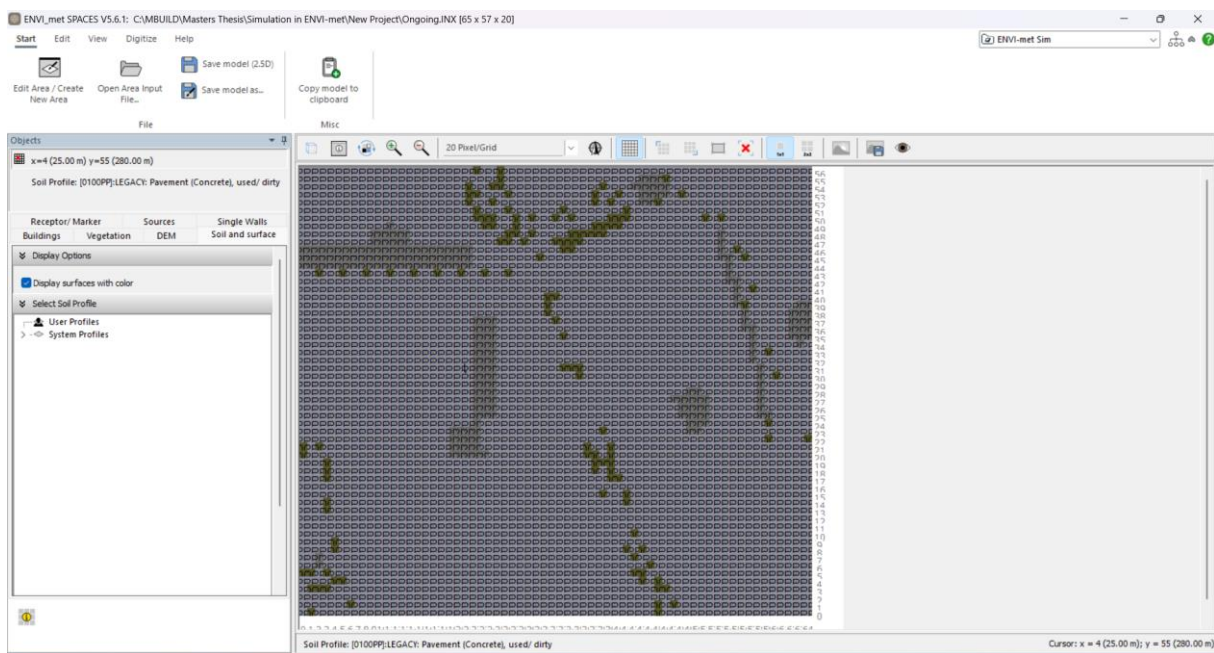


Fig. 38– Showing Parking and Trees (except only two) under 'Soil and surface'; Source: Author

In ENVI-met Spaces, the 'Edit Building Geometry' function is unable to modify individual building heights. Despite attempting this modification, the resulting 3D view in Figure 39 shows no change in building heights, indicating a limitation in the software's capabilities or a constraint within the specific project setup.

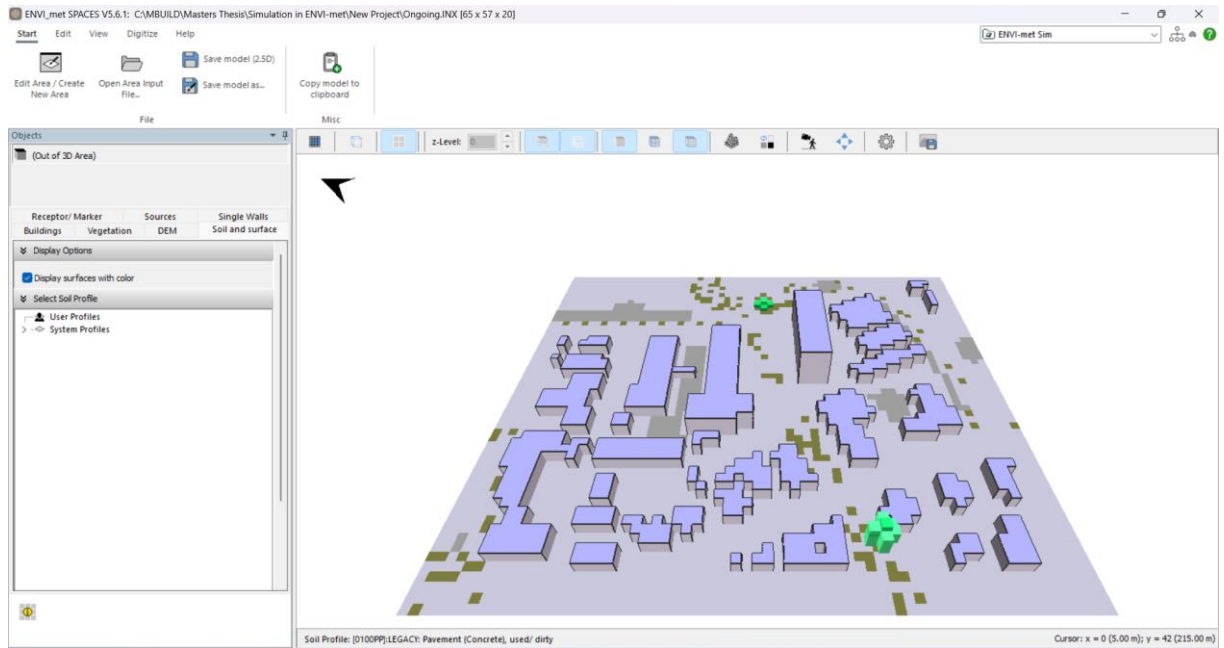


Fig. 39– 3D View of Exported File; Source: Author

As the previously imported file did not accurately reflect the existing conditions, in ENVI-met Spaces, the model was manually adjusted and refined using the existing data from ENVI-met Monde. This has involved modifications to building height, vegetation distribution, parking area, road, pavement, tree, and river (Figure 40). This revised model has been used for simulations representing the existing scenario of the study area.

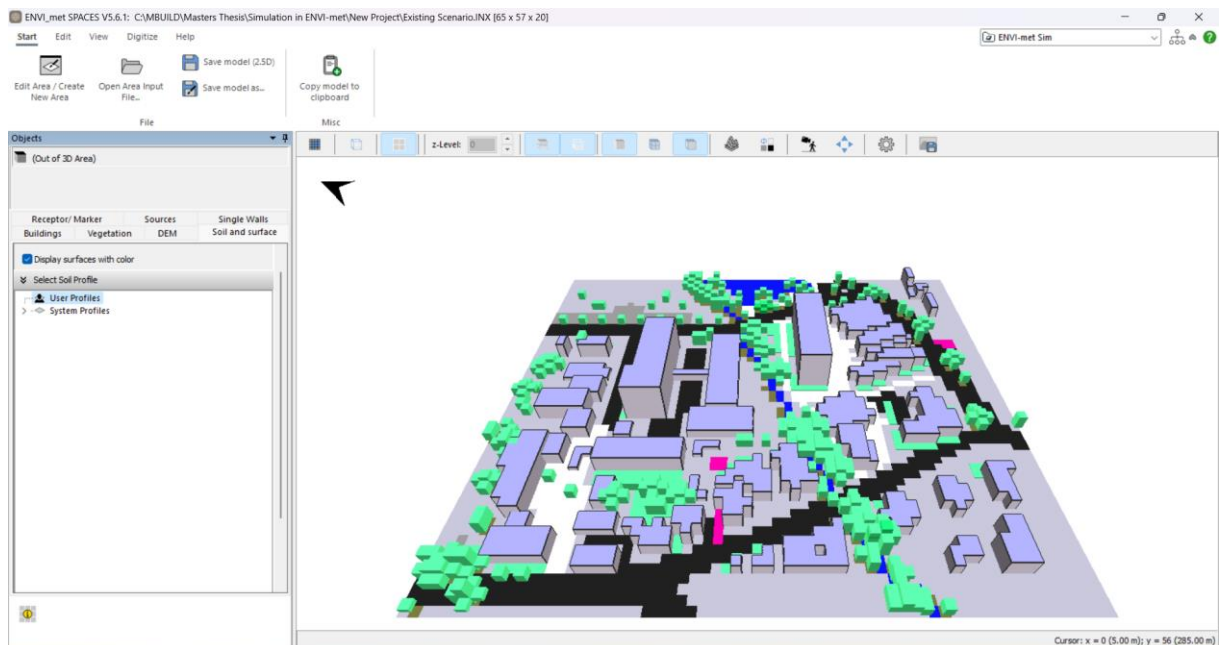


Fig. 40– Modelling of Existing Scenario; Source: Author

To assess the environmental impact of Blue-Green Infrastructure (BGI), the existing ENVI-met model is being modified to incorporate the selected BGI types, as detailed in Table 17. This involved the strategic placement of green roofs on the southwest corners of buildings to mitigate solar heat gain. Green walls are placed particularly on the south and west facades which receive maximum sunlight. The green roof is designed to cover fifty percent of the total roof area, maximizing its potential for evapotranspiration and thermal insulation. Additionally, paving materials with higher albedo are selected to reduce heat absorption and mitigate the urban heat island effect.

The proposed model is further enhanced with additional trees and green spaces strategically placed to provide shade for gathering spaces and pedestrian areas, promoting thermal comfort. The placements of the BGI types are shown in Figure 41 where the icons represent each specific BGI type. These interventions aim to create a more comfortable and sustainable microclimate within the study area. However, due to ENVI-met's limitations in simulating underground features, certain BGI types, such as Vegetated Swales and Tree Trenches, could not be represented in the model. Despite this constraint, the proposed model, as shown in Figure 42, serves as a comprehensive representation of the BGI interventions and their potential impact on the urban environment, enabling a comparative analysis with the existing scenario.

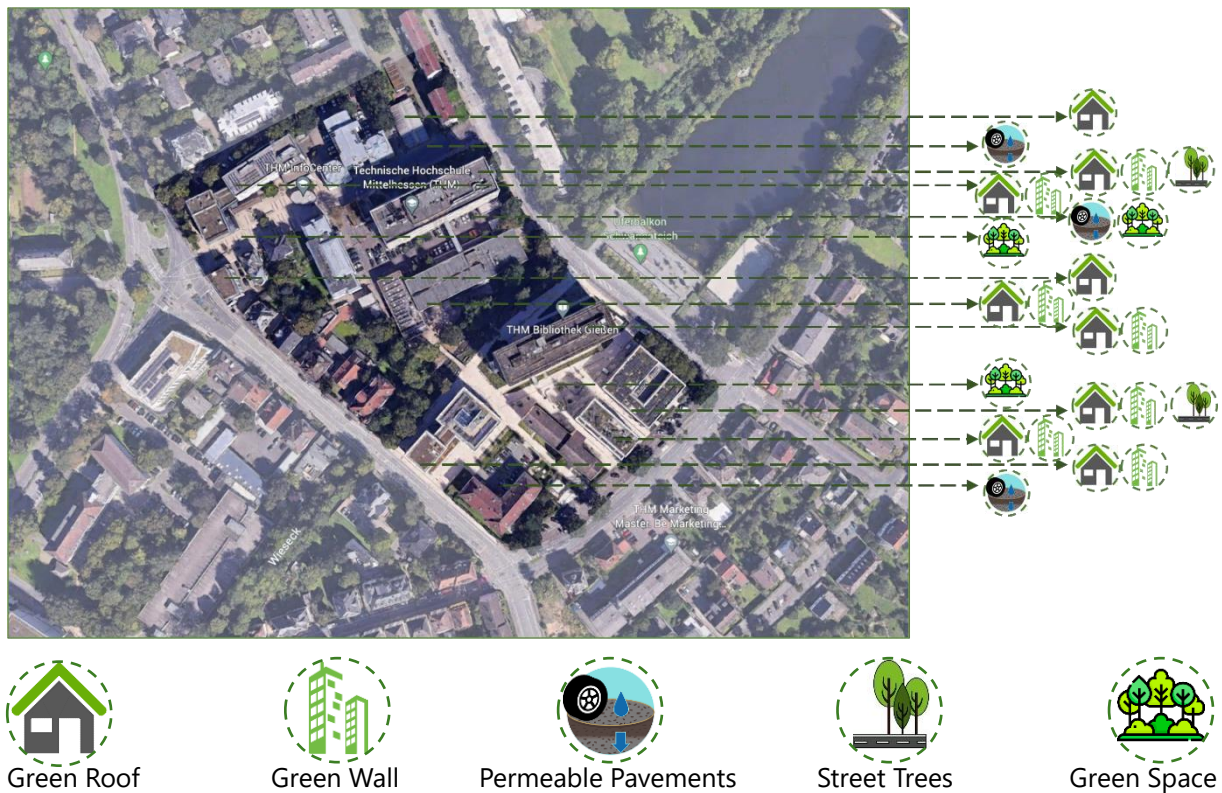


Fig. 41–BGI Placement in the Study Area; Source: Author

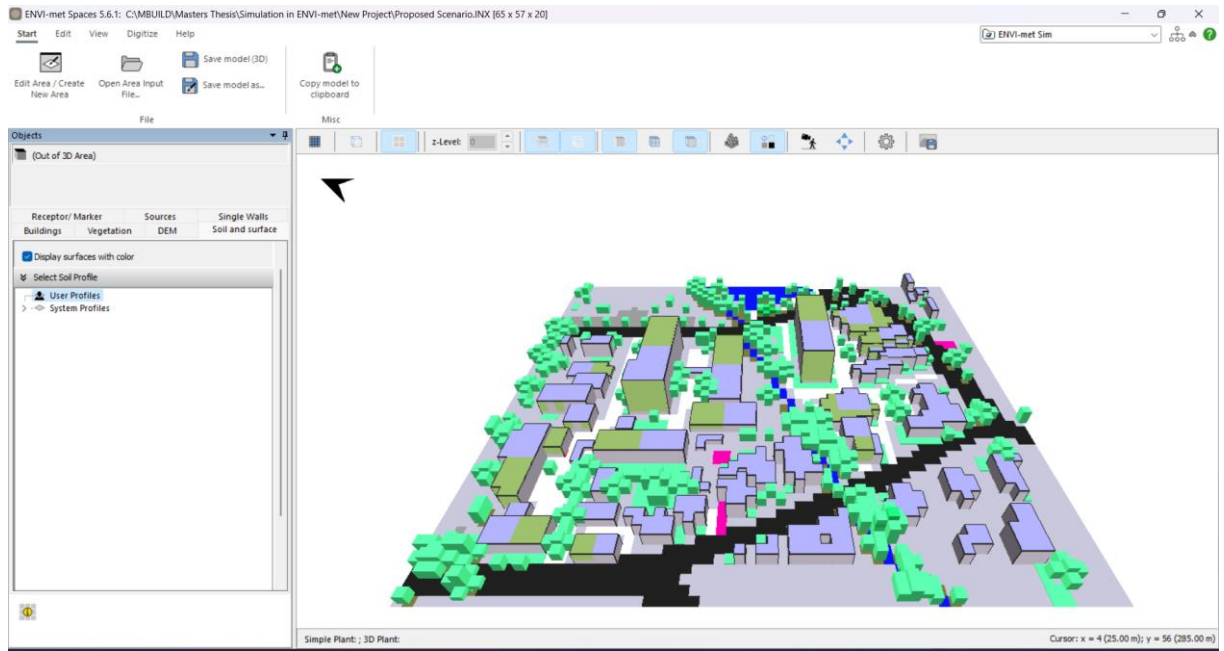


Fig. 42–Model of Proposed Scenario; Source: Author

Using ENVI-guide's simple forcing, boundary conditions, and meteorological data have been set (Figure 43). The weather data has been considered for 26 June 2024 as the hottest day of June. The data are obtained from (Time and Date AS, 2024), and after the data preparation, it is incorporated into the simulation.

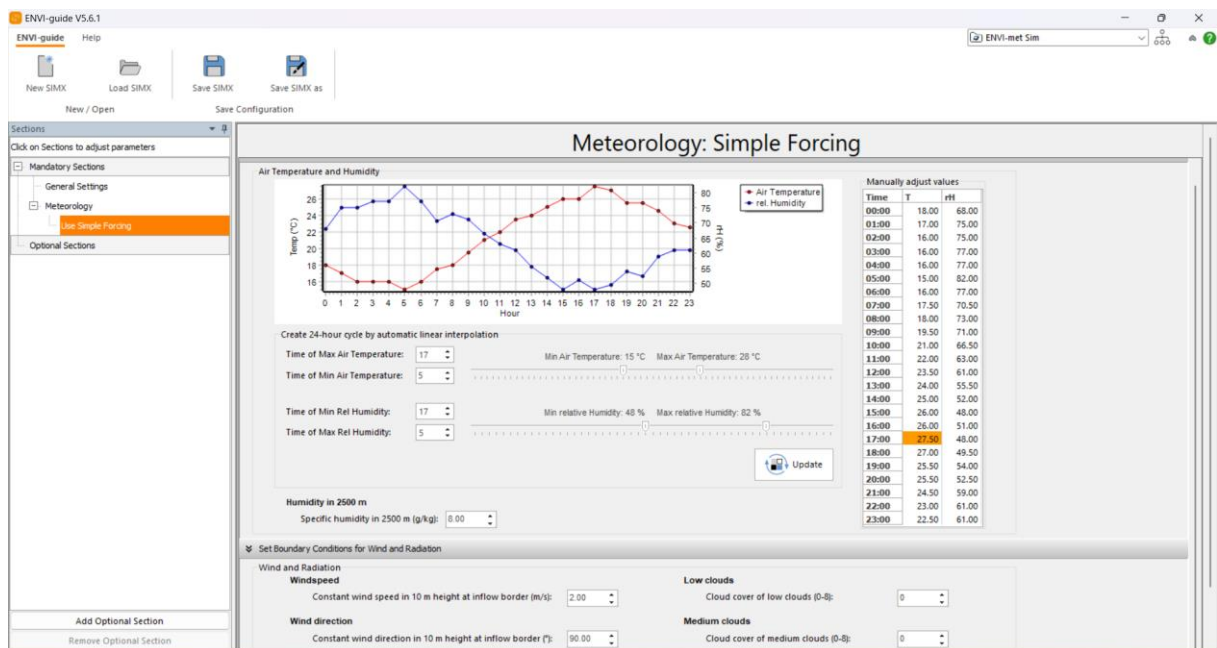


Fig. 43–Meteorology using Simple Forcing; Source: Author

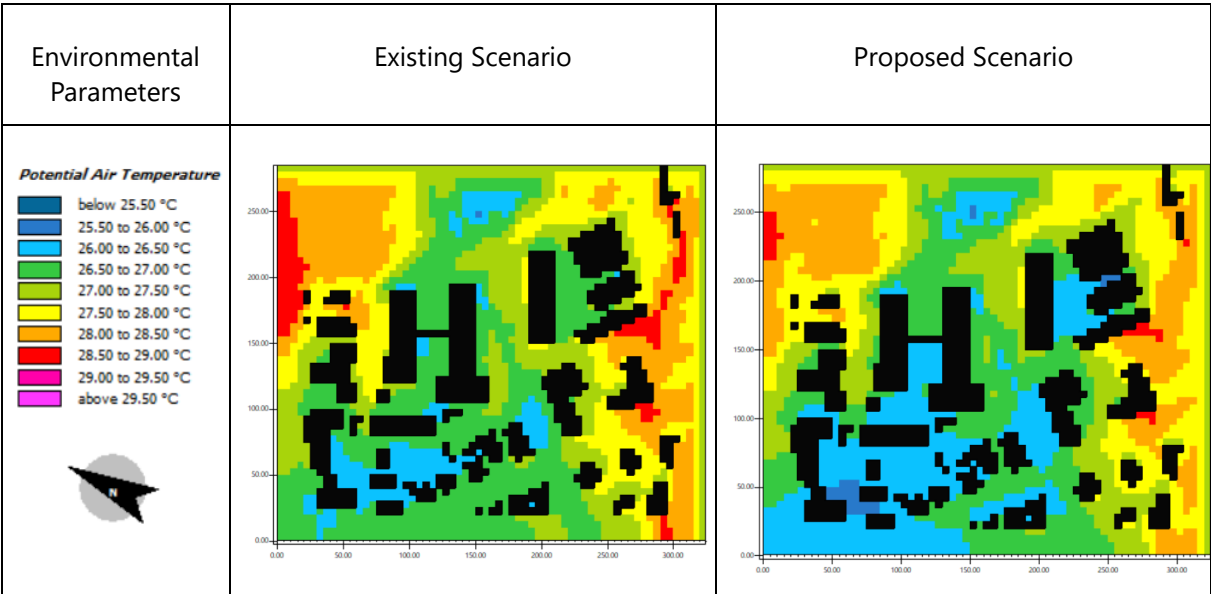
The basic settings used for each simulation within ENVI-guide, are outlined in Table 18. As the highest temperature found from the meteorology graph is 27.5°C, and there is no fraction number for automatic linear interpolation, the highest temperature has been adjusted to 28°C to enhance the accuracy of the simulation results.

Table 18– Employed Basic Settings; Source: Author

Date	26.06.2024
Selected Hour	17:00
Temperature (°C)	28
Relative Humidity (%)	48
Windspeed (m/s)	2.00
Roughness length of surface (m)	0.01
Total Simulation Time (h)	41

4.4. SIMULATION SCENARIOS

Maps generated from the ENVI-met simulations are opened in Leonardo (ENVI-met) for visualization and analysis. To ensure consistency, the same range is maintained for both the existing and proposed scenarios. This study focuses on four key environmental parameters: Potential Air Temperature, Mean Radiant Temperature, Relative Humidity, and Wind Speed, to evaluate the impact of Blue-Green Infrastructure (BGI) within the study area (Figure 44).



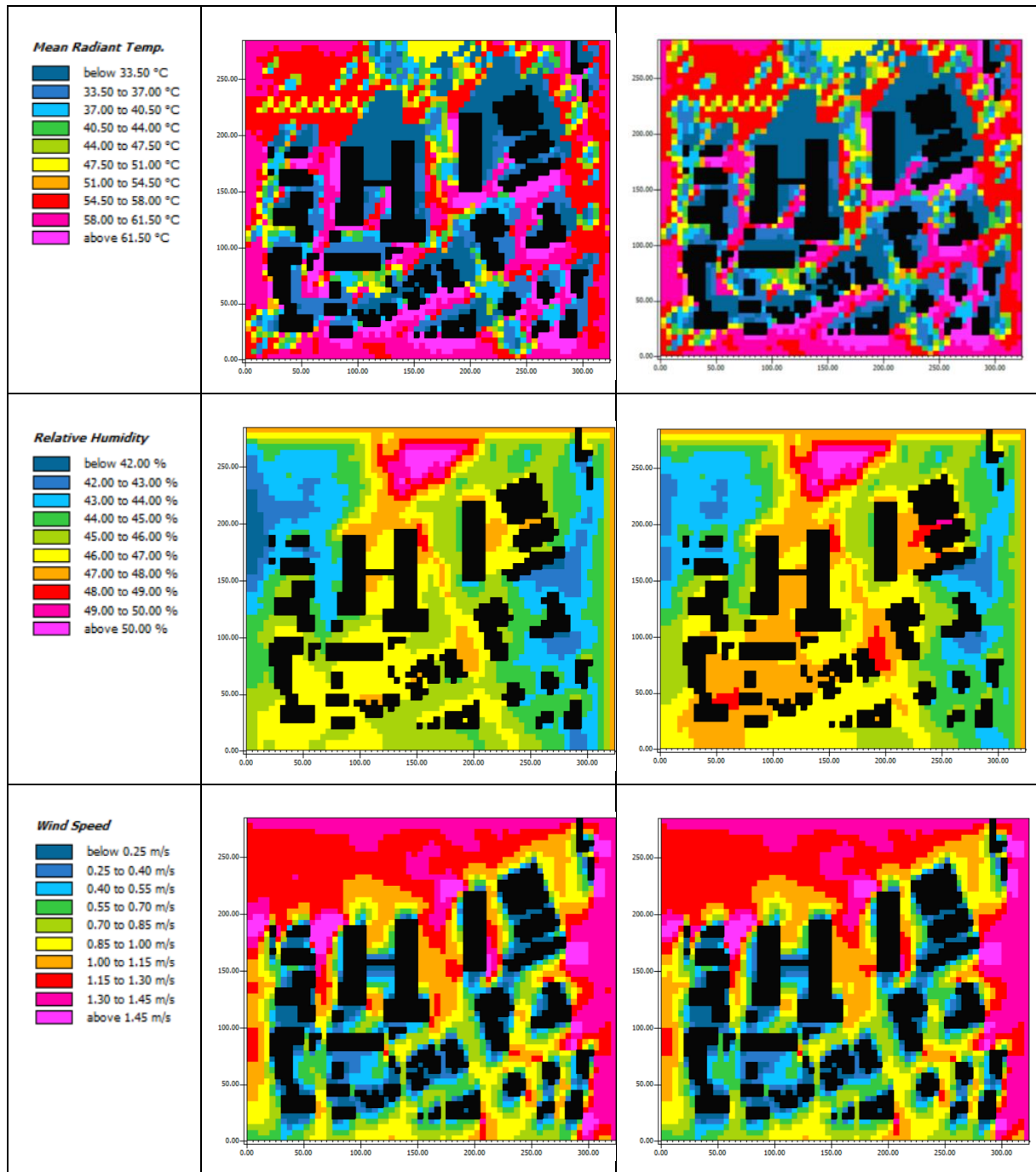


Fig. 44–Images representing Environmental parameters within the Study Area; Source: Author

The data is also visualized in a 3D model for better understanding. Figure 45 shows the distribution of potential air temperature in both the existing and proposed scenarios, using the same color scale for consistency across the 2D and 3D views. In addition, the comparison of Potential Air Temperature between the existing scenario and the proposed scenario has been done (Figure 46) to evaluate the in-depth impact of BGI implementation in urban areas.

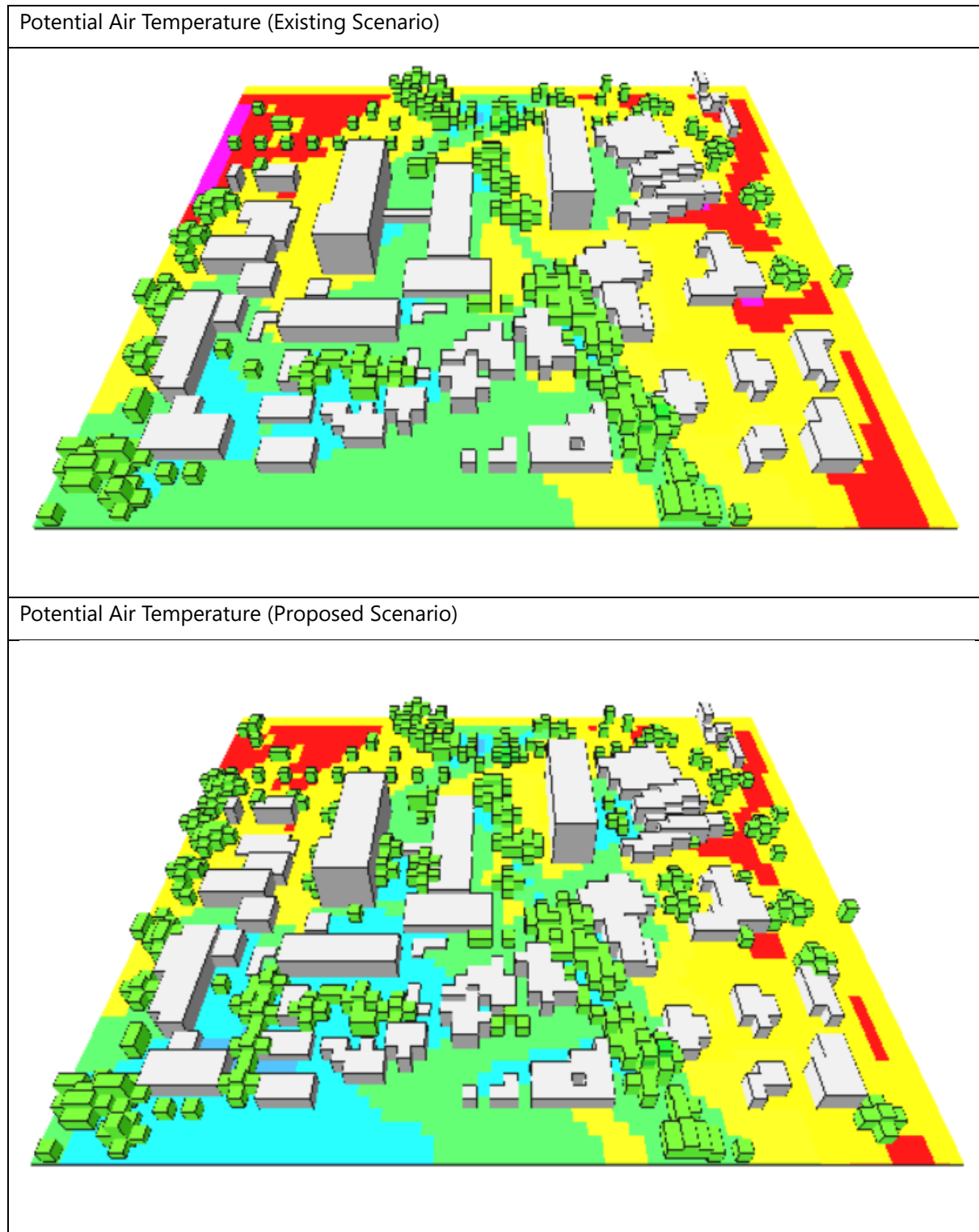


Fig. 45– 3D Visualization of Potential Air Temperature in Study Area; Source: Author

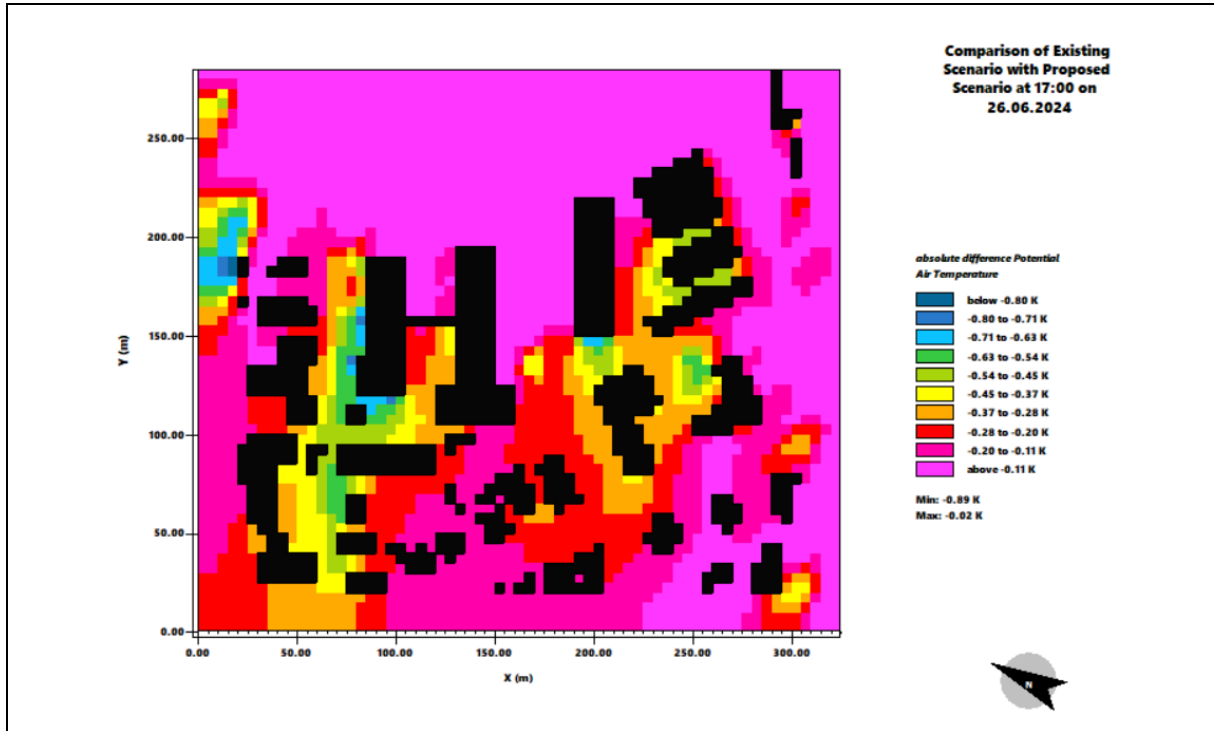


Fig. 46– Comparison of Scenarios showing Absolute Difference Potential Air Temperature;
Source: Author

4.5. ANALYSIS OF SIMULATION RESULTS

i. Potential Air Temperature: Potential Air temperature is a critical variable in ENVI-met, playing an important role in understanding the thermal characteristics of the simulated microclimate. It is essential for evaluating thermal comfort, heat stress, and other microclimatic conditions within the modeled area. In the simulation of the proposed scenario, it can be seen that with the improvement of vegetation and surface materials, the temperature has been reduced in the BGI-implemented areas. The simulation grids containing a temperature range from 26°C to 26.5°C had covered a smaller area, whereas in the proposed scenario the coverage has increased showing the temperature decrease from the range of 26.5°C to 27°C.

The comparison of potential air temperature between the existing and proposed scenarios (Figure 45) reveals a consistent decrease in temperature with the implementation of BGI. The absolute differences in potential air temperature indicate a localized cooling effect of up to 0.63°C in some areas. The spatial distribution of these changed temperatures indicates that the most significant cooling effects are concentrated around areas with higher BGI implementation, such as those with green walls, green roofs, paving with higher albedo, and dense vegetation.

ii. Mean Radiant Temperature: The mean radiant temperature expresses the effects of direct and reflected shortwave and longwave radiation fluxes of the simulated study area. Understanding how these fluxes are modified and absorbed within the intricate urban landscape is essential for developing designs that effectively adapt to mitigate the impacts of climate change. The existing scenario shows higher values in areas with limited vegetation. The existing scenario experiences Mean Radiant Temperature values exceeding 60°C for some grids whereas, in the proposed scenario, the value is substantially reduced, with maximum values staying below 55°C. This reduction indicates the effectiveness of the proposed BGI in mitigating urban heat.

iii. Relative Humidity: Relative humidity is a key environmental parameter in ENVI-met, measuring the moisture content within the simulated microclimate. It changes throughout the simulation, allowing users to analyze how humidity levels vary across locations and time. This understanding is vital for assessing thermal comfort, as well as predicting atmospheric processes such as condensation and evaporation. The existing scenario shows lower Relative Humidity values around the academic buildings and higher values around water bodies. In the proposed scenario, increased vegetation results in higher Relative Humidity values around academic buildings, thereby improving overall thermal comfort. The proposed scenario enhancing BGI contributes to comfortable relative humidity condition that shows an average increase in Relative Humidity by 1-3% compared to the existing scenario.

iv. Wind Speed: Wind speed plays a pivotal role in shaping the urban microclimate, influencing factors such as energy transfer, pollutant dispersal, and the comfort and safety of both people and vegetation. It also significantly impacts the performance of the built environment. A comprehensive understanding of the interaction between solar and wind dynamics is necessary for enhancing and optimizing the microclimate in the built environment. The proposed scenario, featuring enhanced BGI including vegetation increase and modification of surface, leads to a reduction in wind speed around building areas compared to the existing scenario. The average wind speed of the study area ranges between 0.25 m/s to 1.45 m/s. The increased vegetation acts as windbreaks, resulting in more sheltered and comfortable urban spaces.

The simulation results presented in Figures 44, 45, and 46 demonstrate that implementing Building Green Infrastructure (BGI) in the study area has improved the environmental conditions.

4.6. OUTPUT DATA INTEGRATION INTO UIM

The result from Leonardo, specifically the potential air temperature data for the improved condition with BGI implementation (proposed scenario), has been exported as an ASCII file for further analysis and integration, as shown in Figures 47 and 48.

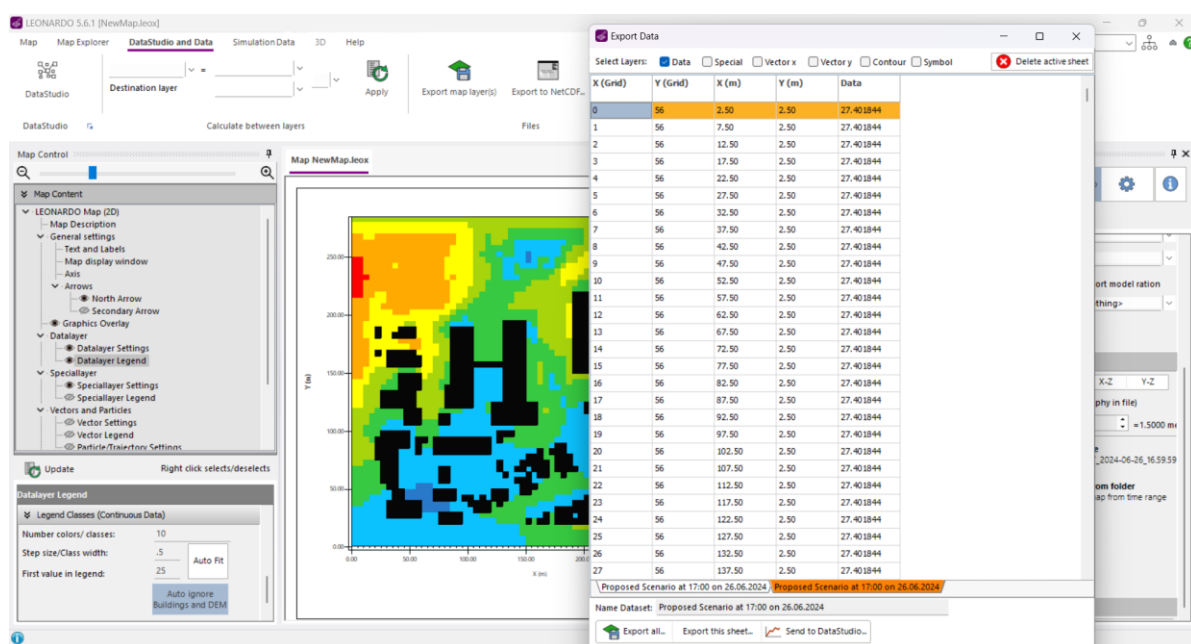


Fig. 47– Export Data from Leonardo; Source: Author

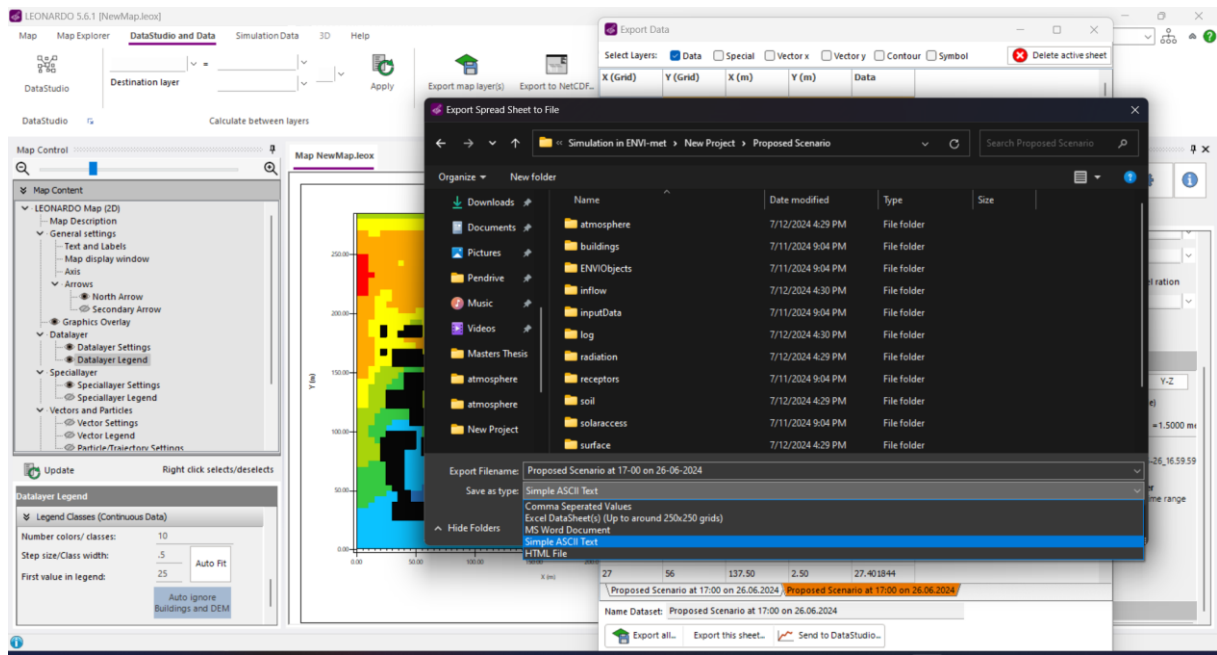


Fig. 48– Export data as ASCII file (.txt); Source: Author

The ASCII data exported from Leonardo can be converted to raster data (.tif) format using various software tools, including ArcGIS Pro (Esri ArcGIS Pro), ArcMap (Figure 49), or FME (Figure 50). These alternative methods highlight the flexibility in achieving the desired outcome. However, due to limited expertise in specific software applications, the conversion process has been shown as an example to confirm the feasibility of the workflow. The output data is a GeoTIFF (.tif) file compatible with the chosen City Information Modeling (CIM) platform, ArcGIS CityEngine, for integration into the CIM/UIM environment.

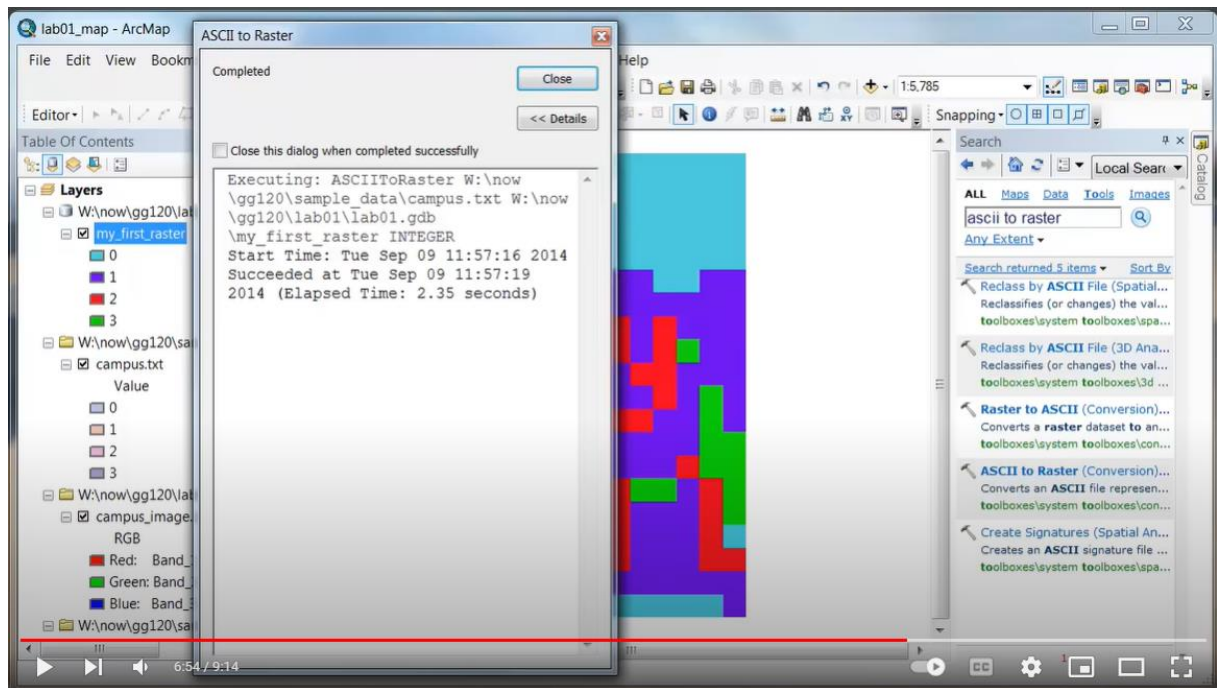


Fig. 49– From ASCII to Raster data using ArcMap; Source: (GISatMidd)

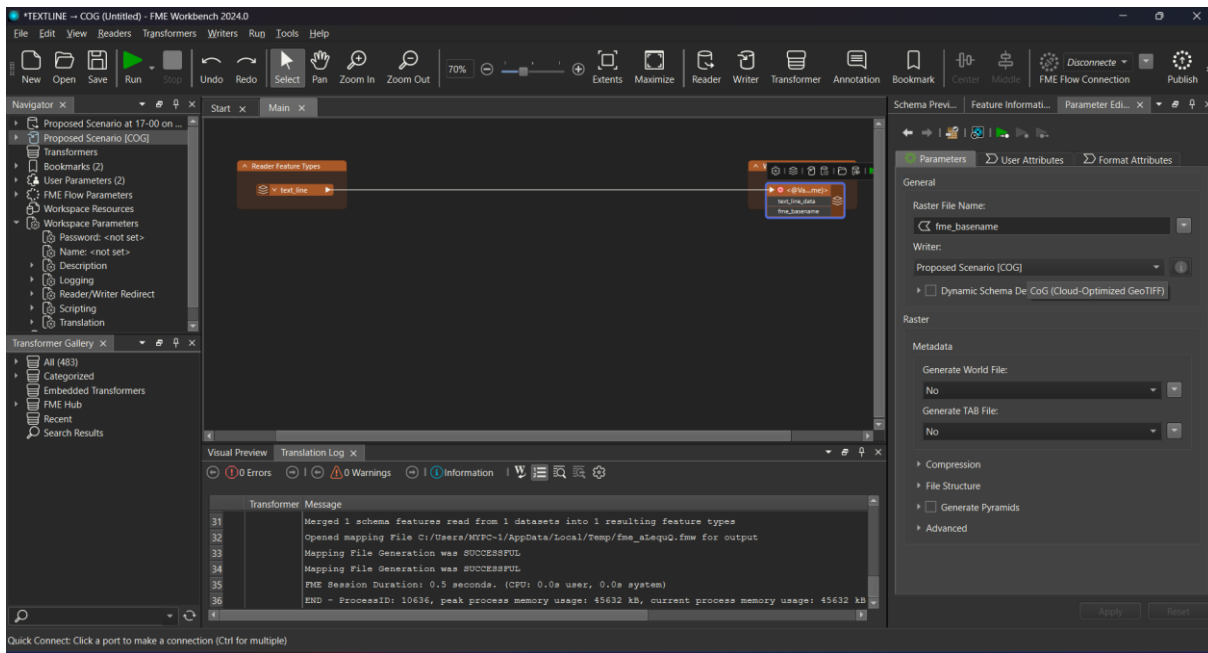


Fig. 50– From ASCII to Raster data using FME; Source: Author

The Esri CityEngine platform supports the import of raster data, which is one of the many data formats it supports (Table 14).



Fig. 51–Visualization of Raster Data in CityEngine; Source: (GIS Visualisations, 2022)

While CityEngine supports the visualization of raster data, as shown in Figure 51, the literature review does not reveal any documented examples specifically showing the visualization of temperature data within the Esri CityEngine platform. As the output from temperature simulations, such as those generated by ENVI-met, is in raster format, and the CityEngine platform supports the integration of raster data, visualizing temperature data within CityEngine is feasible. This capability allows for the raster data, including environmental impact results, to be displayed alongside CityGML models of blue-green infrastructure (BGI) elements and 3D urban models (e.g., the city of Giessen according to this study). The integration of these datasets within the CityEngine scene provides a robust framework for assessing the comprehensive impact of BGI on urban microclimates and their interaction with the existing urban environment.

5

FINDINGS AND RECOMMENDATIONS

5.1. INTERPRETATION OF FINDINGS

5.1.1. CHALLENGES AND LIMITATIONS

During the process of integrating 3D Blue-Green Infrastructure (BGI) models into Urban Information Modeling (UIM) platforms, the following challenges appear.

i. 3D model challenge:

Object Parameters and Level of Details: When creating the BGI model, careful consideration of object parameters and the appropriate Level of Detail (LOD) is crucial. The LOD should be configured to the specific use case within the UIM environment. Excessive detail may result in compatibility issues and increased file sizes.

Export as IFC: Exporting the BGI model to IFC format requires attention to detail, ensuring that all relevant information is captured accurately and that the LOD is appropriate for complying with data transformations.

ii. Coordinate system management:

Consistency: Maintaining a consistent coordinate system throughout the workflow is essential. Discrepancies between the model's coordinate system and the project's reference system can lead to misalignment and errors in each step.

Georeferencing: Properly georeferencing the IFC model is crucial for accurately positioning it within the real-world context of the UIM.

iii. FME workbench challenges:

Expertise Requirement: Utilizing FME Workbench for custom transformations necessitates a certain level of expertise in reading IFC files, understanding CityGML schema, and establishing attribute mapping between the two formats.

Data Transformation: Converting the IFC file format to the CityGML file format requires careful attention to the mapping of attributes and ensuring the correct geometry representation.

iv. FME quick translator limitations:

Coordinate System and Geometry Issues: While FME Quick Translator makes the conversion process easier and quicker, it may not always resolve issues related to coordinate system mismatches or complex geometries in the original IFC file. This can lead to positional inaccuracies or loss of geometric detail in the resulting shapefile.

- v. Coordinate system misalignment: Despite indicating the correct coordinate system, the imported shapefile is displayed in the wrong location on the map. This suggests potential errors in the original IFC model's georeferencing or inconsistencies in the conversion process. Additionally, the vertical positioning (z-axis) of elements within the model posed a concern.
- vi. Student version limitations: The student version of ENVI-met restricted the ability to modify certain attributes of imported GIS layers, such as building heights. This limitation hindered the modification and refinement of the model to accurately reflect existing or real-world conditions.
- vii. Data limitations: During the import of GIS layers into the modeling layer, the water layer was excluded as it lacked available data according to predefined rules. Additionally, when assigning attributes to trees, the database lacked options for 3D plant attributes, as the DB Manager does not currently support such data.
- viii. Object modification challenges: In ENVI-met Spaces, the inability to change individual building heights posed a significant limitation. Moreover, the misclassification of trees from the shapefile as 'Soil and surface' instead of 'Vegetation' required manual correction.
- ix. Subsurface modeling limitations: ENVI-met's inability to model subsurface features created a critical challenge in representing certain BGI types, such as vegetated swales, and tree trenches. This limitation restricts the comprehensive assessment of the impacts of these BGIs within the simulation environment.
- x. Simulation time constraints: The computational demands of ENVI-met simulations, particularly for large and complex models, resulted in significant processing times, hindering efficient design and analysis workflows.
- xi. File format conversion challenges: The need to convert the exported ENVI-met data into compatible formats for import into CityEngine added an additional layer of complexity to the integration process, potentially leading to data loss or inaccuracies.
- xii. CityEngine challenges: While Esri CityEngine successfully imports the terrain model, it does not automatically generate or incorporate the 3D building models created in ENVI-met. This requires a separate 3D city model to be created or imported into CityEngine to visualize the complete urban environment with buildings.

5.1.2. ADVANTAGES AND OPPORTUNITIES

This research identifies the following opportunities and possibilities for advancing the integration of Blue-Green Infrastructure (BGI) models into Urban Information Modeling (UIM).

- i. FME accessibility expansion: FME is a powerful tool for data conversion, supporting a wide range of formats. However, to enhance its usability, providing free tutorials, webinars, and other resources can facilitate users to leverage its full potential.
- ii. Flexible data integration and visualization: ENVI-met's capability to import both OpenStreetMap data and shapefiles makes it a convenient platform for conducting microclimate simulations. Its ability to visualize results in both 2D and 3D, along with generating comparison maps between different scenarios and time periods, enhances the analysis and interpretation of BGI performance in urban contexts.
- iii. Advancement of ENVI-met capabilities: ENVI-met is valuable for analyzing BGI impacts on the microclimate. While its interface is generally user-friendly, enhancing its capabilities by expanding the Database Manager with more diverse data and incorporating plugins for accessible dashboards could further optimize analysis and interpretation.

iv. Improving export data formats: Enabling the export of results directly as ASCII Grid (.asc) files and simplifying the export of NetCDF files could enhance ENVI-met's compatibility with other software and enhance data integration workflows.

v. Continuous model optimization: CityEngine's flexibility in managing various data types presents an opportunity to continuously improve urban models. By incorporating climate modeling results from tools like ENVI-met, it is easier to validate and improve the design before scaling it up. This approach allows for continuous improvement and optimization of BGI interventions within the larger urban context.

vi. Exporting 3D models: Enabling the export of 3D data from ENVI-met, such as buildings, vegetation, and water bodies, in interoperable formats would enhance the integration with CityEngine and other 3D modeling platforms.

vii. Micro-to-macro scale analysis: CityEngine facilitates the visualization and assessment of BGI's impact at both micro (e.g., individual buildings or streets) and macro (city-wide) scales. This enables professionals to understand the localized effects of BGI interventions and their potential benefits when scaled up to the entire city. Additionally, the research methodology can be replicated and refined for different urban contexts, such as residential blocks, to explore the diverse impacts of BGI in various settings.

5.2. DISCUSSION

5.2.1. BGI INTEGRATION

This research demonstrates a workflow for integrating BGI models into UIM, highlighting the importance of data conversion and potential improvements in climate modeling software. By exporting ENVI-met simulation results as raster data and importing them into CityEngine, the microclimatic impact of BGI can be visualized and analyzed at a macro-scale within the 3D city model, enabling refinements to design BGI elements before incorporating them into the city scale.

This workflow could be further rationalized if 3D BGI models could be directly exported from BIM software in file formats such as CityGML or CityJSON, which are readily compatible with CityEngine. However, the current necessity of converting IFC models (often exported from BIM software) to these formats requires specialized software, such as FME, to ensure the preservation of attributes, IDs, and other semantic information during the data transformation process.

5.2.2. BGI AS DISTINCT CITY OBJECT

UIM platforms, such as Esri CityEngine, offer diverse layers for organizing, modifying, and visualizing urban data. While these platforms can readily incorporate BGI models, often imported as shapefiles, a critical challenge lies in representing the interconnected nature of Blue-Green Infrastructure (BGI). CityGML, a standard format for 3D city models, categorizes BGI elements primarily under the 'Vegetation' and 'WaterBody' modules. However, BGI's impact extends beyond these classifications, encompassing a complex interconnection of natural and built elements that influence the urban microclimate and overall environment. As shown in Figure 52, there are the many divisions of 3D assets within CityEngine, which may not adequately capture the interconnectedness of BGI. To address this, a more holistic approach, integrating the BGI model as a distinct city object within the UIM environment, is needed.

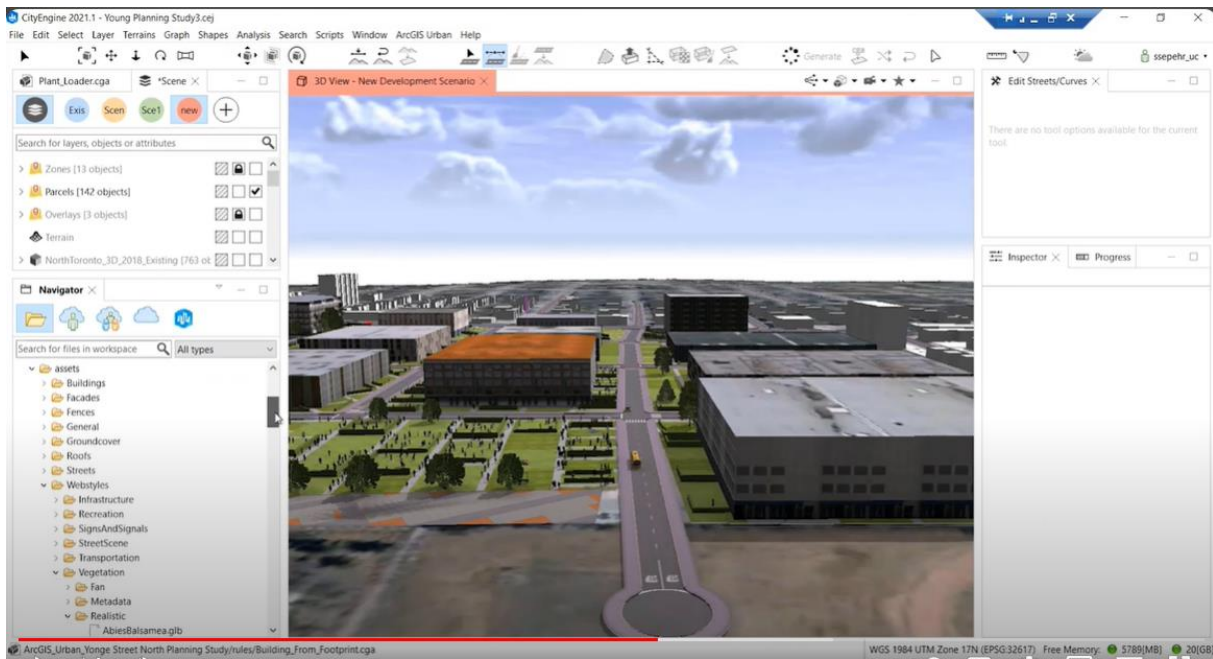


Fig. 52– 3D assets in CityEngine; Source: (Esri Canada, 2023)

A view of Zurich's 3D city model, as shown in Figure 53, utilizes Cesium, a web-based open-source platform for visualizing 3D geospatial data. In this example, vegetation is treated as a separate layer, raising questions about the categorization of specific BGI types, such as tree trenches. This highlights a potential limitation in current UIM platforms, where the fragmented consideration of BGI elements across multiple layers can hinder a comprehensive understanding of their interconnected impacts on the urban environment.

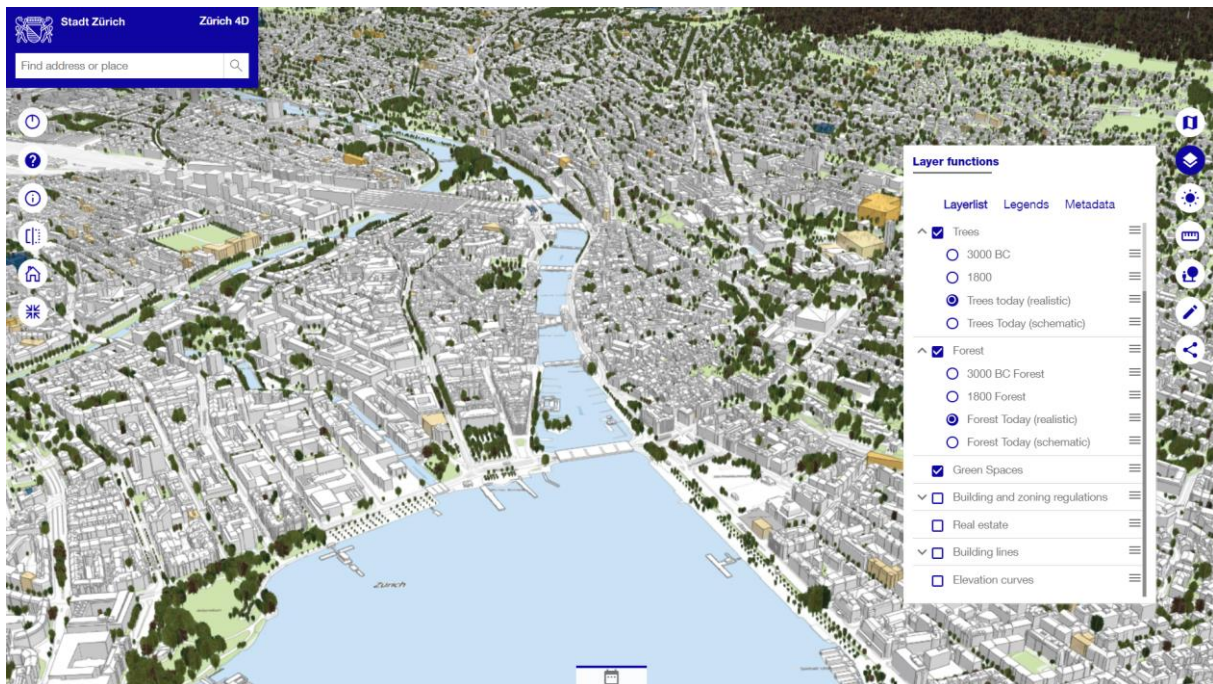


Fig. 53– 3D Model of Zurich City; Source: (Stadt Zürich, 2024)

5.2.3. BGI MAINTENANCE THROUGH DT

Like other Digital Twin applications, digital twins for Blue-Green Infrastructure (BGI DTs) can be utilized to address maintenance challenges which is a key factor influencing decision-making in BGI implementation. The real-world data, essential for BGI DTs functionality, can be collected from sensors connected to both Grey Infrastructures such as buildings, roads, bridges, tunnels, etc, and the implemented BGI itself.

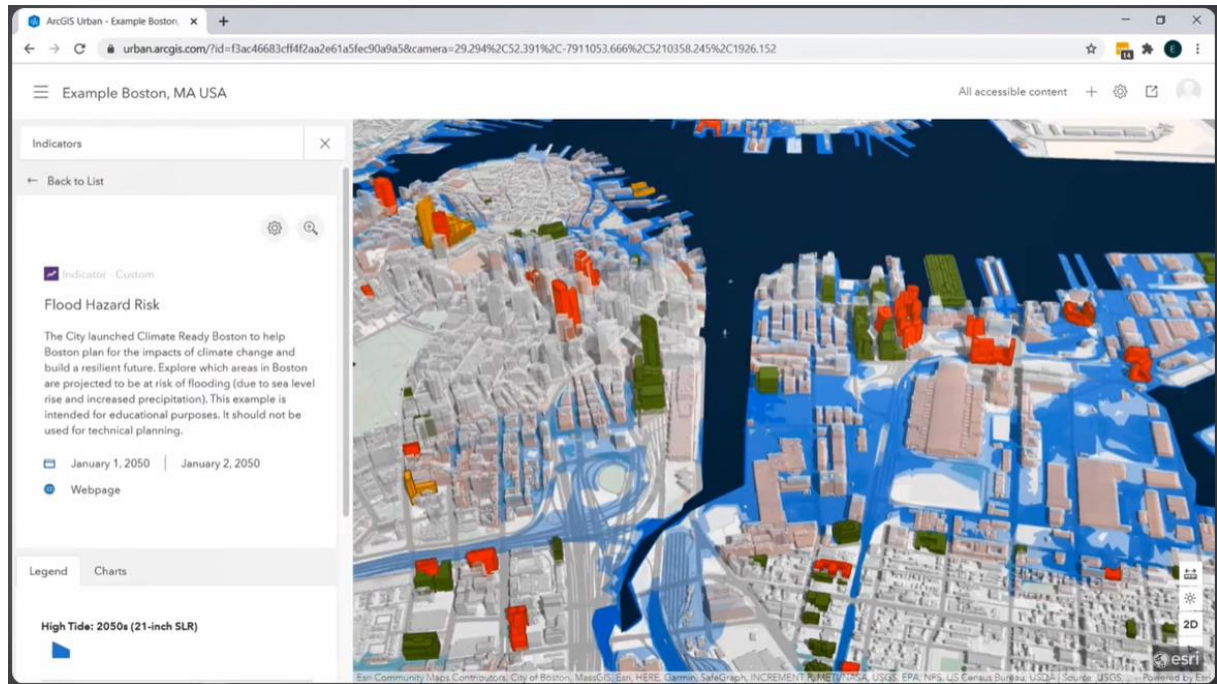


Fig. 54– Visualization of Flood Hazard Risk Scenario; Source: (Wittner, 2021)

Figure 54 shows a scenario in which a 3D city model is used to visualize the impact of a hypothetical rise in water levels on urban areas, identifying vulnerable zones at risk of inundation. While this type of modeling can effectively illustrate potential flood hazards, integrating BGIs into the model allows for the assessment of their efficiency in mitigating these risks. Such an integrated model can demonstrate how specific BGI interventions can reduce or control water levels, providing valuable insights for urban planning and flood management strategies.

At the same time, with the BGI DTs, it is possible to connect the real-time data and control the hazard at a certain level with the environmental sensors (Hamel et al., 2024). Digital Twin assists in Urban Planning through Real-time monitoring, Simulation and scenario testing, Optimization, Public engagement, Maintenance and asset management, System integration, and Support for Decision-making in terms of Smart City Development (El-Agamy et al., 2024).

A framework for the BGI maintenance using digital twins (DTs) is shown in Figure 55. By capturing real-world data from sensors on existing BGI, this information can be transmitted to Urban Information Modeling. Stakeholders can then analyze this data, alongside simulated scenarios, to make informed decisions and implement necessary maintenance strategies. Meteorological sensors play a crucial role in this process by continuously collecting real-time data. This data can be integrated with open-source sensor platforms like the Array of Things (AoT), allowing for efficient data upload to cloud servers (Pan et al., 2024). The collected data can then be downloaded and analyzed to inform decision-making. The various functions of sensors in environmental data monitoring are summarized in Table 19, showcasing their importance in optimizing BGI maintenance and performance.

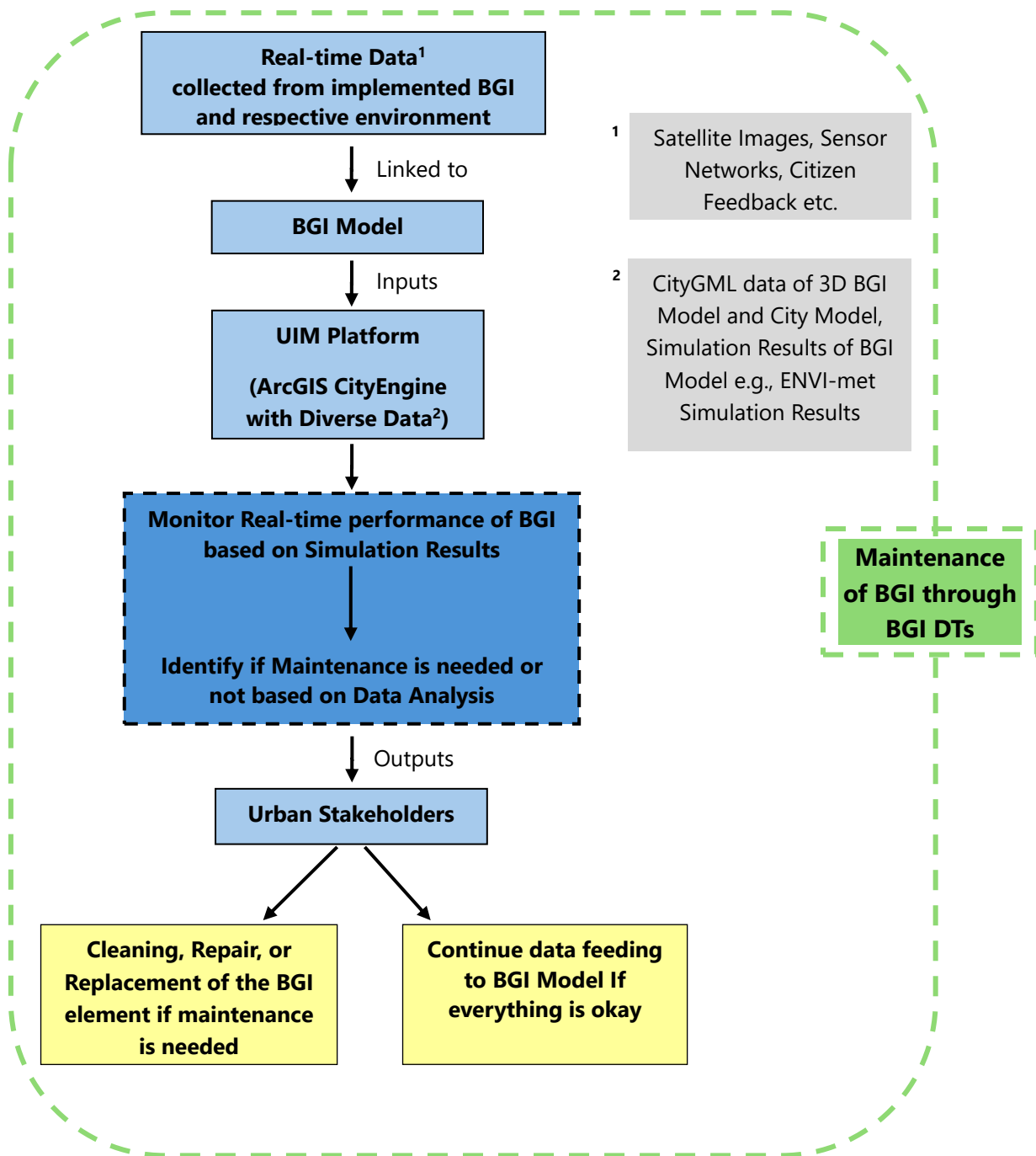


Fig. 55– Framework of BGI Maintenance through BGI DTs; Source: Author

Table 19– Sensors in Environmental Monitoring; Source: Adapted from (Shree et al., 2022)

Function	Description	Data Types
Data Collection	Measure various environmental parameters and collect real-time data	Temperature, humidity, precipitation, air quality, water quality, wind speed, wind direction, noise levels
Monitoring	Continuously track environmental conditions, enabling the detection of changes over time	Long-term trends in temperature, air pollution patterns, water level fluctuations
Alerting	Trigger alarms or notifications when pre-defined environmental factors deviate beyond allowable ranges	Rapid temperature changes, high pollution levels, rising water levels in flood-prone areas
Data Logging	Record data over time, creating a historical record of environmental conditions and making it valuable for policy-making	Climate change trends, seasonal variations in water quality, long-term pollution exposure
Remote Sensing	Sensors with communication capabilities allow data collection from remote or inaccessible locations	Air quality data from mountaintops, oceanographic data, wildlife tracking in remote areas
GIS and Mapping	Sensor data integrated with GIS is used for spatial analysis and visualization, creating maps and other representations of environmental data	Heat maps of urban areas, pollution distribution maps, real-time flooding maps
Public Awareness	Sensor data is made accessible to the public through online platforms (websites, apps), raising awareness and promoting informed decision-making	Air quality index reports, water quality dashboards, and community-based monitoring initiatives

5.2.4. ALIGNMENT WITH THE RESEARCH GOAL

Urban Information Modeling (UIM) serves as a crucial tool for achieving the goal and objectives of this research (Figure 56). By integrating diverse data types, it facilitates visualization, analysis, and simulation, assisting stakeholders in the decision-making process regarding sustainable urban planning practices. UIM also supports diverse data from Urban Digital Twins by enabling the exploration of potential synergies between BGI, DTs, and UIM.

The pilot study, focusing on the practical application of BGI integration within the UIM framework, utilizes the capabilities to analyze scenarios and identify challenges and opportunities. Furthermore, UIM's features allow the integration of real-time data monitoring through BGI DTs, enhancing maintenance processes and optimizing simulation outcomes. Figure 57 presents an overview of the thesis's research pipeline, illustrating a process that aims to enhance urban resilience by mitigating environmental risks and promoting equitable growth, ultimately contributing to the development of smart, resilient cities.

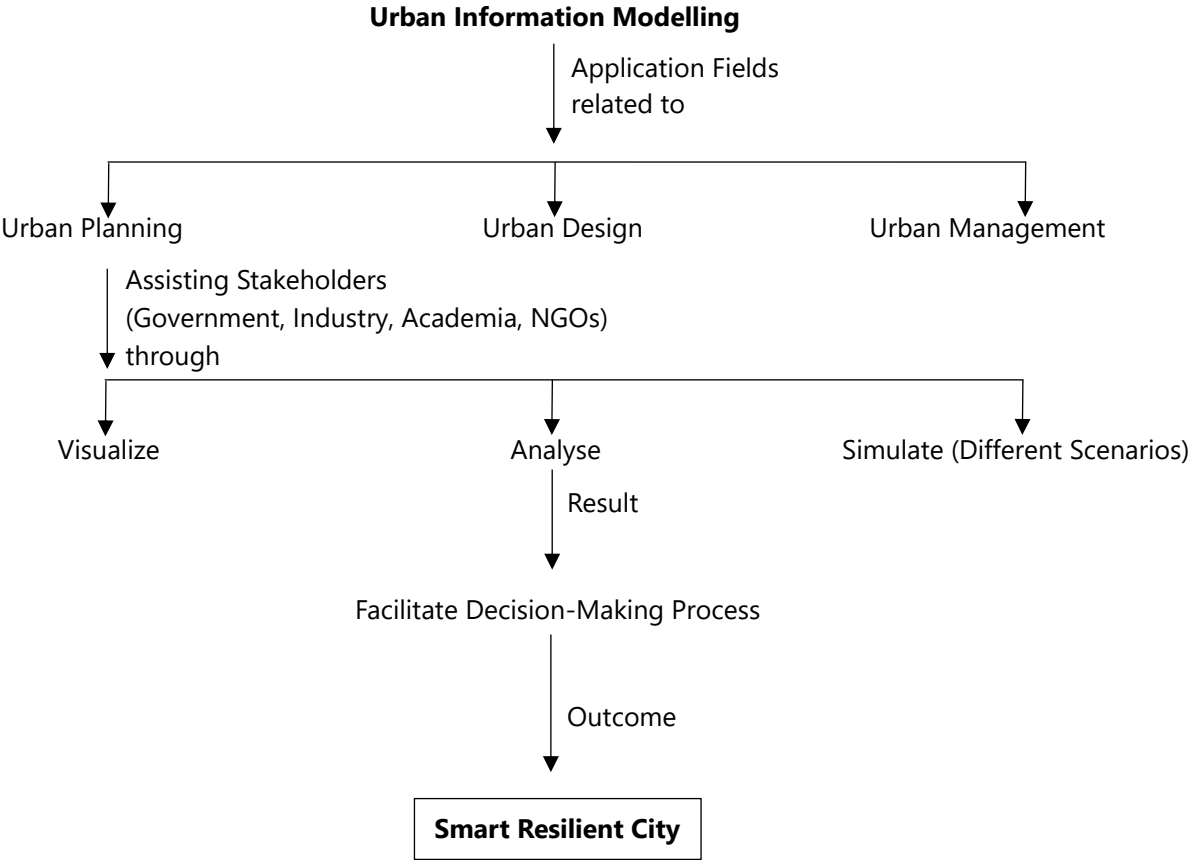


Fig. 56– Alignment with the Research Goal for Urban Planning;
Source: Author

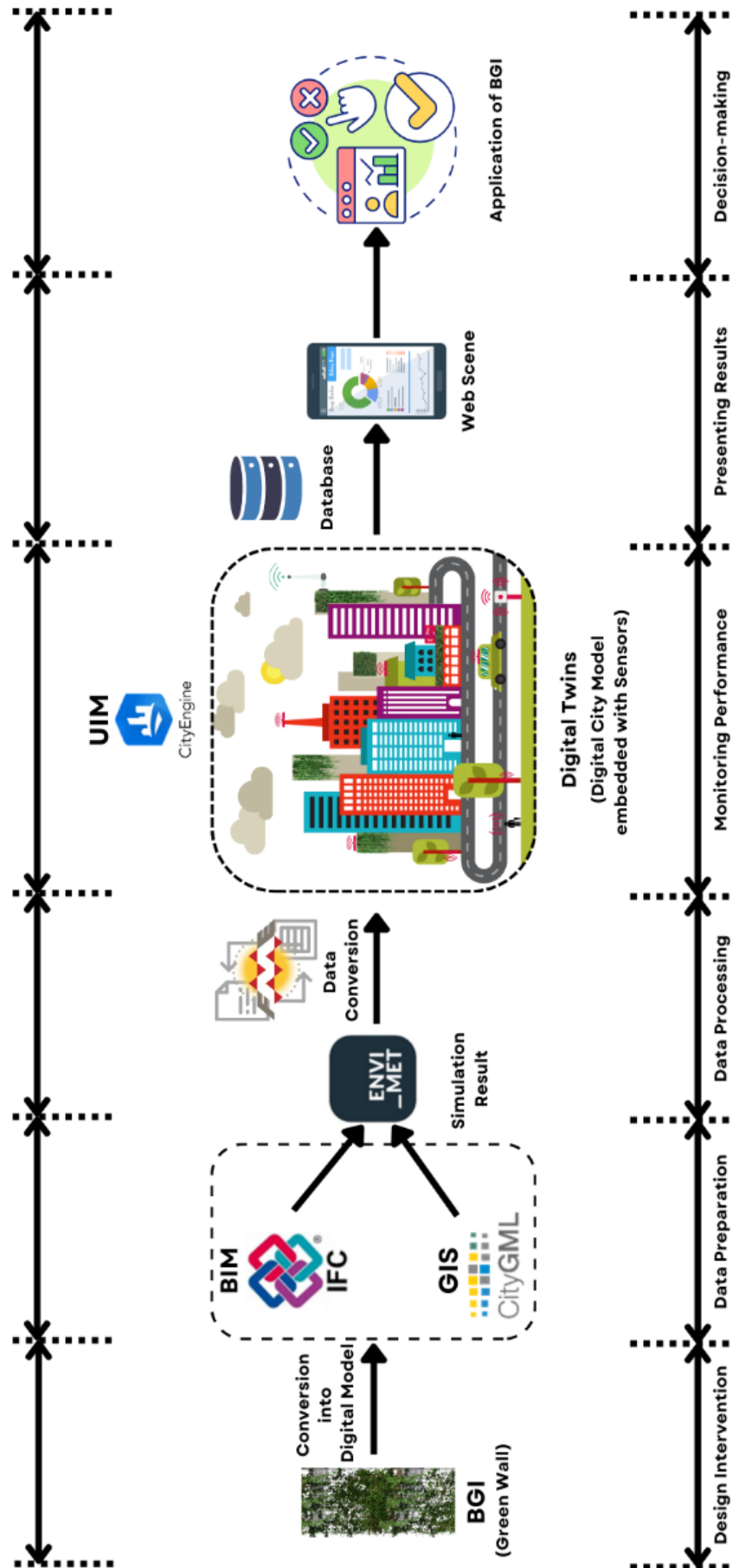


Fig. 57 – Research Pipeline; Source: Author

5.3. RECOMMENDATIONS FOR FUTURE RESEARCH

i. Addressing data interoperability challenges:

A major challenge lies in the data exchange interoperability between BIM and GIS. Enhancing compatibility between different software platforms and eliminating potential errors during conversion is crucial. Future research should prioritize the development of standardized data models and ontologies for BGI elements within CityGML and UIM platforms. This would enhance the integration process and facilitate the seamless exchange of data between different software tools and urban stakeholders.

ii. Advancements in data collection and processing:

Continued advancements in sensor technologies are paving the way for more accurate and cost-effective environmental monitoring solutions. Exploring the use of more advanced sensors, such as LiDAR, to capture a wider range of environmental parameters provides more accurate data for BGI monitoring and digital twin updates. In addition, establishing more comprehensive sensor networks to collect data on urban flows and developing user-friendly data platforms for seamless integration with digital planning tools are essential for managing the vast complexity of urban data.

iii. Refining 3D modeling and representation:

The representation of BGI within CityGML and UIM platforms needs a more unified and comprehensive approach. Future research should investigate the development of rule-based algorithms to automatically identify and extract elements from CityGML surface models and reconstruct them as volumetric BIM models (IFC format). Additionally, recognizing BGI as a distinct and interconnected system within UIM would facilitate a holistic understanding of its impact on the urban environment.

iv. Integrating multi-scale modeling and life cycle assessment:

Expanding the scope of research to incorporate multi-scale modeling, integrating both micro-scale simulations (e.g., ENVI-met) and macro-scale models, would enable a more comprehensive assessment of BGI's impact at different levels of the urban environment. Furthermore, incorporating Life Cycle Assessment (LCA) methodologies into the UIM framework would allow for the evaluation of the environmental impact of BGI throughout its entire life cycle, from design and construction to operation and maintenance.

v. Broadening the scope of BGI impact assessment:

Future research should expand beyond environmental impacts to include comprehensive assessments of the social and economic benefits of BGI integration within UIM. This would provide a more holistic understanding of the value of BGI in creating sustainable and resilient cities. Additionally, exploring innovative approaches (e.g., ArcGIS Experience Builder) for public participation and engagement within the UIM platform can foster collaboration and community-based BGI implementation.

vi. Improving policy and regulatory frameworks:

It is essential to investigate how existing policies and regulations can be modified or adapted to better support the integration of BGI and its digital twins in urban planning processes. This includes addressing data security and privacy concerns, given the sensitive nature of some urban data. By aligning legal and institutional frameworks with technological advancements, the widespread adoption of BGI-based solutions can be facilitated, promoting more sustainable and resilient urban development.

6

CONCLUSION

Recognizing BGI as a core component of the urban environment, this research demonstrates the potential of integrating Blue-Green Infrastructure (BGI) and its digital twins within Urban Information Modeling (UIM) as a powerful tool for sustainable urban planning. By utilizing the capabilities of UIM to visualize, analyze, and simulate the impact of BGI implementations, informed decisions can be made about their design, placement, and long-term maintenance, ultimately enhancing the development of smart and resilient cities. Following the research methodology, this study has developed a framework for incorporating BGI models into UIM and demonstrated its application in a pilot study. Despite the limitations, the findings highlight both the challenges and opportunities of this integration, including the need for standardized data models, advanced sensor integration, and enhanced software capabilities. The research also emphasizes the importance of recognizing BGI as a distinct city object within urban information modeling. By integrating real-time data from sensors and simulating various scenarios, digital twins of BGI can optimize maintenance practices and contribute to mitigating environmental risks such as heat island effects and flooding. While the study provides valuable insights into BGI integration in UIM, further research is needed to address the identified challenges and explore new opportunities. This includes developing rule-based algorithms for data conversion, incorporating multi-scale modeling and life cycle assessment, and expanding the scope to include public participation in decision-making. This research concludes by providing insights for urban planning stakeholders on how to utilize BGI and its digital twins (DTs) to enhance urban quality of life and contribute to the development of smart and resilient cities.

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Annex A

CityGML Feature Classes (Vegetation and WaterObject modules) with Properties, Types, and LODs;
Source: (Open Geospatial Consortium, 2012)

Feature Class	Property	Type	LOD
Vegetation module			
veg:AbstractVegetationObject Type			1 – 4
	_GenericApplicationProperty OfVegetationObject	xs:anyType	1 – 4
veg:PlantCoverType			1 – 4
	class	gml:CodeType	1 – 4
	function	gml:CodeType	1 – 4
	usage	gml:CodeType	1 – 4
	averageHeight	gml:LengthType	1 – 4
	lod1MultiSurface	gml:MultiSurfacePropertyType	1
	lod2MultiSurface	gml:MultiSurfacePropertyType	2
	lod3MultiSurface	gml:MultiSurfacePropertyType	3
	lod4MultiSurface	gml:MultiSurfacePropertyType	4
	lod1MultiSolid	gml:MultiSolidPropertyType	1
	lod2MultiSolid	gml:MultiSolidPropertyType	2
	lod3MultiSolid	gml:MultiSolidPropertyType	3
	Lod4MultiSolid	gml:MultiSolidPropertyType	4
	_GenericApplicationProperty OfPlantCover	xs:anyType	1 – 4
veg:SolitaryVegetation ObjectType			1 – 4
	class	gml:CodeType	1 – 4
	function	gml:CodeType	1 – 4
	usage	gml:CodeType	1 – 4
	species	gml:CodeType	1 – 4
	height	gml:LengthType	1 – 4
	trunkDiameter	gml:LengthType	1 – 4
	crownDiameter	gml:LengthType	1 – 4
	lod1Geometry	gml:GeometryPropertyType	1
	lod2Geometry	gml:GeometryPropertyType	2
	lod3Geometry	gml:GeometryPropertyType	3
	lod4Geometry	gml:GeometryPropertyType	4
	lod1ImplicitRepresentation	core:ImplicitRepresentationPropertyType	1
	lod2ImplicitRepresentation	core:ImplicitRepresentationPropertyType	2
	lod3ImplicitRepresentation	core:ImplicitRepresentationPropertyType	3
	lod4ImplicitRepresentation	core:ImplicitRepresentationPropertyType	4
	_GenericApplicationProperty OfSolitaryVegetationObject	xs:anyType	1 – 4

WaterObject module			
wtr:AbstractWaterObjectType			0 – 4
	_GenericApplicationProperty OfWaterObject	xs:anyType	0 – 4
wtr:WaterBodyType			0 – 4
	class	gml:CodeType	0 – 4
	function	gml:CodeType	0 – 4
	usage	gml:CodeType	0 – 4
	lod0MultiCurve	gml:MultiCurvePropertyType	0
	lod1MultiCurve	gml:MultiCurvePropertyType	1
	lod0MultiSurface	gml:MultiSurfacePropertyType	0
	lod1MultiSurface	gml:MultiSurfacePropertyType	1
	lod1Solid	gml:SolidPropertyType	1
	lod2Solid	gml:SolidPropertyType	2
	lod3Solid	gml:SolidPropertyType	3
	lod4Solid	gml:SolidPropertyType	4
	boundedBy	wtr:BoundedByWaterSurface PropertyType	2 – 4
	_GenericApplicationProperty OfWaterBody	xs:anyType	0 – 4
wtr:AbstractWaterBoundary SurfaceType			2 – 4
	lod2Surface	gml:SurfacePropertyType	2
	lod3Surface	gml:SurfacePropertyType	3
	lod4Surface	gml:SurfacePropertyType	4
	_GenericApplicationProperty OfWaterBoundarySurface	xs:anyType	2 – 4
wtr:WaterSurfaceType			2 – 4
	waterLevel	WaterLevelType	2 – 4
	_GenericApplicationProperty OfWaterSurface	xs:anyType	2 – 4
wtr:WaterGroundSurfaceType			2 – 4
	_GenericApplicationProperty OfWaterGroundSurface	xs:anyType	2 – 4
wtr:WaterClosureSurfaceType			2 – 4
	_GenericApplicationProperty OfWaterClosureSurface	xs:anyType	2 – 4

Annex B

7/2/24, 4:23 PM

A Survey on Perceptions and Preferences of Blue-Green Infrastructure

A Survey on Perceptions and Preferences of Blue-Green Infrastructure

As part of my master's thesis, I am conducting this survey to gather professionals' perceptions of Blue-Green Infrastructure (BGI), their preferences for different BGI types and locations, and any feedback they may have. The data collected will be kept anonymous and used solely for academic purposes. Please take 5 minutes to complete this short questionnaire, and if possible, share it with others.

Your participation is greatly appreciated.

* Indicates required question

1. 1. What is your profession? *

Mark only one oval.

- ☐ Architect
- ☐ Civil Engineer
- ☐ Ecologist
- ☐ Educator
- ☐ Energy Consultant
- ☐ Environmental Engineer
- ☐ Hydrologist
- ☐ Landscape Architect
- ☐ Sociologist
- ☐ Sustainability Consultant
- ☐ Urban Designer
- ☐ Urban Planner
- ☐ Other: _____

<https://docs.google.com/forms/d/1MjF6vCrdHEJ37L-J9zUZaG3pTfPJEq8aypvmDd1m-dQ/edit>

1/5

7/2/24, 4:23 PM

A Survey on Perceptions and Preferences of Blue-Green Infrastructure

2. 2. Have you heard of Blue-Green Infrastructure (BGI) before? *

Mark only one oval.

☐ Yes

☐ No

☐ Other: _____

3. 3. If yes, how familiar are you with BGI?

Mark only one oval.

1 2 3 4 5
 Not ☐ ☐ ☐ ☐ ☐ Extremely familiar

4. 4. In your opinion, what are the main benefits of BGI? (Select all that apply) *

Check all that apply.

- ☐ Enhanced aesthetic value
☐ Enhanced biodiversity
☐ Improved air quality
☐ Improved public health
☐ Improved stormwater management
☐ Improved water quality
☐ Increased property value
☐ Increased recreational spaces
☐ Reduced energy cost
☐ Reduced flooding risk
☐ Reduced noise
☐ Reduced urban heat island effect
☐ Other: _____

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5. 5. How important do you think BGI is for sustainable urban planning? *

Mark only one oval.

1 2 3 4 5
Not ☐ ☐ ☐ ☐ ☐ Extremely important

6. 6. Are you familiar with the case study area? *



Mark only one oval.

☐ Yes
☐ No

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7. 7. In your opinion, which of the following BGI types would be appropriate for the given images? *



Check all that apply.

- ☐ Bioswales
☐ Green roofs
☐ Green spaces
☐ Green walls
☐ Permeable pavements
☐ Street trees
☐ Tree trenches
☐ Vegetated swales
☐ Other: _____

8. 8. Are you familiar with any implications of Digital Twin technology in Sustainable Urban Planning? If yes, please specify. *

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9. 9. Do you consider it important to utilize the Digital Twins of BGI in urban planning to create smart and resilient cities? *

Mark only one oval.

- ☐ Yes
- ☐ No
- ☐ Other: _____

10. 10. Is there anything you would like to share about your experiences or opinions regarding the integration of Blue-Green Infrastructure (BGI) in Urban Planning?

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