Developing a Framework for building-level analysis of green facade potentials on mitigating urban heat island, using BIM and GIS integration

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[July 2021]

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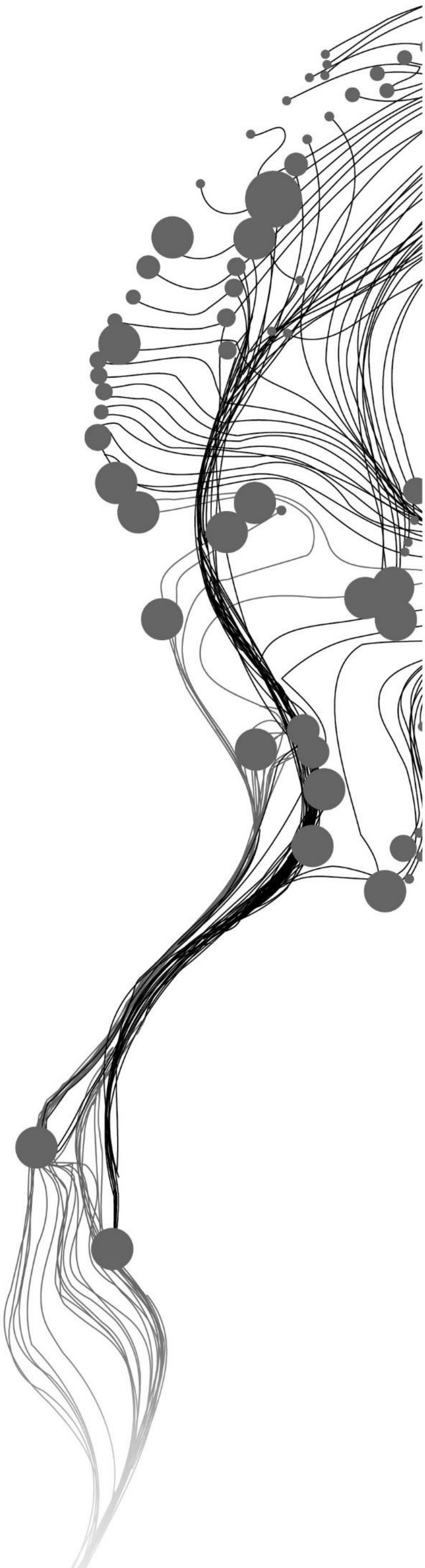

Developing a framework for building-level analysis of green façade potentials on mitigating urban heat island, using BIM and GIS integration

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Enschede, The Netherlands, [July, 2020]

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Following the rapid urbanization growth, serious environmental challenges are being posed to modern societies. Urban Heat Island (UHI) is one of the most critical global challenges caused by rapid urbanization affecting people. Therefore, improving the resilience of the cities against UHI is a critical concern to consider in urban planning. In this regard, urban green infrastructures play a crucial role in limiting heat problems in the urban context. Vertical surfaces in cities have a great potential to increase greeneries in cities and contribute to mitigating UHIs regarding scarce spaces in cities. In recent years, the advent of Building Information Modelling (BIM), which provides a semantically rich 3D design of buildings, offers a great potential to investigate the use of green façade to mitigate the UHI effect. Geographic Information System (GIS) in usually used to study UHIs. In this context, there is a gap to integrate BIM data with GIS to evaluate the impact of green façade on UHIs systematically.

This study proposes a framework to assess the impact of green facades on mitigating UHIs by integrating BIM and GIS. Data requirements, different approaches to integrating BIM and GIS, and different methods to simulate UHIs were explored through literature review.

After collecting the required GIS data, all layers are separately imported to the BIM environment in DWG format, maintaining the shared coordinate with the BIM model. Moreover, the BIM model needs to be simplified since it includes many details that are not required for the simulation. Later, the model can be transferred to the UHI simulation engine. After adding the weather data, running the simulation both with and without greenery represents the cooling effect of green facades.

Subsequently, the developed framework was implemented on a case study, a building in Deventer, The Netherlands, for 24 hours in a heatwave. Comparing the bare building and the building with a green façade shows a significant decrease in temperature.

Finally, the evaluation of the framework was performed through a workshop with six experts from Witteveen en Bos, a consulting engineering company in The Netherlands, to assess the usability of the framework. From the workshop, it was concluded that the proposed framework is able to fulfil the needs of planners, architects and decision-makers in building-scale and city-scale toward a resilient, sustainable city using urban green infrastructure. However, the complexity of the framework may prevent it from being used in daily practices.

Keywords: Green façade, UHI, BIM, GIS, ENVI-met

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This place was my university, library, office, garden, cinema, and canteen during the thesis. I would like to thank myself and all the people in the world for surviving the Covid pandemic and this challenging situation.

Marjan Moradi

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ABBREVIATIONS

BIM	Building Information Modelling
BLHI	Boundary Layer Heat Island
CFD	Computational Fluid Dynamic
CityGML	City Geography Markup Language
CLHI	Canopy Layer Heat Island
GIS	Geography Information System
IAI	International Alliance of Interoperability
IFC	Industry Foundation Classes
LAI	Leaf Area Index
LoD	Level of Details
OGC	Open Geospatial Consortium
PET	Physiologically Equivalent Temperature
PMV	Predicted Mean Vote
SDG	Sustainable Development Goals
SUHI	Surface Urban Heat Island
UGI	Urban Green Infrastructure
UHI	Urban Heat Island

1. INTRODUCTION

1.1. Background and justification

With the growing urbanization trend over the past century, the built environment has been expanding rapidly, posing serious environmental challenges to modern societies. Figure 1 represents the global trend of urbanization, which is increasing significantly. Urban Heat Island (UHI) is one of such detrimental environmental impacts of rapid urbanization (Mutani & Todeschi, 2020). The glossary of meteorology, an American Meteorological Society (2020), defines UHIs as "Closed isotherms indicating an area of the relatively warm surface; most commonly associated areas of human disturbance such as towns and cities." UHI forms in the air due to a difference in cooling between urban and rural areas. The rise of temperature in cities causes problems for the environment and societies, especially for vulnerable groups like children and older people. Furthermore, it causes an increase in the use of energy to cool indoor environments (Tiziana Susca, 2019). Moreover, climate change and global warming are worsening the level of UIHs (Sturiale & Scuderi, 2019).

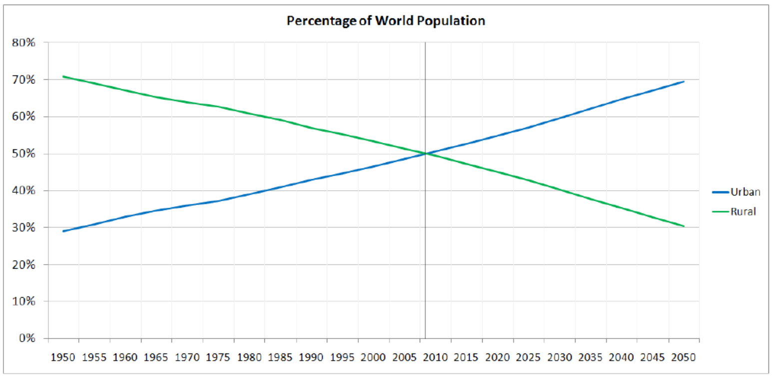


Figure 1- Percentage of the world population- United Nations, http://esa.un.org/unup/p2k0data.asp

The 2030 agenda established by the United Nations General Assembly emphasizes city planning's effect on reducing climate change emissions toward sustainable and resilient cities. The mentioned agenda was set in 2015 in the form of 17 Sustainable Development Goals (SDGs) and 169 targets to be achieved by 2030. Goal 11, sustainable cities and communities, aims to "make cities and human settlements inclusive, safe, resilient, and sustainable" (Envision2030, 2015). Therefore, improving the resilience of cities against UHIs is one of the challenges urban planners face in recent years. In this context, Urban Green Infrastructures (UGI) play a crucial role in mitigating UHIs in urban environments as an adaptation and mitigation action against climate change.

There have been many experimental and simulation studies on greenery as a SUHI mitigation strategy establishing the positive effect of UGIs on local climate (T. Susca, Gaffin, & Dell' Osso, 2011; Tiziana Susca, 2019). Mutani and Todeschi (2020) prove that the land surface temperature and the air temperature will decrease by increasing the green areas, leading to a more liveable and sustainable urban context. They analysed the outdoor vegetation in urban and building scales using satellite images and the outdoor thermal comfort using weather station data. They employed Geography Information System (GIS) for analysing the presence of vegetation. Djedjig, Bozonnet, and Belarbi (2015) built three streets on a small scale to do an experiment assessing the effect of green roofs and facades on the local urban microclimate. They showed that the radiative balance of the streets could be improved by green facades, which enhances hygrothermal comfort in cities. However, they proved that green roofs are less significant compared to green walls. In another study, the authors indicated that green walls on the east and west facade of the studying building reduce the cooling load of nearby buildings by 37% for Athens's summer climate (Djedjig, Bozonnet, & Belarbi, 2016). For this study, Djedjig, Bozonnet, and Belarbi used a building simulation program called TRNSYS to evaluate the hygrothermal impacts of green facades on building energy performance. Besides, a reduced scale mock-up helped them to calibrate the results by comparing it with numerical data.

On the other hand, another study indicates that trees (13% reduction) have the best performance as UGI compared to green roofs (marginal reduction) and green facades (5%- 10% reduction) in pedestrian thermal comfort. The authors claim that setting greenery purposefully in heat-exposed areas is more practical and efficient than just having a high density of arbitrarily distributed green cover (Zölch, Maderspacher, Wamsler, & Pauleit, 2016). They proved their claim by a 3D micro-scale model, i.e., ENVI-met, based on Computational Fluid Dynamics (CFD), in a dense residential area in Munich city. Another study done in the real-world scale, comparing a green wall and a bare wall in the same environment in the city center of Madrid, shows a temperature reduction in summer between 2.5 °C and 2.9 °C. The researchers investigated 144 measurements of climatic air temperature parameters, humidity, air velocity, and solar radiation to reach this result (de Jesus, Lourenço, Arce, & Macias, 2017).

1.2. Research problem

As mentioned above, recently, researchers demonstrated great potential in reducing the SUHI effect through the increased use of greenery in the built environment. Considering microclimate information in designing buildings and cities will lead to more thermal comfortable outdoor environments that enhance the community's well-being and health. However, the focus of research so far has been primarily on the use of greeneries on horizontal surfaces. While useful, this ignores the enormous potential of using vertical surfaces to mitigate UHI. In large cities, especially in areas with a high density of urban canyons, vertical surfaces significantly contribute to reflecting the light and trapping heat inside cities and respectively, reinforcing the UHI phenomenon. Therefore, covering these vertical surfaces with vegetation contributes to reducing the ambient temperature.

In recent years, the advent of Building Information Modelling (BIM), which provides a high-resolution and semantically rich 3D design of buildings, offers a great potential to investigate the use of green facade to mitigate the UHI effect. While the research has been done in different case studies and locations and methods, this scope lacks a framework to integrate BIM data with GIS to systematically evaluate the impact of the green facade on UHIs. This is especially important because, depending on the orientation of vertical surfaces and the morphology of the surrounding buildings, different surfaces can contribute differently to UHI mitigation. Besides, depending on the material used on the facade, not all surfaces can be considered candidates for green surfaces. This highlights the significance of micro-level analysis of the building surfaces (or in other words, surface-specific analysis) to investigate the extent to which each surface (1) has potential for the use as a green surface, and (2) contributed to the mitigation of UHI.

BIM is a system that integrates 3D modelling concepts and information management principles to facilitate the management of projects' lifecycle and communication among different users like architects, contractors, and engineers, as shown in Figure 2 (Kubba, 2017). BIM also streamlines collaboration and information sharing for the whole project team through a virtual model of a structure (Kubba, 2017). BIM models are usually multidimensional models that provide comprehensive semantics about time, spatial relationships, costs, materials, as well as quantities and properties of building components. This semantics can be integrated into other recent technologies consisting of point clouds of existing buildings, 3D printers, GIS., etc. (Lester, 2017).

The presence of semantic data in the 3D model makes BIM models appropriate for a wide range of building simulations in terms of energy use, solar radiation, lighting, ventilation assessment, and carbon emissions (Lu, Wu, Chang, & Li, 2017). Moreover, BIM can be used in the urban planning process considering different roles such as land developing, land registration, mapping the city, and planning (Open Geospatial Consortium & Future City Pilot, 2017). For example, Yamamura, Fan, and Suzuki (2017) used BIM to assess Tokyo's energy performance in a smart city planning context. On the other hand, GIS is a computerized system based on cartography, geography, and remote sensing technology, allowing users to collect, digitize, manage, analyze, visualize, and present spatial information. Thus, GIS is a database system that can also be used for spatial reference data functions and certain processing data operations (H. Wang, Pan, & Luo, 2019).

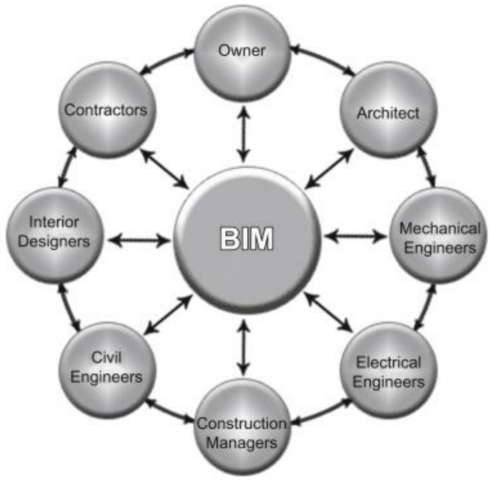


Figure 2- The relationship of BIM to the various stakeholders and project team members (Kubba, 2017)

Even though GIS and BIM function at different scales and Level of Details (LOD), they can enable the users to combine data at the micro-level, i.e., through BIM and macro-level, through GIS, for a building and its surrounding environment. The integration of BIM and GIS can add more details to the general GIS data and provide the required context for BIM data (Ohori, Diakité, Krijnen, Ledoux, & Stoter, 2018).
Although BIM has a great potential to explore the effect of UGIs on UHIs, to the best of the author's knowledge, there is no framework for the systematic use of BIM and GIS to analyse buildings' vertical surfaces in terms of potentials for greenery. In this research, a framework will be developed to address this gap. As a result, green facades' effect on mitigating UHIs will be assessed by combining BIM and GIS using a new framework. Thus, the framework will support architects and decision-makers to design buildings toward a resilient and sustainable city. In this way, it is possible to test the effect of designed structures in the environment in the context of UHI on a local climate scale.

1.3. Research Objectives and Questions

1.3.1. Objective

The main objective of this research is to develop a framework for the surface-specific evaluation of green facades and their impacts on mitigating UHIs through the integration of 3D BIM and GIS data.

1.3.2. Sub-Objectives

1. To identify what methods have been used to integrate BIM and GIS and to simulate UHIs
2. To develop a workflow for the integration of BIM and GIS models in the context of green facade analysis;
3. To develop a framework for the simulation of the impact of green facades on UHI in the BIM-GIS integrated environment;
4. To evaluate the framework's productivity and constraints.

1.3.3. Question

How to perform a comprehensive surface-specific analysis on a building's vertical surfaces to explore the impact of green facades on the mitigation of UHIs?

1.3.4. Sub-Questions

1. **To identify what methods have been used to integrate BIM and GIS and to simulate UHIs through literature review.**
   1.1. What methods, tools, and workflows are used to integrate BIM and GIS and simulation of UHIs?

2. **To develop a workflow for the integration of BIM and GIS models in the context of green facade analysis.**
   2.1. What are the required input data for this integration?
   2.2. What types of data are needed to perform this analysis?

3. **To develop a framework for the simulation of the impact of green facades on UHI in the BIM-GIS integrated environment.**

   3.1. What parameters influence the effect of UGI on SUHI?
   3.2. What are the existing UHI simulation models and tools?
   3.3. Which tool is more suitable for the analysis of vertical surfaces in terms of interoperability with the BIM-GIS integrated model?

4. **To evaluate the framework's productivity and constraints.**
   4.1. What are the strengths and limitations of this framework?
   4.2. How is the efficiency and user-friendliness of the framework?

1.4. The overall approach of the study

The research methodology to meet the objective of this research consists of four phases, namely, (1) Exploration and literature review, (2) Development of BIM-GIS Integration Workflow, (3) Development of UHI Simulation Framework, and finally, (4) Framework Evaluation.

1.4.1. Phase I- Exploration

In phase I of the research, the research sub-objective one will be addressed by reviewing previous research on BIM-GIS integration and physics-based & data-drive UHI simulation methods. This literature review will help gain the background knowledge required to select appropriate BIM-GIS integration and UHI simulation engine. The literature review also aims to help gain insight into different regulations, standards, primary and secondary data, tools, and potential steps used and proved by researchers. On the other hand, the integration process considering which environment is used for integration (i.e., BIM to GIS integration or GIS in BIM integration) will be investigated in this phase.
Additionally, interviews with urban planning experts and sustainability experts from Witteveen en Bos will be conducted to identify the end-user requirements from the expected framework. A semi-structured interview will be held to allow interviewees to add to the discussion freely. This would better allow explicating the design intent and mindset of the interviewees. Through the interviews' codification and having it confirmed by the interviewees, the user requirements will be translated to a set of assessment criteria (e.g., scalability, adaptability, user-friendliness, etc.). These criteria not only will lead the subsequent research steps but also will serve as evaluation metrics at the end of this research.

1.4.2. Phase II- development of BIM-GIS integration

In an effort to address the second research sub-objective, this phase is dedicated to the development of the BIM-GIS integration workflow. In this phase, first, an integration workflow will be developed. This workflow should allow retaining the surface-specific data from the BIM while providing a geometric

representation of the building surroundings from the GIS model that would make microclimate analysis possible. The development of this workflow should be in view of a possible UHI simulation framework that will be developed in the next step. Therefore, the insight about the UHI simulation engine gained from the previous phase will be leveraged to determine the requirements of the BIM-GIS integration workflow.
Next, the GIS data and BIM models provided by Witteveen en Bos will be investigated to determine whether or not the required attributes for BIM-GIS integration are available. Depending on the findings of this step, a set of data preparation steps will be developed to structure how data should be made ready for the proposed framework. To better codify these preparatory steps, an ontological data structure will be developed for BIM-GIS integration that needs to be used for UHI analysis of vertical surfaces. By synthesizing all the findings of this phase, a clear workflow for BIM-GIS integration will be proposed.
The two datasets which are going to be combined are in GIS and BIM systems. For the GIS part, the software ArcGIS and for the BIM part, Autodesk Revit is the potential applications. The main challenges for BIM-GIS integration at this stage are the different data structures and the different LoDs in each system. In general, BIM provides highly detailed semantic data in building scale, while GIS supports spatial data in fewer details but covers a large environment. In this phase, the intended framework will be developed to reach the interoperability between GIS and BIM, which is a set of procedures to be used to perform the integration.

1.4.3. Phase III- Development of UHI simulation framework

This stage enables us to reach sub-objective three by a UHI simulation framework development. At first, available UHI simulation tools will be investigated. However, these tools should be compatible with the BIM-GIS integrated model resulted from the previous phase. According to the previous stage, it is assumed that there is a georeferenced model in this stage adopted to the local environment's heat map. However, just the building's outer skin is vital for this research; LoD3 of the model is appropriate. The next step is to select an appropriate UHI simulation engine for the framework. After that, data requirements will be studied to identify the required data for the selected simulation tool. Subsequently, the available data will be explored to find if they meet the requirements or not.
Based on this exploration, a step-by-step data preparation process will be developed for the UHI simulation. As a result of this phase, the UHI simulation framework will be developed to be used in the following step.

1.4.4. Phase IV- Evaluation

The framework, simulation, and results should be evaluated based on the company's requirements. In this regard, the outputs of previous stages will be evaluated by implementing the proposed framework on the target building BIM model. As mentioned in section 4.3.1, workshops and interviews with the experts during the research allow assessment principles to be identified. Based on these principles, the framework's strengths, weaknesses, and limitations can be recognized and improved.
Besides, to assess the compatibility with the users' expectations, a demo of the study and a questionnaire will be developed for the assessment by the experts from Witteveen en Bos.
Represents a summary of the mentioned phases are represented in Figure 3.

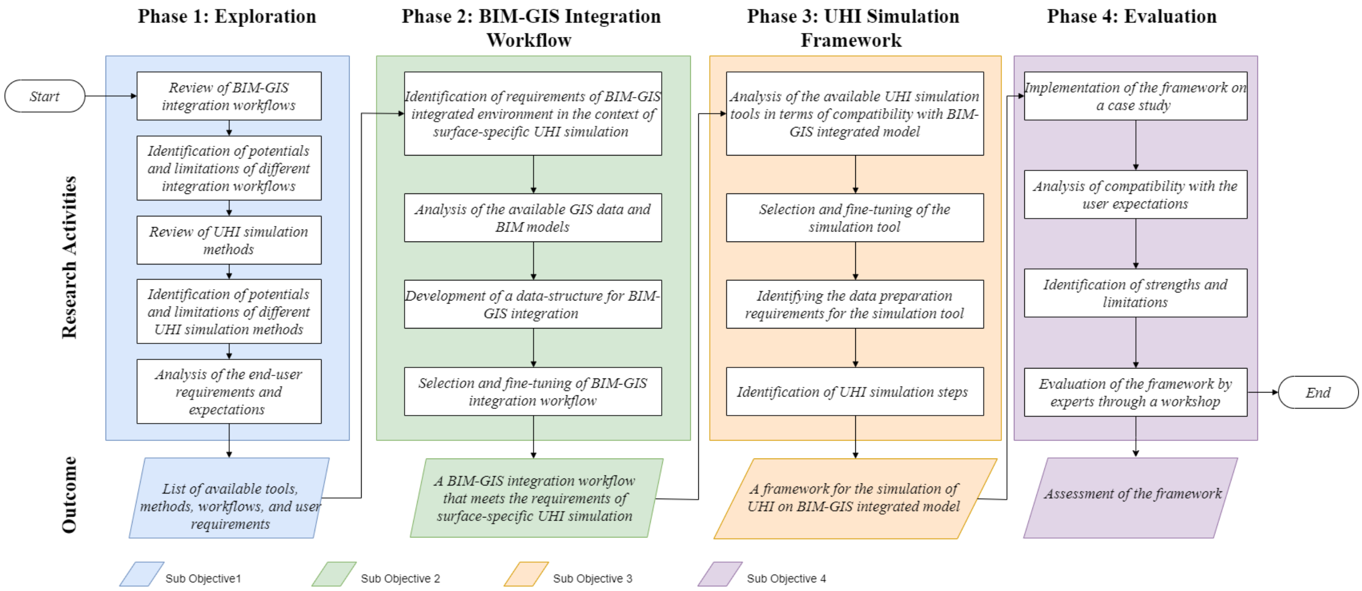


Figure 3- Research Design Overall Approach

1.5. Research scope

This thesis explores the flow of GIS and BIM data to ENVI-met by creating a framework. At the start point of the research, there was no similar research. The main goal is to make a workflow to generate a connection between BIM and green facades' effects on heat stress and UHIs. The research does not calculate the UHI; the microclimate indicators are calculated by ENVI-met. Moreover, in the time frame of the master thesis, it is out of scope to test all possible green facades in different parts of the building, and with different grass types, due to the reason that each simulation takes a lot of time. Last, this project does not cover the economic points of the green facades.

The primary required data for this study is a BIM model and the GIS data of the surrounding area. A district will be defined on the local scale to simulate the local climate, which needs to include the case study building, its adjacent building, current urban green and water bodies, and roads. Since only one of the effective factors of UHI (i.e., vegetation) will be assessed, the other factors should be explored and defined as constant factors. In this regard, microclimate can be affected by two parameters: (a) lower tropospheric of weather layers, and (b) construction materials, soil, water bodies, plants as energy exchange agents. The latter are urban environment components that can be explored by the GIS data and, if needed, a survey in the district area to check the materials of the buildings. In addition, the weather data, including temperature, humidity, wind speed and direction, and sun path, can be obtained from closest weather station reports such as the National knowledge institute for weather, climate, and seismology (KNMI) in The Netherlands.

1.6. Study area

For the purpose of this study, the city of Deventer was selected due to the available data providing by the company. Deventer is one of the historical Dutch cities located on the Ijssel river. Figure 4 shows the location of the city in The Netherlands.

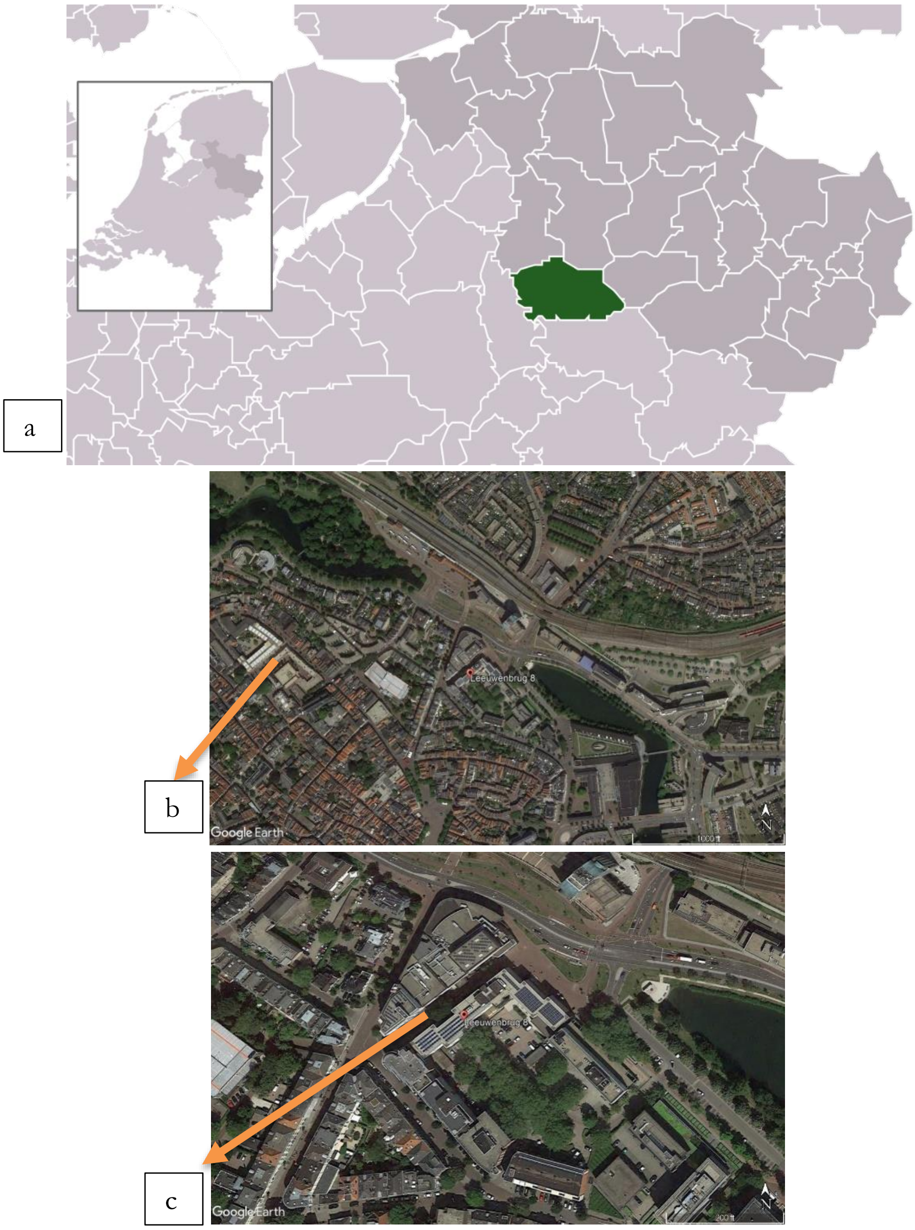


Figure 4- The study area: a) Deventer City and its location in Overijssel- Source: Wikipedia; b and c): The Location of the case study building in the city- Source: Google Earth

The BIM model for the research is provided by the company, which is the company building in Leeuwenbrug 8 7411 TJ Deventer. Therefore, the study aims to investigate if Witteveen en Bos's building were covered by vegetation, how much it could have affected the local temperature of the environment.

1.7. Thesis structure

The thesis is organized into four main chapters:

- Chapter 2 reviews related literature about the context of the research. In this chapter, different ways of integrating BIM and GIS, the approaches and tools, as well as reviewing different methods for simulation of UHIs, will be explained. Moreover, some topics like green facades, UHIs, heat stress and outdoor thermal comfort are described.

- Chapter 3 explains the methodology of this study. It includes approaches used to bring the GIS data in the BIM environment, preparing data for the integration, the method of UHI simulation and bringing the semantic data to the UHI simulation tool.
- Chapter 4 represents the study results, interpretation of the results and discussion and analysis of them.
- Chapter 5 discusses the results and provides the limitations of the study and some recommendations for further studies.

1.8. Summary

This chapter clarifies the background of the study and introduces the research gap in this field. The research questions and the methods to answer the questions are described. In summary, the study aims to develop a framework to integrate BIM and GIS data to assess the cooling impact of green facades. The innovation of this study is in integrating data from two different domains and a new tool for simulating UHIs.

2. LITERATURE REVIEW

In this chapter, the theoretical background of the related topics is explained. Firstly, urban climate and UHIs are explained to reveal the context behind this study. Furthermore, outdoor thermal comfort, heat stress, and PET will be clarified. Then green facades as a solution of mitigation temperature are described, followed by introducing ENVI-met as a microclimate simulation tool to measure the intended indicators. Then, a description of BIM and its integration with GIS data are presented.

2.1. Urban climate

Global warming has caused heat waves and UHIs. Moreover, a heatwave is a trapped air that is a combination of hot weather and high humidity and can last for several days. This challenge is becoming worse regarding, on the one hand, the increased population exposure, and on the other hand, increases in duration, frequency, and level. Around 166000 heat-related deaths happened from 1998-2017, consisting of 70000 death in Europe 2003 heatwave (Heatwaves, 2018). In addition to direct health issues, water, energy, and power shortage resulting in problems in food production, transportation would happen.

Moreover, UHIs happen when there is a relative difference in temperature between a rural area and its surrounding. Oke(1988) represents some reasons for UHIs, like darker urban surfaces rather than the surrounded area, less vegetation and the capacity of urban surface materials for storing heat. Voogt and Oke (2003) define three types of UHIs: Boundary Layer Heat Island (BLHI), Canopy Layer Heat Island (CLHI), and Surface Urban Heat Island (SUHI).

According to Oke, CLHI is the urban atmosphere layer consisting of the surfaces to nearly mean building height and its intensity is dependent on street surfaces, water bodies, and buildings. BLHI is above CLHI affected by the main urban surface like morphology and geographical location of the city. While BLHI and CLHI are the atmospheric temperatures, SUHI is the surface temperature difference between rural and urban areas. Figure 5 represents each of these types.

Measuring and modelling each of these types are different. In this study, SUHI is going to be investigated, which can be affected by UGIs. According to Rizwan, Dennis, and Liu, (2008), there are three general techniques for measuring UHIs; (1) space technology that employs remote sensing data to obtain needed information, (2) numerical modelling that is a mathematical model of effective factors such as thermal properties, albedo, wind speed, sky view factor, air temperature, radiation, etc., and (3) small-scale physical models that measurement tools are employed to measure microclimate parameters in an experimental environment under simplified condition.

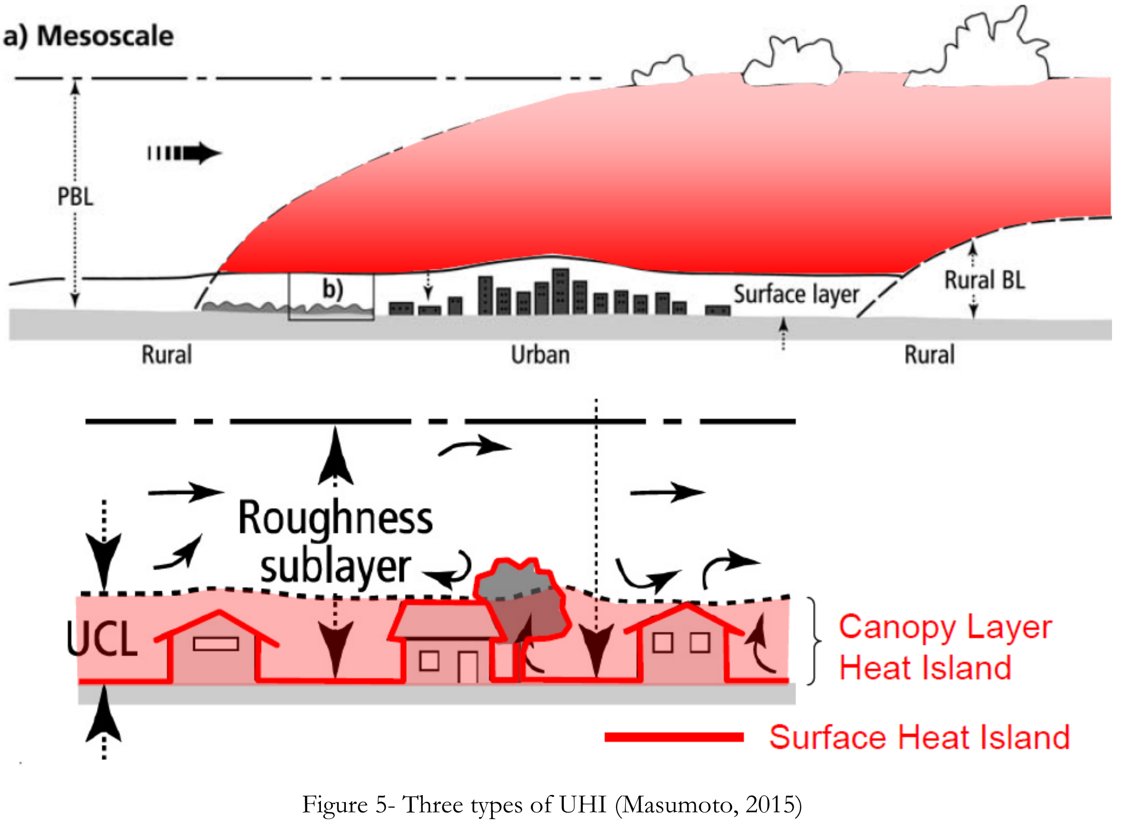


Figure 5- Three types of UHI (Masumoto, 2015)

2.2. Outdoor thermal comfort and Physiologically Equivalent Temperature (PET)

While indoor thermal comfort can be measured by effective temperature or the Predicted Mean Vote (PMV), it is more complex for outdoor thermal comfort because factors like radiation, air humidity, and wind speed need to be taken into account. In this regard, Höppe (1999) introduced Physiologically Equivalent Temperature (PET) to assess outdoor thermal comfort. According to Hoppe (1999), "PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed". Based on Hoppe's equation, outdoor thermal comfort depends on key meteorological parameters as well as personal factors like metabolic rate and clothing level (Höppe, 1999). In addition, Matzarakis and Mayer (1966) developed an index of relating thermal stress level and human sensation to PET and PMV, shown in table 1.

Table 1- PET and PVM classes, human sensation, and thermal stress level

PVM	PET	Human sensation	Thermal stress level
-3.5	4℃	Very cold	Extreme cold stress
-2.5	8℃	Cold	Strong cold stress
-1.5	13℃	Cool	Moderate cold stress
-0.5	18℃	Slightly cool	Slight cold stress
0.5	23℃	Comfortable	No thermal stress
1.5	29℃	Slightly warm	Slight heat stress
2.5	35℃	Warm	Moderate heat stress
3.5	41℃	Hot	Strong heat stress
		Very hot	Extreme heat stress

Therefore, to assess the outdoor thermal comfort in the case study area, PET must be calculated both with and without the green facade. Besides, for indoor thermal comfort, air temperature and PVM will be used.

2.3. Green facade

As explained in section 1.1, research has proved that green facades positively influence SUHI by helping to mitigate the adjacent temperature. In general, green facade is a broad term that describes any form of vegetation growing on, up, or against buildings' walls, temporary or permanently. (Zaid, Perisamy, Hussein, Myeda, & Zainon, 2018). Zaid et al. (2018) demonstrated that, in general, green facades mitigates wall surface temperature and, consequently, indoor temperature. They significantly affect urban microclimate and contribute to thermal comfort through emission reduction, regulation of evaporation rate, and providing shading effects. Thus, pedestrians walking in an area with green walls feel less heat. It should be noted that green facades impact the wall temperature, while the outside temperature is less affected by them. Likewise, on summer days, the insulation effect of green facades leads to a reduction in the use of air conditioners, meaning less heat production by air conditioners for outside air. It is worth mentioning that different coverage areas, the climate, the types of vegetation, and the system of the green wall affect their performance. Additionally, various terms such as vertical garden, bio wall, green wall, living wall, or bio facade wall are used for such kinds of vertical green surfaces. According to Beecham, Razzaghmanesh, Bustami, & Ward (2018), green walls can be divided into two classifications of green facades and living walls based on the installation and growing method. In this division, green facades rely on ground-level rooting, while a living wall is a system that plants are planted on a structure attached to the wall. Factors such as cost, maintenance, installation, aesthetic, variety of plant types, and operation time are influential in selecting the green wall. For example, it takes several months to cover an entire wall for green facades, whereas living walls provide the chance to

operate instantly after installation (Beecham et al., 2018). In this study, the terms green facade or green wall point to the general meaning of green wall.
Furthermore, parameters such as building orientation and local weather have an impact on plant selection. In this regard, due to the lowest maintenance and longer lifecycle of the system, native plants and evergreen plants are ideal. To be more specific, variables such as canopy thickness, canopy cover, vegetation morphology, plant height, leaf emissivity and leaf reflectivity contribute to thermal cooling benefits(Cameron, Taylor, & Emmett, 2014). Based on Cameron et al. (2014) experiments, semi-herbaceous Stachys, Hedera and the silver-leaved could be the best options for the cooling efficiency of green walls. Both plants are dense; Stachys cools the outside air by evaporation and shading the facade, and Hedera reduces the outside temperature through its shadow. Likewise, for other species which their canopy increase with time as they grow, the better cooling potential will be provided by them.

2.4. UHI simulations

As clarified in section 2.1, satellite data, numerical data from weather reports, and small-scale physical models can be used for the simulation of UHI. For example, in a study to simulate UHI and near-surface air temperature in Athens, researchers employed weather research and forecasting model combined with a single-layer urban canopy model to create a spatiotemporal model of a summer heatwave over the city during three days (Giannaros, Nenes, Giannaros, Kourtidis, & Melas, 2018). In another effort to evaluate UHI mitigation solutions, Wang and Akbari (2016) used ENVI-met software to simulate environmental conditions consisting of air temperature, wind speed, human weighted mean radiant temperature and physiologically equivalent temperature for a small part of Montreal city on a summer day. Each of these factors' effects is investigated to help provide guidelines for three UHI mitigation strategies. ENVI-met is a 3D software to explore outdoor micro-climate in an interactive environment. They used Google Map to identify the geometry of buildings, simulated a 30-h period for a summer day using historical weather data, and defined the exact surface materials, building height properties, and land use in the software. They proved that vegetation and increasing urban albedo mitigate UHI during the daytime. In contrast, urban sky view factor (a parameter dependent on urban morphology and form) control can reduce UHI during night-time.
ENVI-met a is high-resolution three-dimensional modelling software that analyses urban microclimate and various environmental factors using urban morphology. Environmental parameters such as wind speed and direction, air temperature, PET, humidity, and radiant temperature are the output variables of ENVI-met with a 1-5s temporal and 0.5-10 m spatial resolution to quantify interactions among the local environment and the outdoor microclimate. These variables are in dynamic subsystems ranging from Buildings, Radiation, Soil physics, Vegetation etc. Moreover, it takes green walls and green roof effects into account while considering current building envelopes and vegetation(Y. Wang, Berardi, & Akbari, 2016). ENVI-met model takes into account dynamics and thermodynamics laws and consists of:

- Flow around and between buildings
- Exchange processes at the ground surface and building walls
- Building physics
- Impact of vegetation of the local microclimate
- Bioclimatology
- Pollutant dispersion ("Features - ENVI-met,")

According to the model system, EVNI-met calculates:

- Longwave and shortwave radiation fluxes considering adjacent vegetations and buildings
- Heat flux and evaporation from vegetations into the air with a very detailed simulation of plants
- Facade and roof temperature of the buildings including three layers materials
- Heat and water exchange inside the soil system
- Calculation of biometeorological indices such as PMV/PPD, Mean Radiant Temperature, UTCI or PET via Biomet
- Calculation of air pollution and diffusion of particles (deposition at leaves and surfaces, sedimentation) and gases (reactive gases of the NO2, Ozone, NO and inert gases)

Another research is done by Bulatov, Burkard, Ilehag, Kottler, & Helmholz (2020) to identify UHIs through an infrared and thermal simulation of a semantic 3D model. Land cover classes, 3Dgeometry, and roof materials were taken to create a 3D semantic mesh containing temperature and radiance based on actual weather data. Their results indicated that, compared to other methods, this method has higher accuracy for recording surface temperature and developing guidelines considering sustainable land covers and roof materials (Bulatov, Burkard, Ilehag, Kottler, & Helmholz, 2020). Furthermore, using LiDAR point clouds for 3D urban morphology, i.e., Landsat 8 for land surface temperature and Sentinal-2A for calculating the normalized difference vegetation index, Asadi, Arefi, and Fathipoor (2020) created an artificial neural network model to simulate the cooling effect of green roofs on UHIS. They prove that by increasing the number of green roofs by 3.2% in the study area, the average land surface temperature decreases by 1.96 °C.

2.5. BIM-GIS integration

Generally, when combining BIM and GIS, there are mismatches between them due to the differences in the data structure, coordinate system, semantics, and LoD. Therefore, the integration of these systems at the technical level is critical. Some efforts to integrate BIM and GIS in different methods for specific goals are reviewed in the following. Isikdag, Underwood, & Aouad (2008) prove that the Industry Foundation Classes (IFC) can provide the chance to convert geometric and semantic information from BIM to a geospatial environment. IFC is a standard BIM format, an object-based data model developed by the International Alliance of Interoperability (IAI) to assist data exchange in architecture, engineering, and construction.

On the other hand, City Geography Markup Language (CityGML) can be used as a geospatial environment adaptable to IFC standards (Lu et al., 2017). However, to avoid losing details in the conversion process, El-Mekawsy, Östman, and Hijazi (2012) introduced a unified building model that combines CityGML and IFC models. Furthermore, Hor, Jadidi, and Sohn (2016) proposed a new integration method using semantic web technologies and Resources Description Framework (RDF) graphs. Likewise, Deng, Cheng, and Anumba (2016) developed a reference ontology using an instance-based method to generate rules for accurate mapping of entities and representations between BIM and GIS at different LODs.

In a similar effort, Isikdag, Underwood, and Aouad (2008) showed that BIM in the pre-construction phase could be done at the semantic level using semantic web services and geospatial analysis. In this method, first BIM and GIS data are translated into a semantic web data format. After that, integration and queries of spatial and temporal data are enabled by a set of standardized ontologies (Isikdag et al., 2008). Kang and Hong (2018) developed a method of integrating IFC and CityGML, which performs a high LOD mapping intuitively using screen buffer scanning-based multiprocessing employing semantic mapping rules. There is another method that utilizes 3D GIS tools like 3D difference and 3D intersection for construction projects. By applying 3D spatial operators in Geo-Data Base Management System (Geo-DBMS), the problem of point in 3D polygon is covered via this method (Musliman, Abdul-rahman, & Coors, 2010).

Another method integrates GIS data with a 3D model using City Engine modelling software to improve the 3D model developed by JIa and Liao (2017). Another method is developed by Atazadeh, Rajabifard, and Kalantari (2017) to combine CityGML and IFC to correspond spatial data to define the legal and physical properties of multi-story buildings to achieve a 3D digital management. The other technique enables an online framework for integrating BIM and GIS as well as attaining spatial data combinations in different domains like multi-scale modelling at different LODs based on semantics and geometry (Mei & Feng, 2015). In parallel, Open Geospatial Consortium (OGC), which is a virtual organization organizing interoperability programs to solve geo-processing problems, in the OGC web service phase 4 testbed, investigated the ways of CAD/GIS/BIM data integration at the web service level (Open Geospatial Consortium, 2007).

The literature review shows that most of the integration of BIM and GIS methods are done in the format of IFC and CityGML open standards. Likewise, depending on the issue, the combination can either merge data using a semantic platform, extract data from one system to use it in another one, or extract data from both systems using a third-party environment.

However, there are many challenges in integrating techniques, such as mismatch of data in the conversion process, losing details of BIM data in the simplification process, and inaccurate outputs. Furthermore, each of these studies has been done in a specific context, and there is a gap in assessing UGI effects on UHIs through utilizing both systems.

Based on the above literature review, filling the gap of simulating UHIs in BIM system can lead to a comprehensive sustainable design method in which designers can assess how much they can contribute to decreasing the ambient temperature by green facades.

2.6. Summary

The main concepts of the research, relevant studies and possible techniques are reviewed in this chapter. The foundation of this thesis is based on current literature and existing science. The gaps of the scientific papers in detecting the cooling effect of UGIs are introduced in this chapter to be taken into account in shaping the study.

3. PROPOSED FRAMEWORK

In this section, the general framework proposed in this research is explained. The overall framework is presented in Figure 6. As shown in this figure, the proposed framework consists of two main phases. In the first phase, the GIS model of the surrounding area is prepared and then integrated with the simplified BIM model of the target study building. In the second phase of the proposed framework, the integrated model is used to run various simulation for the analysis of the impact of the green façade on the UHI effect.

3.1.1. BIM-GIS integration workflow

The GIS data needs to be 3D or at least have height attributes that can be used to extrude a 2D footprint and approximate the realistic geometry (i.e., 2.5D). The first step in this phase is to collect the relevant GIS data. At least, the following data are required for the UHI analysis: (1) road network, (2) building footprints, (3) urban water bodies, (4) urban greeneries, and (5) building height data. For many municipal areas, the CityGML model that incorporates all these data are publicly available. If this is not the case, the cadastral databases (e.g., PDOC in the Netherlands) can be used to collect these data separately and then integrate them in a GIS platform.

Moreover, for the UHI study, it is important that the GIS model includes material data (i.e., at least external façade material). This data can be obtained, in not available as a GIS layer, through the site observation or virtual exploration using platforms such as Google Earth Pro 7.3.3 . The material needs to be assigned to every single building. This can be done by creating an additional attribute manually in the GIS platform. Since the principle of the UHI simulation engine is often based on solids using a pixel containment algorithm, it is required for objects to be closed solid volumes and not a mesh. Another important point to consider in this phase is that to avoid double counting of the study building, the GIS representation of target study building need to be removed. This step should be done before starting the UHI simulation. Finally, all 3D components, such as roads and trees, need to be higher than the base surface in the UHI simulation engine; otherwise, they are not recognized and will be invisible in the model. Likewise, all buildings in GIS layers must be closed surfaces to be visible. Moreover, there would be problems if vegetation layers touch the building. Thus, it is required to make space between buildings and trees.

All GIS layers should be imported separately in the BIM environment to be able to transfer them as separate layers to the UHI simulation engine. Since buildings materials carry significant weight in UHI in terms of sun-related behaviours (e.g., reflection, emissivity, absorption, etc.), it is necessary to have separated layers based on material. To bring GIS data to the BIM environment, the data should be converted to the format supported by the BIM environment. Most often, the DWG format serves this purpose. The transformation of data from a GIS format to DWG is achievable by modelling software such as Civil3D. During the transfer of GIS data to the BIM environment, it is essential to use a uniform coordinate system. This can be achieved by using the GIS coordinate system as the baseline and share this coordinate system with the BIM model. Thus, in the BIM environment, reference points must have the same coordinate with the GIS layers.

Because BIM models consist of many details, it is required to simplify the model as much as possible. For UHI studies, it suffices to retain the exterior façade objects (exterior walls, windows, curtain walls, etc.) and footprint of the building.

Other objects, e.g., interior walls, floors, doors, and windows' frames, are not necessary for UHI simulation and can be removed because they make the file heavy and the simulation very slow. Given that the application of the green façade depends heavily on the nature and type of the façade objects, it is crucial to classify the façade objects and use them as separate layers. In this way, different green façade strategies can be studied based on the consideration of different types of objects, or a combination thereof, that can be used for the greenery. For example, it is possible to consider the use of greenery only on the curtainwalls and not on windows and walls.

It should be noted that because the UHI simulation engine often uses closed solids, the simplified BIM model needs to represent the external objects as solids and not surfaces. Therefore, in case façade objects are represented as surfaces, they can be extruded for a small amount to form a solid. After this stage, the integrated BIM and GIS data are ready to be translated to the UHI simulation software.

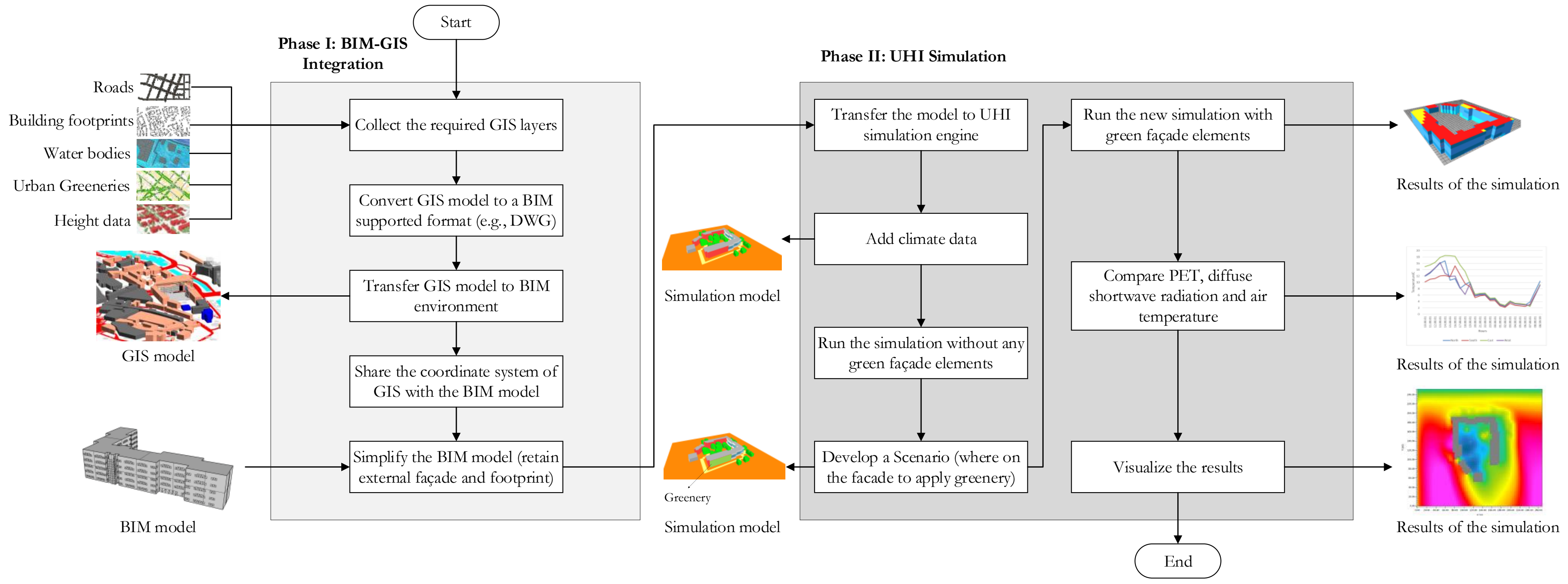


Figure 6- The general process of the framework

3.1.2. Development of UHI simulation workflow

This phase aims to apply the prepared data in the previous step in a UHI simulation engine. For the simulation of the UHI impact, variables like air temperature, building surface temperature for UHI(Voogt & Oke, 2003) and PET for outdoor thermal comfort (Matzarakis & Mayer, 1996) need to be taken into account. Therefore, the UHI simulation engine should consider these parameters in the analysis. To set up the simulation, it is necessary to select a start date and the simulation duration. For instance, it is rational to select a heatwave period in the case study area to study UHI, since it is a kind of natural hazard which can affect the people's lives and health situation in terms of heat.

Moreover, the grid size needs to be determined. The grid size has a significant impact on simulation results. On one hand, a small grid size can be used for a high-resolution analysis that allows designers to consider the use of greeneries on individual façade objects or even part of them. This can be helpful for detailed design phase of buildings. On the other hand, a high-resolution analysis has a prohibitive computational cost resulting in a long simulation time. This takes a toll on the applicability and practicality of the proposed framework for regular design projects, in which excessive computation power is often not available. Increasing the grid size decreases the computational time and efforts, but this comes at the cost of losing granularity in design decision making (i.e., objects will be bundled together). Therefore, it is of cardinal importance to choose the minimum grid size that is allowed by the computational power at the disposal of the designer. This can be anywhere in the range of 0.5-10m.

Weather data can be imported to the UHI simulation engine in two formats, i.e., simple forcing or full forcing. For the simple forcing option, only average temperature, wind speed, and wind direction are used. However, in the full forcing option, more data such as relative humidity, precipitation, amount of clouds, etc., can be used, leading to more accurate results. For importing weather data in the simulation engine in the full forcing manner, there are two approaches. The first and simple approach is to use EPW files, i.e., a weather data file saved in EnergyPlus (Weather Data | EnergyPlus) format. EPW is used for energy simulation tools. The second approach is to use CSV files, as shown in table 2. For an accurate UHI simulation, the time interval for the parameters must be 30 minutes, and the data must strictly follow this template.

Table 2- Weather data requirements for ENVI-met

Parameter	Unit	Description
Date	[DD.MM.YYYY]	The date of the data registration
Time	[hh:mm:ss]	The time of the data registration
SW DIR/ low clouds	[W/m²] or 0-8[1]	Direct shortwave/ Cloud cover in the height below 6500ft
SW DIF/ med. Clouds	[W/m²] or 0-8	Diffuse shortwave/Cloud cover in the height of 6500ft- 20000 ft
LW/ high clouds	[W/m²] or 0-8	Long radiation/Cloud cover in the height of 20000ft-40000ft
Abs. Temperature	[K]	Temperature in Kelvin
Rel. Humidity	[%]	Relative humidity in percentage
Wind Speed	[m/s]	Wind speed in meter/second
Wind Direction	[∘]	Wind direction in degrees (0°~360°)
Precipitation	[mm]	Precipitation in millimetre

To compare the results with and without green façade, it is required to run the simulation first without any green facade element. Then, different scenarios for applying green facades to the building can be developed by placing green objects in the desired location on the BIM model. This can be done by simply placing a thin box on the desired location and then assigning green façade properties to it in the UHI simulation engine. Finally, a comparison of such microclimate parameters as air temperature, PET, diffuse shortwave radiation, surface temperature, etc., represent that how green facades are effective in mitigating heat stress. The air temperature of the urban canopy from the ground to the tops of buildings is an appropriate indicator to be measured since it is experienced by people for assessing UHIs and public health risks. In contrast, as described in section 2.2. PET is an indicator to assess outdoor thermal comfort, which is a combination of wind, air humidity, radiation, air temperature and the human body's metabolism. Therefore, to assess the effect of greeneries on people on hot days and outdoors, it is reasonable to calculate and compare these variables in both situations with and without green façade.

[1] In meteorology, the measurement unit for cloud cover amount is oktas or eights of the sky. The sky is divided into eight boxes and the cloud cover is estimated in a way that how many of those boxes are filled with clouds ranging from 0 oktas (clear sky) to 8 oktas (completely cloudy)

3.2. Summary

This chapter clarifies the study methodology and the proposed framework. First, it explains how to obtain the required data. Later the method of the BIM-GIS integration is described. Furthermore, the UHI simulation approach is illustrated through the ENVI-met tool.

4. IMPLEMENTATION AND CASE STUDY

As described in section 1.6., the framework is implemented and tested in a case study based on the Witteveen en Bos headquarter building in Deventer. The following steps demonstrate the process of the framework implementation on the case study building. Also, ENVI-met 4.4.5 student version is selected for UHI simulation since to evaluate the UHI, variables like air temperature, building surface temperature and PET can be taken into account, which are feasible with ENVI-met. For the calculating PET variable, the Biomet, a post-processing tool in ENVI-met, can be used. Moreover, 3D maps can be generated to visualise the building surface temperature. The maps can be visualised for a particular time of the day, i.e., the hottest times, while the static data can be available for the entire simulation period for each cell separately.

4.1. Data requirements and initial setups

The primary required data for this study was the BIM model of Witteveen en Bos's building provided by the company and the surrounding area's GIS data. To simulate the local climate, a district was defined on the local scale, in this case, the surrounded area of the target building. In this stage, the required GIS data was gathered from different sources (explained below) and was prepared to be added to the BIM model. The company provided the tress layer in CityJson format. The footprint of buildings and their height, as well as other urban data like roads and water, were downloaded from https://3d.kadaster.nl/basisvoorziening-3d/. The study area is separated from sheets 33 and 2, as shown in Figure 7.

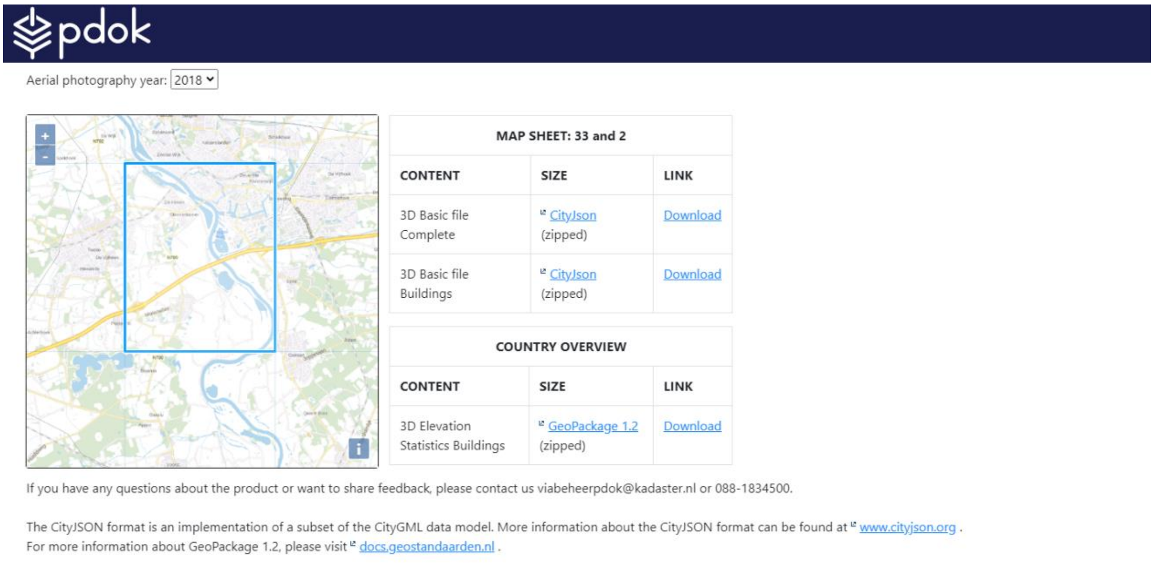


Figure 7- The study area in PDOK

The EPW file was not up to date for the weather data, and they were from the year 1995. Therefore, the second way, i.e., the CSV file of the weather data, was adopted. Based on the requirements described in section 3.2.2. and table 2, the weather station of Wageningen University (https://met.wur.nl/veenkampen/data/) was chosen due to the fact that it contains all the required data, despite the fact it is not very close to the study area. Since the CSV file should strictly comply with the template that ENVI-met needs (table 2), the data had to be pre-processed in Excel.

As the GIS data was in CityJson format, the plugin, CityJson file loader in QGIS was used to convert CityJson to SHP. Then, the materials of the surrounded buildings, which were manually extracted from Google Earth Pro (version 7.3.3.7786. 2020), were imported into ArcMap as separated layers. This is because it is essential for each material to be a separate layer. After adding a column in the attribute table, the material for each footprint was added manually. Then with the "select by material " tool, a layer for each material was assigned.

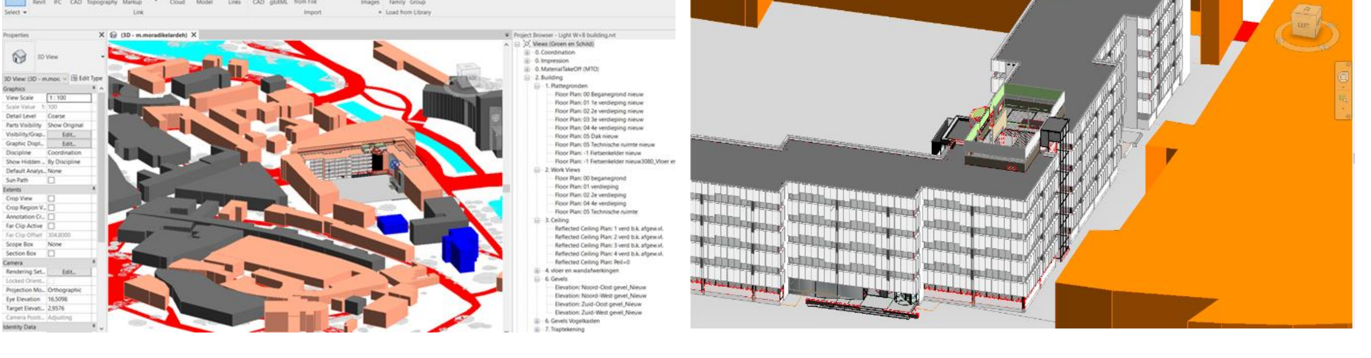
For this study, a type of green facade without an air gap was selected. The plant type is Funkia (Hosta), and its thickness was considered 0.30 m, which is the default value in ENVI-met. Leaf Area Index (LAI), which is the amount of leaves over the wall area in m², was considered to be 1.50 m2/m2. The leaf angle distribution was considered 0.50, which is a parameter 0-1. 0 means leaves are parallel to the surface, and one means they are perpendicular to the surface.

4.2. BIM-GIS integration

The next step was to bring these GIS files into the BIM model, which was done in Revit, i.e., BIM software from Autodesk. To do this, it was needed to convert SHP files to DWG format using Civil3D software.
In Civil3D, during the process of the conversion from SHP to DWG, the coordinate RD new Amersfoort 22996 was assigned to each layer. Therefore, all layers have the same coordinate system to be ready for the next step. Furthermore, as the explanation of section 3.2., it is crucial to make all the objects solid.
To bring the GIS layers to Revit, DWG files were linked to Revit while maintaining the coordinate system. Then, the coordinate of a specific point was specified in the BIM model, considering the coordinate of the point in Civil3D shown in Figure 8.

Figure 8- Sharing the coordinate system of layers from Civili3D to Revit

Figure 9 represents the GIS data, with separate layers based on material, integrated with the BIM model in Revit. As can be seen, the LODs of the BIM model and GIS data are different; thereby, it is crucial to simplify the BIM model in the next step (Figure 10).



(a) (b)
Figure 9- (a)BIM-GIS data integration- (b)Different LODs of BIM and GIS data

Next, the integrated data needed to be prepared for ENVI-met. There is a plugin in Revit Dynamo, "Dragon fly", to prepare the simulation directly in Revit. However, at the time of this research, the plugin was not completed yet, and the tutorial for it was not ready. Hence, the translation of current data from the BIM environment to ENVI-met was done in Rhino software 6. However, before that, the Dynamo code (available in the Appendix) was scripted to extract the exterior surfaces of the model, which are big enough to be calculated in ENVI-met simulation, as can be seen in Figure 10.

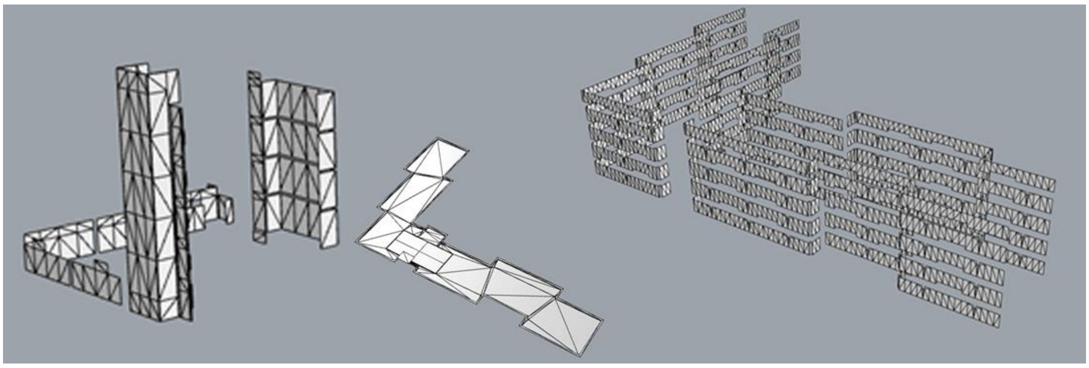


Figure 10- Coding in Dynamo to simplify the BIM model and extract windows, footprint and curtain wall layers

After this simplifying stage, as Figure 11 represents, the data was transferred to Rhino to be prepared for the simulation. One of the challenges is that Envi-met was too slow for such a big district. Therefore, the district was reduced in several steps.

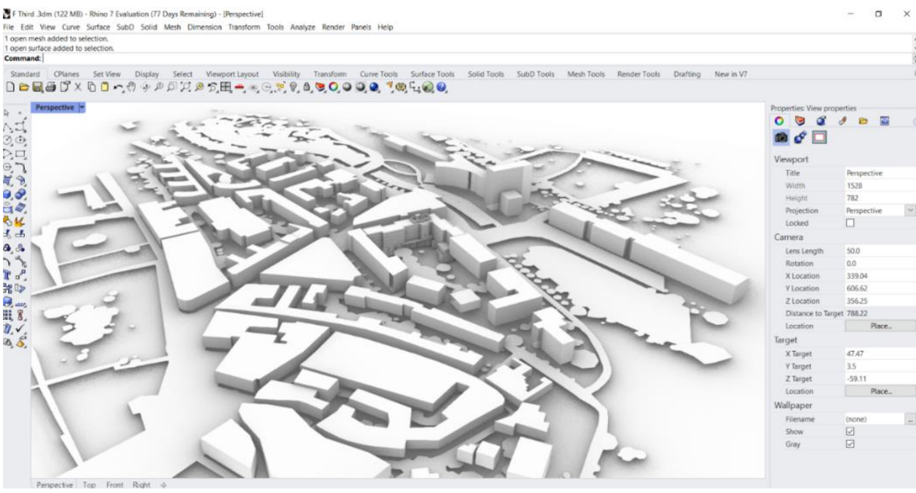


Figure 11- Data integration of BIM and GIS data in Rhino

To avoid double counting the GIS representation of the case study, the overplus GIS was removed in this step in Rhino. However, this could have also been done in the Civil3D environment.
Furthermore, since it is necessary to have closed volumes in ENVI-met, Figure 12 represents the closed volume of the study building that was manually drawn to be appropriately prepared for adding the windows and curtainwall layer.

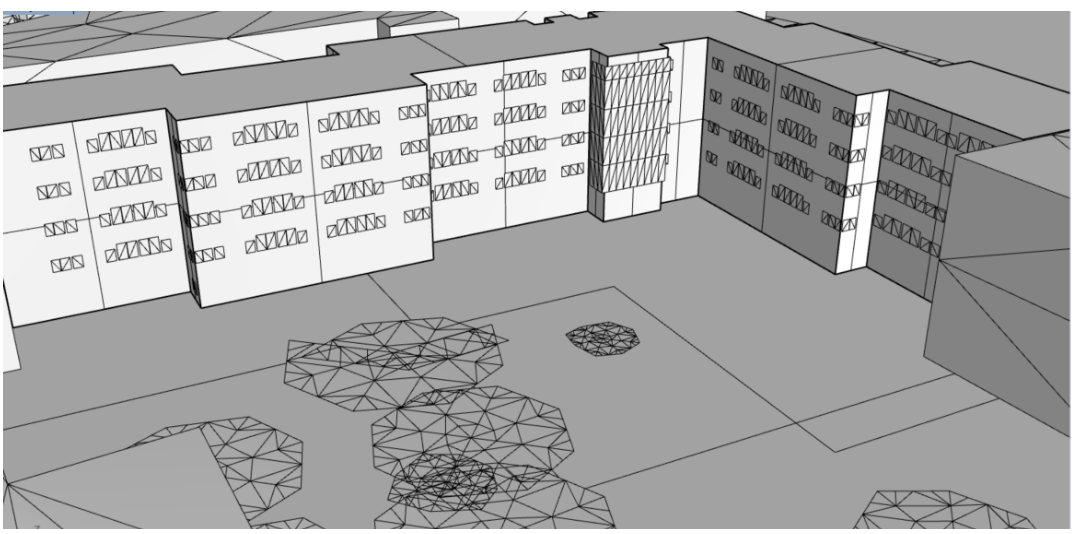


Figure 12- Simplified model of the building including windows from the BIM model

4.3. UHI simulation

To assess the effect of green facades on mitigating temperature in the study area, the district was simulated in ENVI-met both with and without green facade to identify the difference. The greening strategy for this study is to assign greenery to all exterior walls except windows and curtain walls (Figure 13). However, it is possible to have different greening strategies.

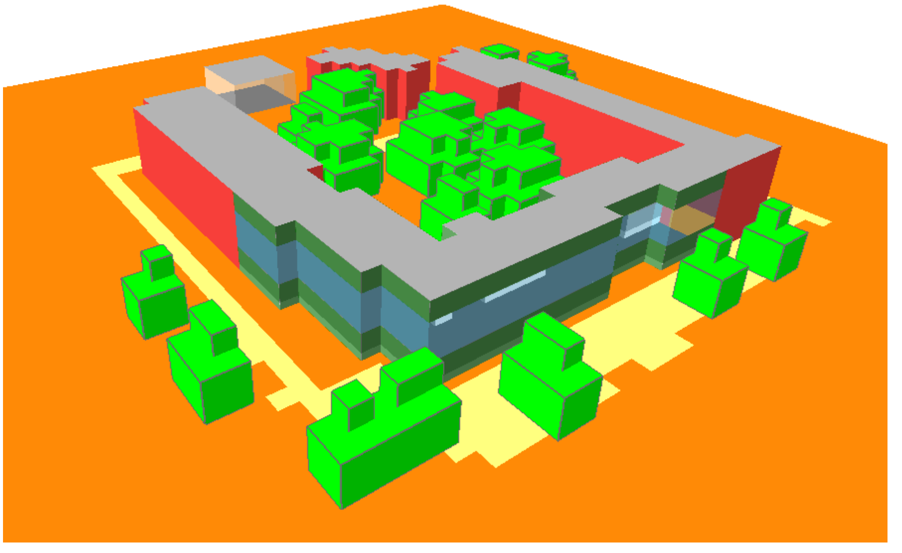


Figure 13- The greening strategy for the case study; green façade for all exterior walls except windows

In this step, a code in Grasshopper (available in the Appendix), a plugin of Rhino, was developed to transfer all data to ENVI-met software for simulation.
Figure 14 shows the ENVI-met environment with both BIM and GIS data.

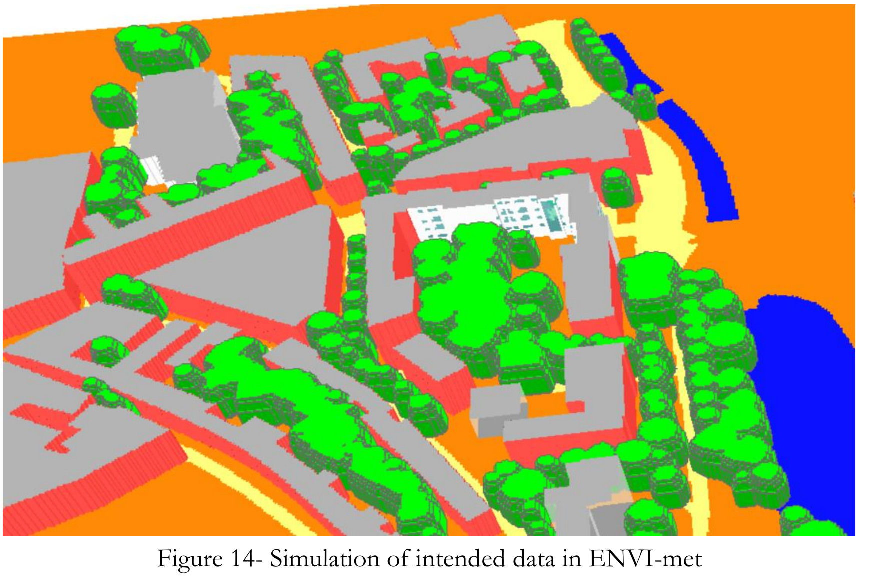


Figure 14- Simulation of intended data in ENVI-met

4.3.1. ENVI-met set ups for the case study

Running the simulation started based on a resolution of 1*1*1m for a duration of 8hours. However, it was found that with the student version of ENVI-met, it is not reasonable to have more than 200*200 grids, which is 1*1 km in 5m resolution. For this reason, a change in the first BIM model was done to draw windows of 5*5m instead of 1meter high windows in the study building model. In this way, 4*4*4m resolution in ENVI-met could work well with the student version. Likewise, the case study area was minimised to the nearest neighbouring objects of the case study. After this modification, the simulation duration was changed to a 24-hour duration on 8th August 2020. The following table summarises simulation settings. The running time of the simulation was decreased from 7 days to 20 hours after this setting.

Table 3- Model parameters

Model inputs	Value
Simulation date	8th August – 9 a.m
Simulation duration	24 hours
Simulation model size	268*252*120
Number of grids	67*63*30
Grid size(m)	4*4*4
Wind	2.2 m/s – 300˚
Facade vegetation species **Thickness** **LAI** **leaf angle**	Funkia (Hosta) 0.30 m 1.50 m2/m2 0.50
W+B building material **Adjacent buildings**	Aluminium+ Glass Brick
Trees	10m, dense, distinct crown layer, medium trunk

The settings used for calculating PET are shown in table 4. These are the defaults, and they can be changed if needed.

Table 4- Personal human parameters for calculating PET

Body parameters	Age of person (y)	35
	Weight (kg)	75
	Gender	male
	Height (m)	1.75
	Surface area (DuBois-area) m^2	1.91
Clothing parameters	Static Clothing Insulation (clo)	0.90
Person's metabolism	Total metabolic rate (W) (met)	164.49 (=86.21 W/m^2) 1.48

4.4. Summary

This chapter explains the implementation of the proposed framework in a case study. First, the data preparation is explained. Subsequently, the employed methods and tools are demonstrated. Next, the GIS layers are imported into the BIM environment. And then, after simplifying the BIM model by coding in Dynamo, they are transferred to Rhino, with scripting a code in Grasshopper, to be prepared for ENVI-met. Finally, in ENVI-met, after performing the initial settings, results are obtained through running the simulation.

5. RESULT AND DISCUSSION

5.1. Results

The following maps and graphs represent the outcomes of the workflow for the case study. To explore the UHI causes, potential air temperature, PET, and building surface temperature both with and without green facade were assessed and visualised for the following model shown in Figure 15. Moreover, to explore if the orientation of the green facade is effective or not, a comparison of different orientations was also performed.

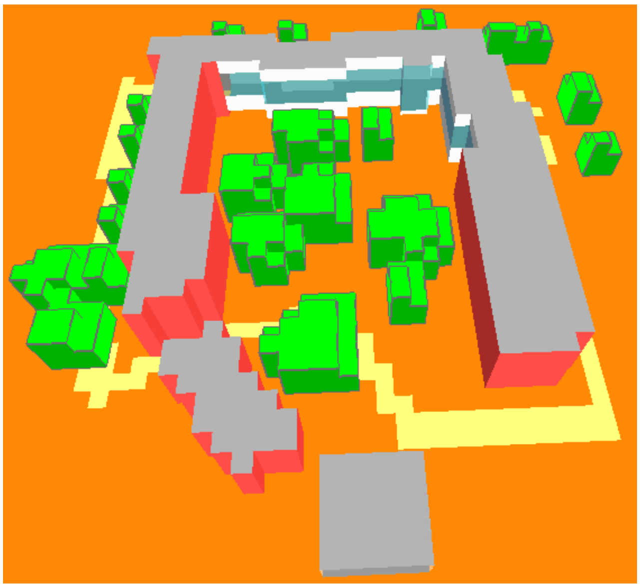


Figure 15- The finalized model for the simulation

5.1.1. Air temperature

Figures 16 and 17 represent the air temperature of the case study in a heatwave, 8th August 2020 at 14 o'clock.

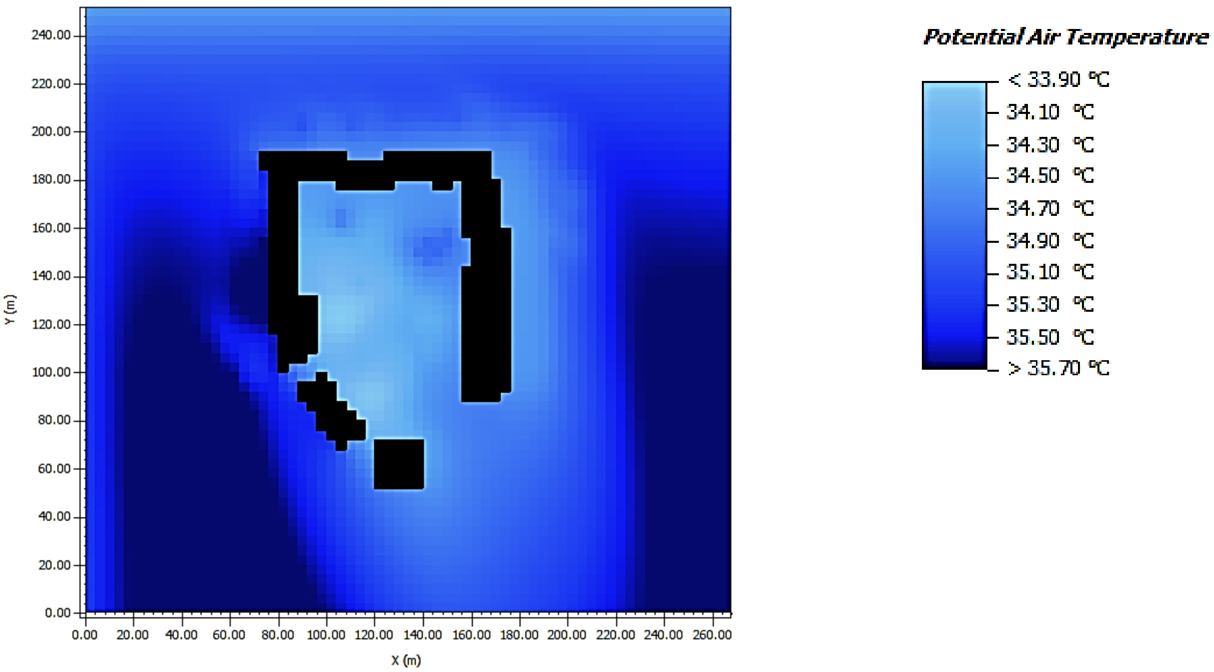


Figure 16-Air temperature without green facade at 14:00, 8th August 2020

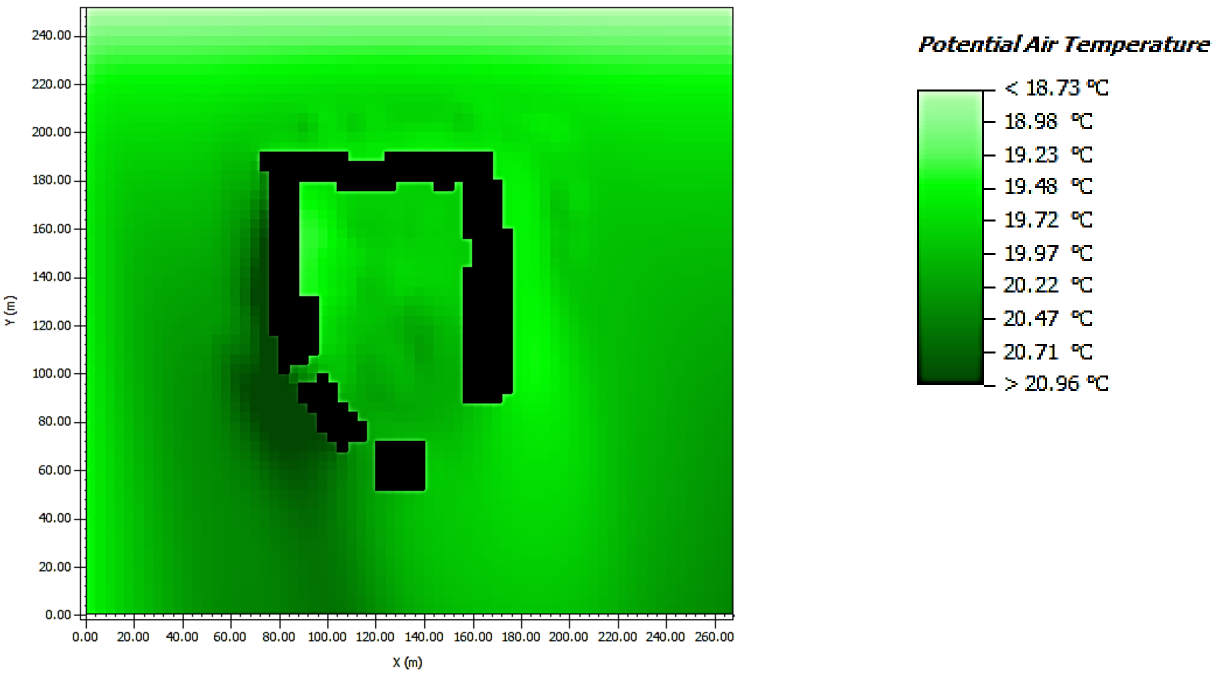


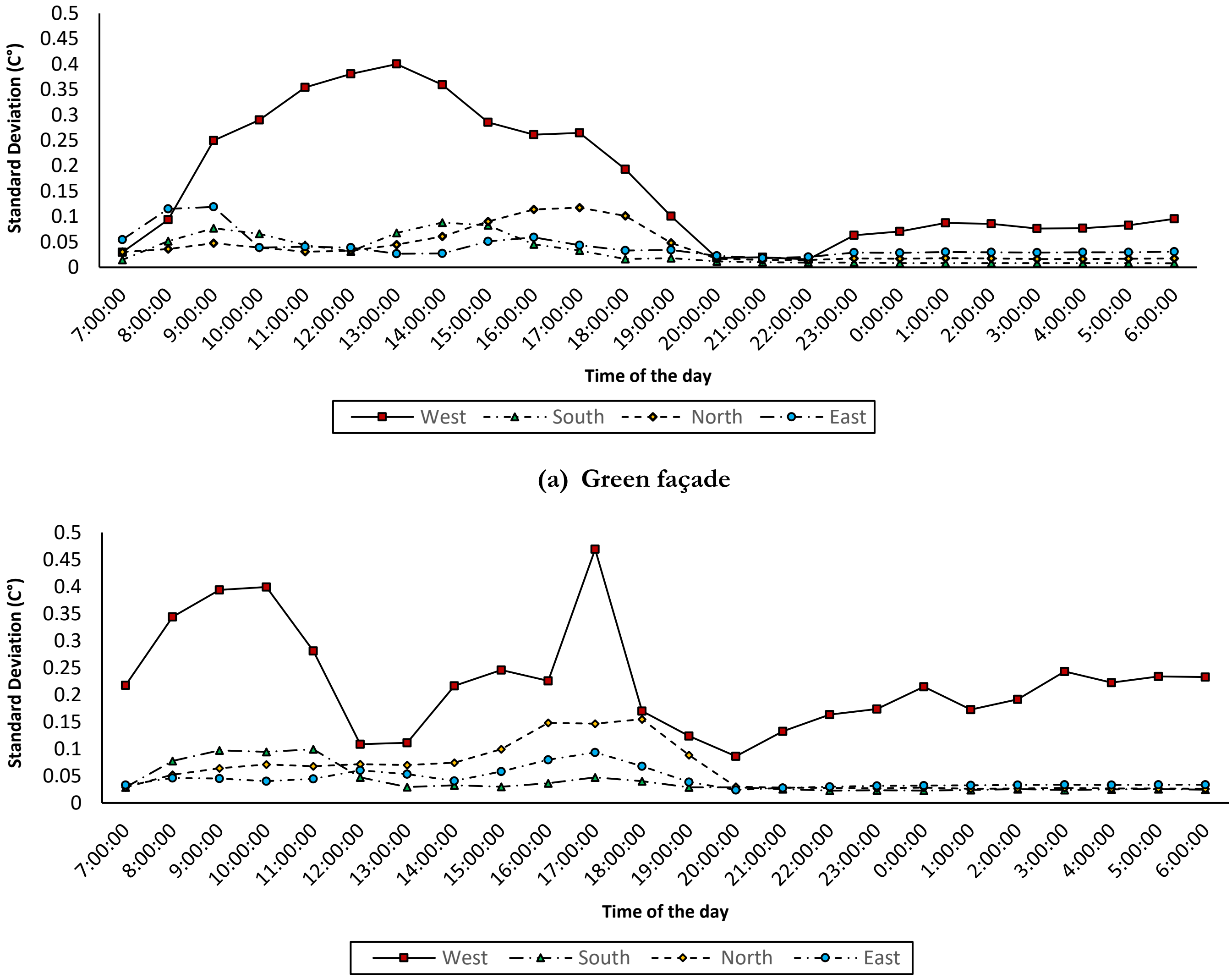
Figure 17-Air temperature with green facade at 14:00, 8th August 2020

As shown in Figures 16 and 17, the temperature variance along each side of the building is rather marginal. To be more specific, when the nearest cells to the building envelop is considered (i.e., cells immediately adjacent to the building façade), the average hourly temperature variances along each side of the building over 24 hours are shown in Table 5.

Table 5- Average hourly temperature variance over 24 hours

Building Side	Average Temperature Variance (c°²)	
	Green facade	Regular façade
North	2.7×10^{-3}	5.3×10^{-3}
East	2.3×10^{-3}	2.2×10^{-3}
South	1.7×10^{-3}	2.2×10^{-3}
West	4.3×10^{-2}	5.9×10^{-2}

However, when the temperature variances are compared over time, it is observed that the temperature variance along different sides of the building is not consistent, as shown in Figure 18. Depending on the side, the maximum temperature variance happens during the daytime and then stabilises, i.e., reduced, during the nighttime. As shown in Figure18, the temperature variance on the west side is considerably more significant than on the other sides.



(a) Green façade

(b) Regular façade

Figure 18- Trend of temperature variance along different sides of the building over a day

The 3D building surface temperature with and without the green facade is visible in Figure 19 and 20.

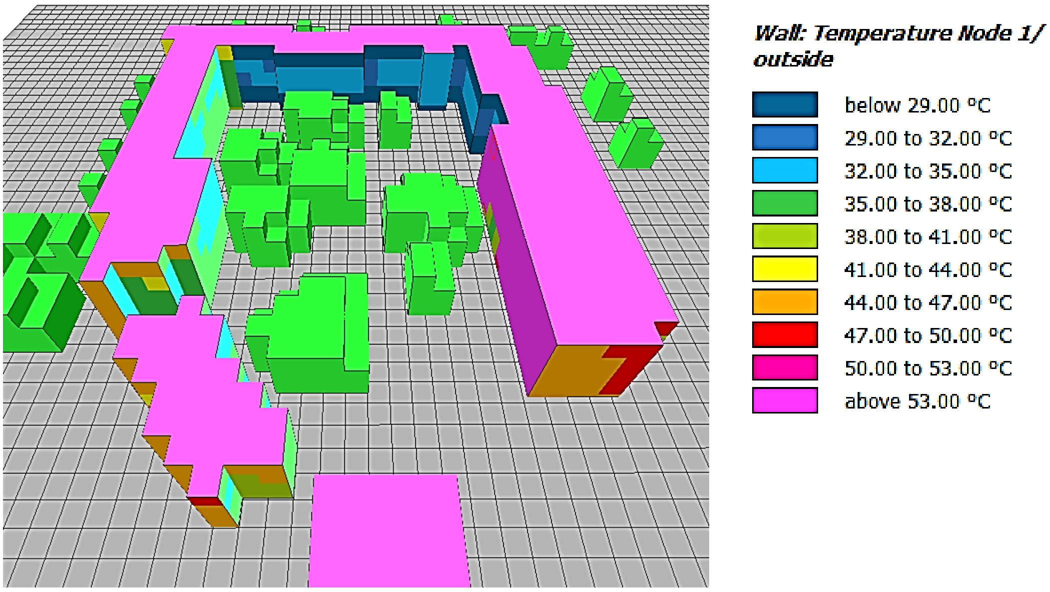


Figure 19- 3D building surface temperature without green facade at 14:00, 8th August 2020

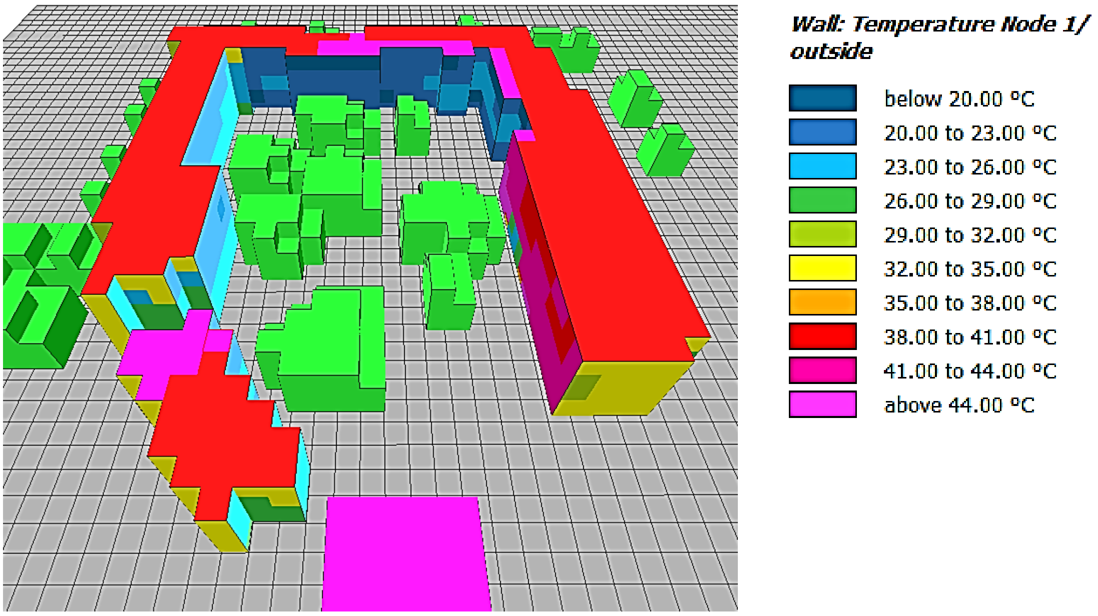


Figure 20- 3D building surface temperature with green facade at 14:00, 8th August 2020

Figure 21 represents the difference in air temperature for the nearest cells to the building with and without a green facade. Based on this graph, the northern wall is more affected by the green facade. Furthermore, the most remarkable difference in the temperature is from 11 to 18 o'clock (12℃ – 15℃), and the maximum difference is about 15℃.

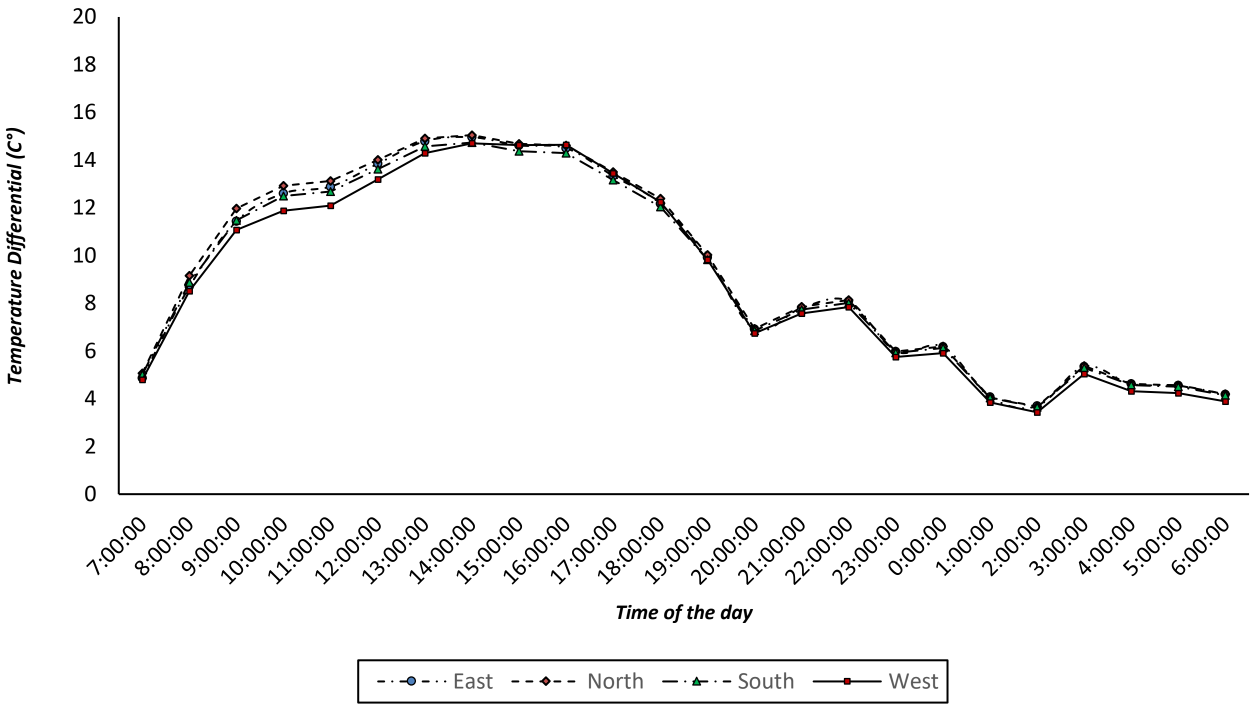


Figure 21- Differences in air temperature between the models with and without green facade for all orientations

To assess the impact of distance from the green façade on temperature,
Figure 22 illustrates explicitly that when the distance from the façade increases, the temperature likewise shows a subtle increase. For this assessment, one random cell for the Eastern wall was selected, and all the cell values in that row were measured.

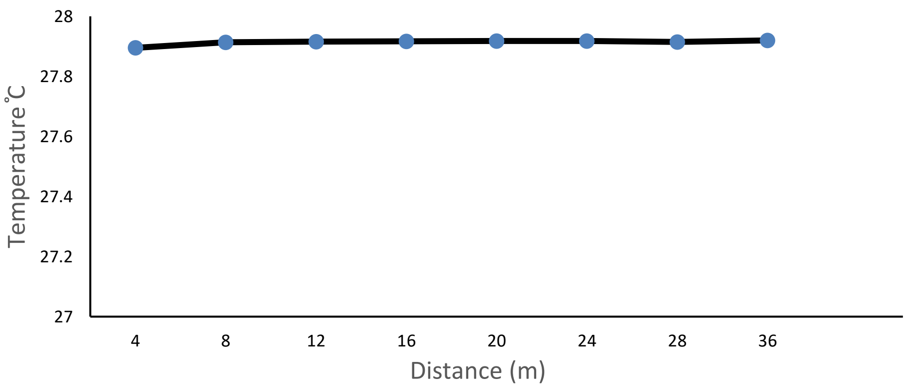


Figure 22- The impact of distance from the green facade

5.1.2. PET

The following Figures describe the pet values for the model with and without the green façade on 8th August 2020 at 14 o'clock.

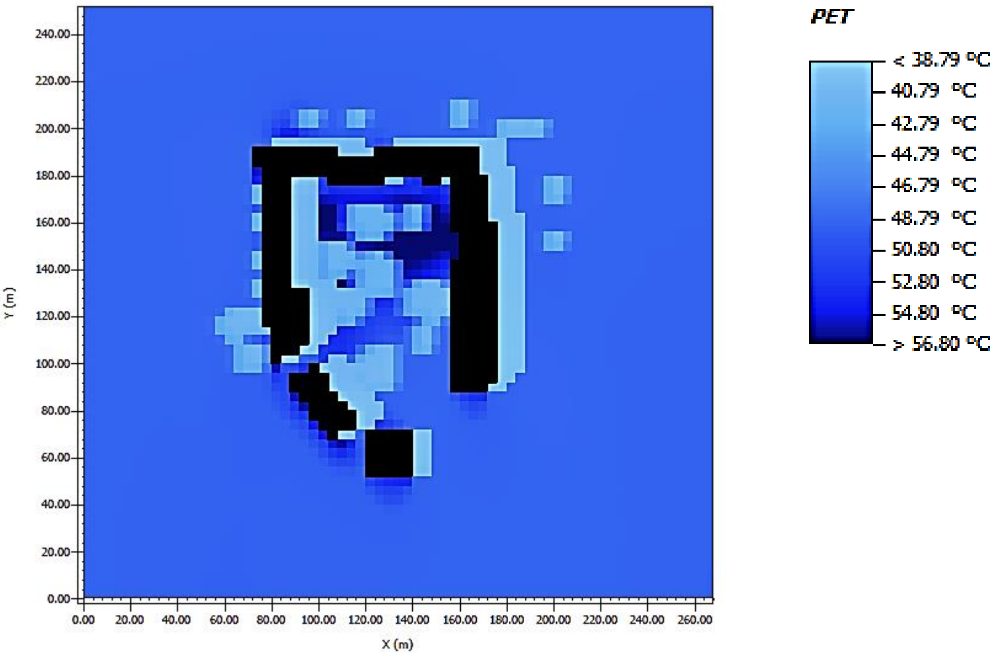


Figure 23-PET amounts for the simulation without a green façade at 14:00, 8th August 2020

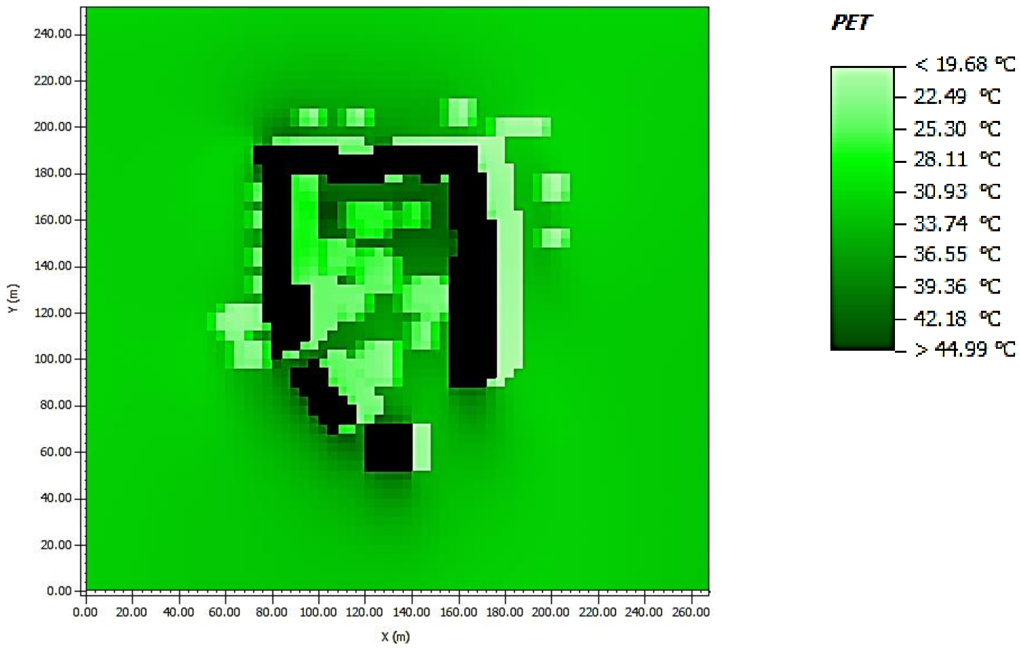


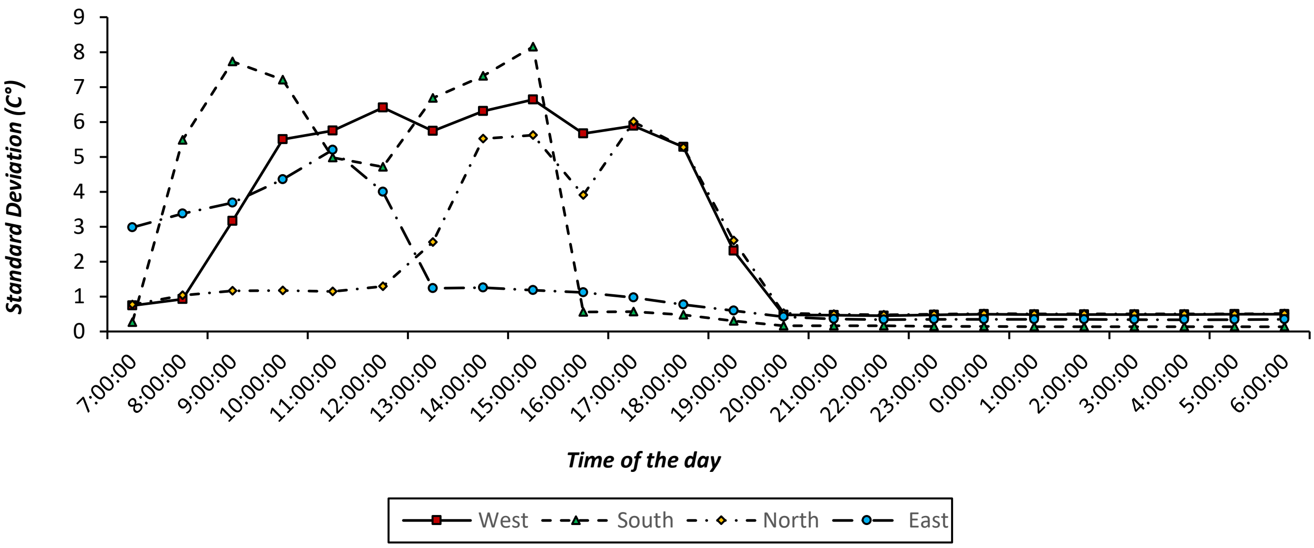
Figure 24- PET amounts for the simulation with a green façade at 14:00, 8th August 2020

According to Figures 23 and 24, in contrast to the temperature, the PET variance is considerable along each side of the building. More precisely, table 6 demonstrates the average PET variance for the nearest cells to the building over 24 hours compared to table 5 shows a considerable difference.

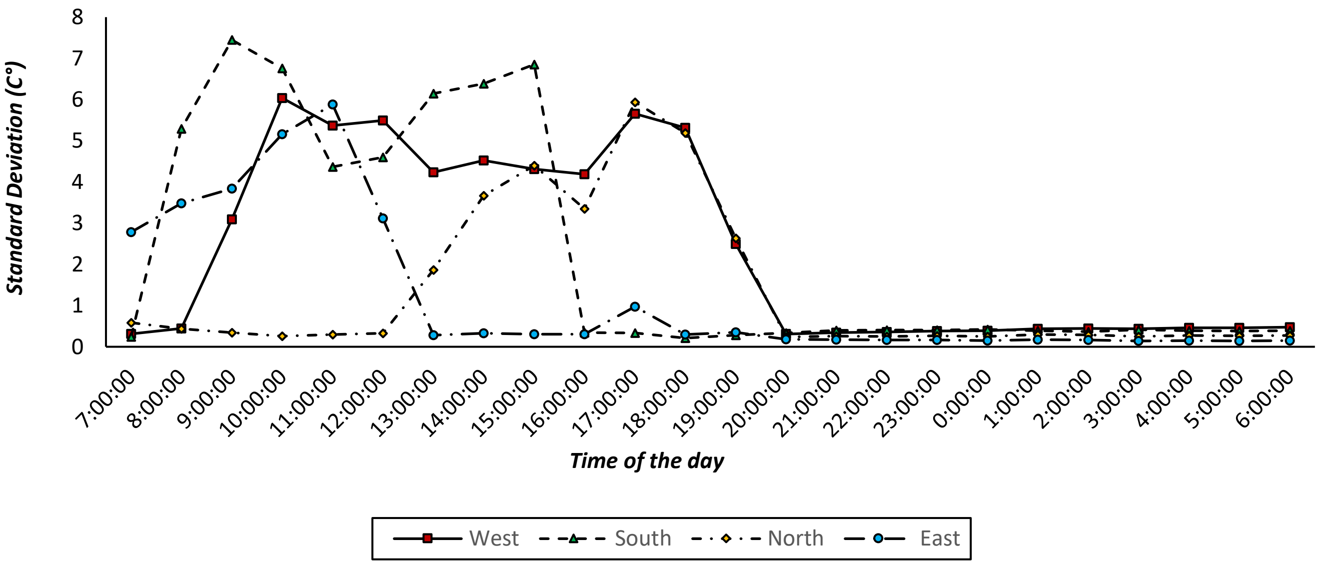
Table 6- Average hourly PET variance over 24 hours

Building Side	Average PET Variance (c°²)	
	Green facade	Regular façade
North	4.37	4.47
East	6.86	4.92
South	14.78	12.38
West	13.97	10.35

Moreover, comparing PET variances over time, based on Figure 25, each side has a significant difference from others. As the graphs demonstrate, the maximum standard deviation for PET happens from 9:00 until 18:00, and after 20:00, it is almost the same for all orientations.



(a) Green Façade



(a) Regular Façade

Figure 25- Trend of PET variance along different sides of the building over a day

Figure 26 shows the difference of PET amount between green façades and the regular facades for different orientations. The enormous difference is from 10 to 19 o'clock, where the differential PET value changes from 10°C to 18°C. According to Figure 26, for this case study, the best time to have the most benefits of the green facade in terms of PET is 13 -14 o'clock for north and west walls, 14 o'clock for south walls, and 14 to 17 o'clock for east walls, which are more impressive.

The results of analysing the effect of green façade on PET amounted to a maximum difference of 18 ℃ between a green and a bare wall for the east orientation at 14 o'clock and 17 ℃, 13 ℃, and 13 ℃ respectively for the north, west and east orientations.

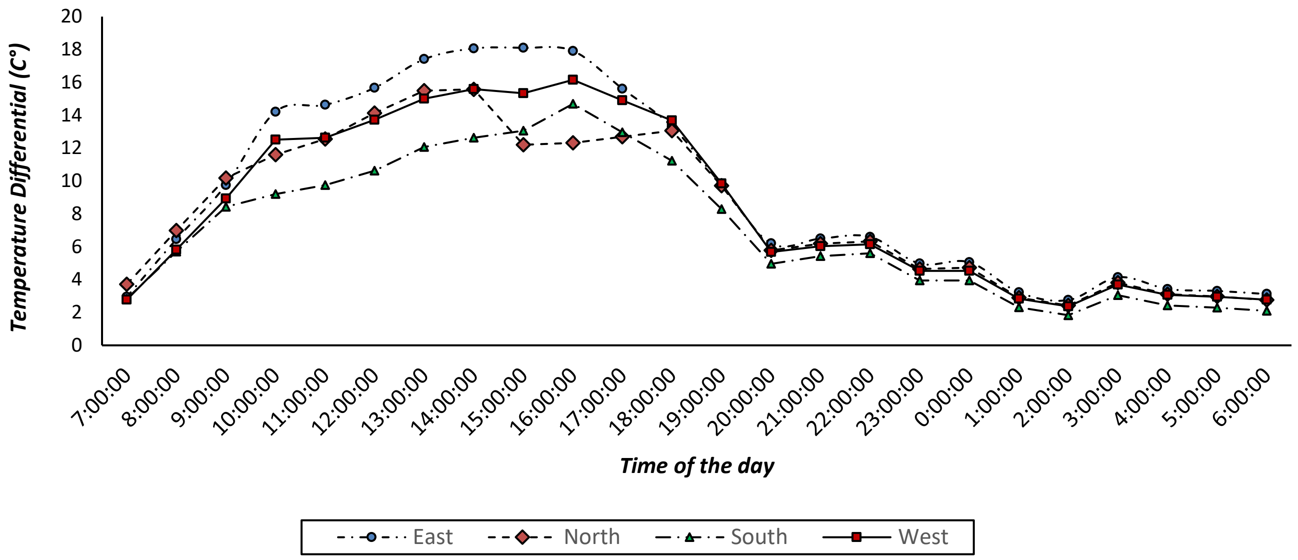


Figure 26- Differences in PET between the models with and without green facade for all orientations

The outputs enable architects and urban planners to design different alternatives and achieve outputs for each option to finalise the optimised design in terms of UHI. Analysing PET is a valuable opportunity to assess the impact of design on outdoor thermal comfort. Furthermore, the 3D visualisation of the surface temperature could help to employ different scenarios in the BIM model and see the result of each scenario in 3D.

5.2. Evaluation

This section will evaluate the framework's user-friendliness and strengths and weaknesses. For the evaluation, first, a tutorial video of the framework (link in the Appendix) was made, and six professionals were asked to watch it and fill out a questionnaire. The participants included one urban planner/architect, one project manager (BIM expert), two special engineers, one environmental engineer, and one special data scientist. The questionnaire (in the Appendix) included explanatory questions and used Likert scale, i.e., score from 1 to 5 where 1 means "Disagree" and 5 means "Agree". Later, a workshop was held with the same professionals to discuss different perspectives about the framework. Four people filled the questioner; the statistic results can be seen in the Figures below. The pre-processing of data seems challenging from the view of who filled the form (Figure 27).

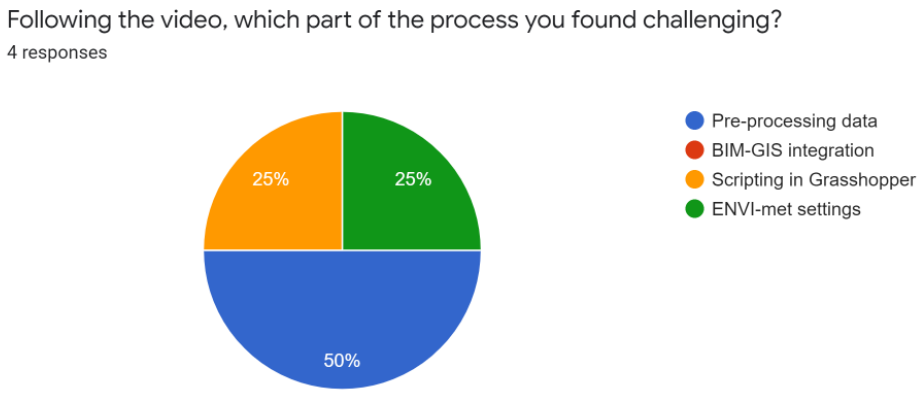
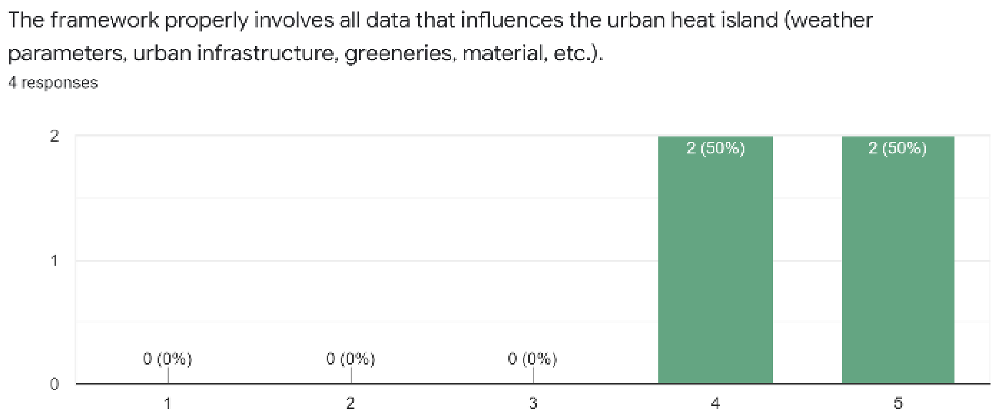
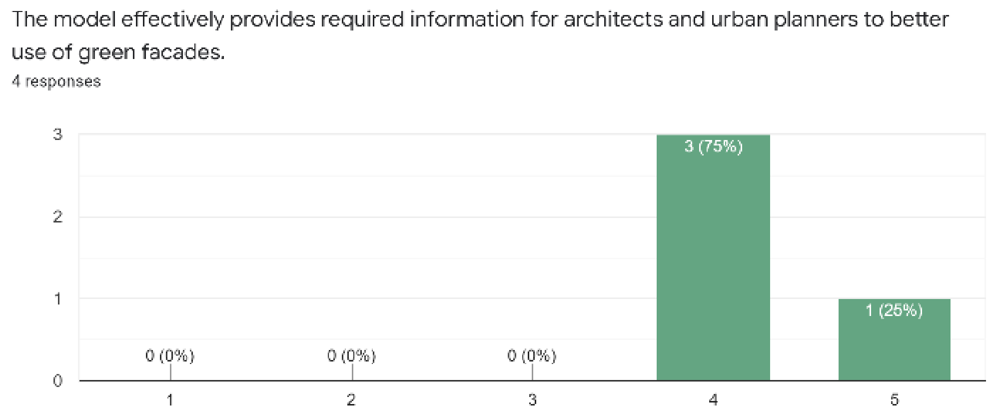


Figure 27- Difficulty level analysis of different stages of the framework

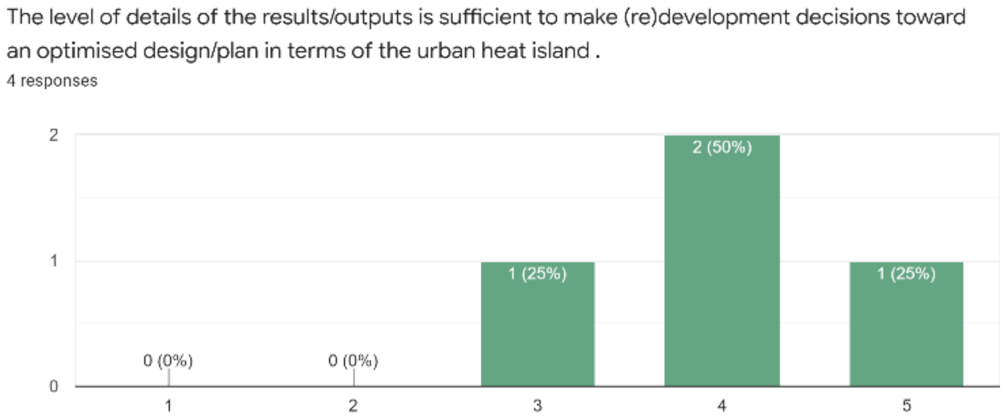
The most critical issue raised in the workshop was the complexity of the framework and the need to make it simpler. However, it was discussed that this complexity would end in detailed results in high resolution, which is valuable for users. Moreover, the numerous software used in the framework makes it less practical to use due to the reason that not all people have enough knowledge of all software. The analysis of responses for the evaluation of the framework, Figure 28, shows that the participants agreed that the framework involves all required data that influence UHI (average score 4.5). Furthermore, the participants approved that it provides enough information for architects and urban planners to use green facade as a natural based solution for its cooling effect (average score 4.25). However, it may not be used in daily practices due to the complexity of the process. Additionally, the level of details of the outputs could represent sufficient information for making (re)development decisions in terms of UHI (average score 4.25) toward a healthy city design (average score 3.75).



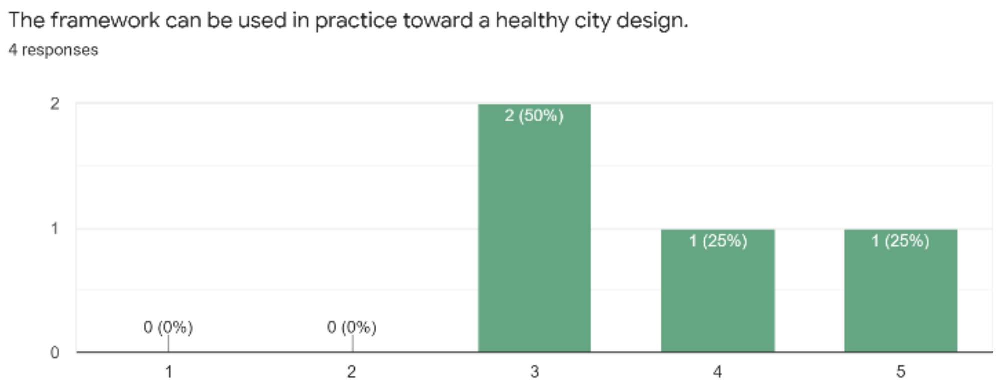
(a)



(b)



(c)



(d)

Figure 28- Results of the question about the usability of the framework

According to the answers and the discussion in the workshop, the data integration and connecting two systems of BIM and GIS in microclimate analysis context is the value and uniqueness of the framework as it can be seen in Figure 29 (average score 4.25).

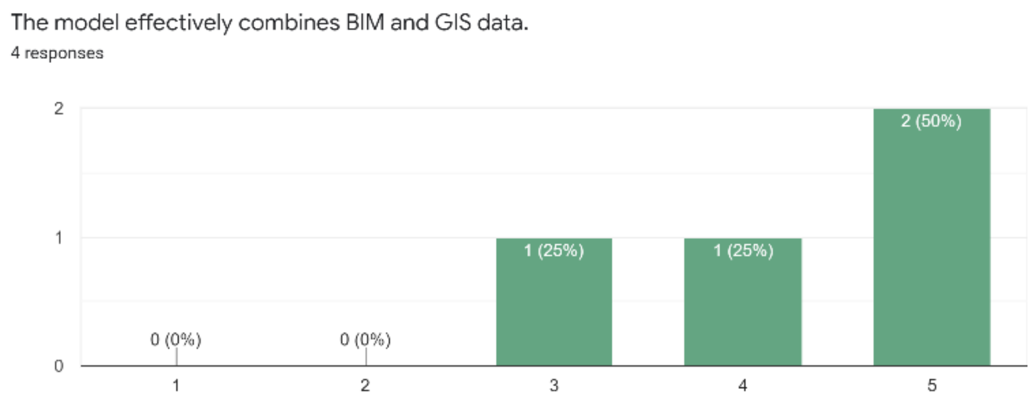


Figure 29- Efficiency of BIM-GIS integration

In Miro, an application used as a kind of online whiteboard for visual collaboration, a board was made and asked the participants to write keywords in terms of Strength, Opportunities, Weakness and Threats. Table 7 represents points listed by the experts in the workshop.

Table 7- SWOT table, retrieved from the evaluation workshop

Strength Visual/3D Detailed Comprehensive Integrated data Practical Applicable to different areas and case studies	**Weaknesses** A lot of manual work Commercial software Complex to reproduce for different alternatives
Opportunities Automate some parts QGIS or ArcGIS to decrease the number of software	**Threats** Use of licenced software Time intensive A lot of knowledge needed Different software; updates and contingency

Each of the experts wrote a keyword that seemed critical from their view and discussed it. One of the critical points discussed was the 3D simulation of the data, which is beneficial for analysing and decision making in the early phases of planning and design. They suggested that it is valuable to make some of the steps more automated in future works to avoid manual work leading to saving time. Moreover, more users would use the framework, and lack of knowledge for all the software could be solved by such automation.

5.3. Limitations

There are some limitations to the required data for the simulation. The shape file of trees and vegetation may not be accessible everywhere. Similarly, it is required to have the height of the buildings besides their footprint, which may not be available for all regions. Besides, complete weather data based on table 2 is required for an advanced simulation, which is not available for many regions. Even for this study, this data was downloaded from a further weather station.
Moreover, all the tools used for this study, except QGIS, are commercial and is not accessible for everyone. Furthermore, for the simulation of UHI, the ENVI-met student version was used, which firstly takes time to learn and secondly not sufficient for simulating a district with high resolution (i.e., the science version of the tool is needed for this). Even with

the science version, and an up-to-date computer, the tool is not very fast because it needs to perform the simulation at the pixel level. For this case study, with the student version that uses just one core of the CPU, and the university server with the processor Intel® Xeon® Gold 6134 CPU @ 3.20GHz, 128 GB RAM, the processing time took 20 hours for a 67*63*30 grid cell model with the grid size 4*4*4m and for a day cycle(24h).

5.4. Discussion

The main object of this study was to make a framework for assessing the cooling effect of green facades through a BIM-GIS integration. In this section, in line with the objective and the sub-objectives, the study results are discussed.
The different ways of BIM-GIS integration and UHI simulation were studied through a literature review. A BIM-GIS integration approach was chosen that could accommodate UHI simulation. The most crucial point in this selection was to maintain the semantic data of BIM to be able to perform surface-specific analysis. For the simulation of UHI, ENVI-met was selected due to the adjustment with the BIM-GIS integrated model. Moreover, ENVI-met provides the opportunity to measure PET and the building surface temperature of the model.
In the implementation phase, the results show a significant change in temperature of the closest point to the façade, with and without greenery. The maximum difference in air temperature is 15̊C which is considerable. Moreover, in this case study, with the mentioned scenario for green façade and with a 24-hour simulation, in the particular period (8^{th} August 2020), the best time to benefit from the green facades is between 11-18 o'clock, which is usually the hottest time of a summer day. It worth mentioning that, according to the analysis for different orientations, the general effect of green facades on the air temperature for all orientations is the same.
For architects, urban designers, and urban planners, it is practical to use this workflow in the design process to assess and maximise the effect of UGI from climate adaptation perspectives. In this regard, different alternatives for the building form in architectural scale and the neighbourhood design in urban scale could result in the optimised option. At the decision-making level, housing policies can be improved by such information to minimise the global warming effect on citizens.
Municipalities could produce clear maps with enough information regarding the advantages of green facades and encourage housing corporations and homeowners to consider green facades.

5.5. Summary

In this chapter, the result for implementing the workflow is presented. Moreover, the evaluation of the workflow, the limitations and the discussion on the results are described. The implementation is performed on a BIM model of Witteveen en Bos company in Deventer. The simulation was performed two times, with and without a green façade. The final outputs represent a significant decrease in air temperature close to the building after adding a green façade.

6. CONCLUSION AND RECOMMENDATION

In this chapter, the research questions are answered, and also recommendations for future works are offered.

This research aimed to develop a framework to assess the effect of green facades on mitigating UHI by integrating BIM and GIS. The Witteveen en Bos building in Deventer, Netherlands, was chosen as the case study to implement the framework.

6.1. Research questions

To reach the aim of this study, the following research questions were addressed:

1. **To identify what methods have been used to integrate BIM and GIS and to simulate UHIs through literature review.**
   - What methods, tools, and workflows are used to integrate BIM and GIS and simulation of UHIs?

IFC is a standard BIM format that provides the chance to integrate semantic BIM data to the geospatial environment. Moreover, there are some efforts to combine IFC and CityGML. Besides, some semantic web services try to translate BIM and GIS data to semantic web data. Furthermore, 3D Geo-DBMS is a context to bring semantic 3D data to this environment. Also, City Engine is a tool that provides the possibility of the integration of GIS data with a 3D model. In addition, OGC provides studies for data integration of CAD/GIS/BIM at the web service level. Besides these open-source systems, commercial tools are certainly practical. In this study, commercial tools were used to combine BIM and GIS data in the context of UGIs.

2. **To develop a workflow for the integration of BIM and GIS models in the context of green facade analysis.**
   - What are the required input data for this integration?

A BIM model and the GIS data of the surrounded of it are the primary required data. The GIS data needs to have surrounded roads, buildings (with the material), vegetation and water bodies. For the weather data of the case study area, for a basic simulation, it needs an average temperature, wind speed and wind direction, and for an advanced simulation, it needs to be based on table 2.

- What types of data are needed to perform this analysis?

Data types are GIS, BIM, and CSV (weather data)

3. **To develop a framework for the simulation of the impact of green facades on UHI in the BIM-GIS integrated environment.**

   - What parameters influence the effect of UGI on SUHI?

The current situation of the vegetation, materials, water bodies, the form of the buildings and the surrounded area, the orientation of the walls, the current weather situation, the type and amount of the vegetation, and the time of the day and year are the most influential parameters on the performance of UGI.

- What are the existing UHI simulation models and tools?

Generally, using remote sensing data to measure required information, statical models based on weather data and small-scale physical modelling of the case study are the techniques for measuring UHIs. Besides, some tools like Envi-met are used for measuring weather information based on models.

- Which tool is more suitable for the analysis of vertical surfaces in terms of interoperability with the BIM-GIS integrated model?

For this study, ENVI-met was selected as the UHI simulation tool due to its adaptability with the integration of BIM and GIS, considering adding vertical vegetation to the model.

4. **To evaluate the framework's productivity and constraints.**

- What are the strengths and limitations of this framework?

Table 5 describes the strength and limitations of the framework based on the experts' ideas.

5. How is the efficiency and user-friendliness of the framework?

According to the workshop results, the framework consists of complex instructions; however, to reach such detailed outputs, the complexity is not avoidable.

6.2. Future recommendation

This study focuses on developing a workflow to connect BIM and GIS systems for assessing the effect of green facades on thermal comfort and mitigating temperature. To further broaden the knowledge in this area, points for future research are suggested. In addition, recommendations are formulated for municipalities, designers, urban planners, and housing corporations for using green facades according to the research results.

With this workflow, it is feasible to assess the effect of other types of natural cooling options like trees, green roofs, and water bodies. Further research can be done to use different alternatives of natural cooling systems to explore their impact. Moreover, it is practical to combine other cooling strategies like sun blinds to optimise heat reduction. Through experimenting with different alternatives, the maximum cooling effect of such natural solutions could be achieved. In addition, trying different plants will lead to finding the most effective species based on the case study.

It is helpful to add explicit materials of the building for a comprehensive assessment. In this study, a general wall material was assigned to the building. ENVI-met provides the opportunity to define the different layers of the wall. Therefore, more reliable results are feasible.

For this study, the simulation duration was 24 hours. However, it is highly recommended to perform a more extended simulation, at least five days, to validate the results and perform a sensitivity analysis. Furthermore, studying larger districts provides the opportunity to analyse the wind parameter based on the urban morphology and other surfaces leading to more reliable outputs and proposing appropriate solutions.

It is suggested that to perform the simulation for other seasons to assess the effect of green facades on insulation that may also lead to a reduction in energy use and cost. This study does not cover the change in energy consumptions and costs based on the green facade. Further research can assess the change in energy use in buildings, with and without green facade in different seasons.

Thermal comfort is explored in this study based on a physical perspective, focusing on human-biometeorological (PET) and climatological (air temperature) indices. According to Klemm, Heusinkveld, Lenzholzer, Jacobs, & Van Hove (2015), UGI enhances perceived thermal comfort (physical and psychological impacts), which is not covered in this study. Therefore, it is meaningful to address perceived thermal comfort in urban heat studies. Furthermore, linking PET, psychological effects, and air temperature in a model would lead to more comprehensive knowledge.

From the technical perspective, it is suggested to use the science version of EVNI-met to set higher resolution settings resulting in more accurate outcomes as well as less simulation time due to the use of all capacity of the computer CPU.

This study aims to utilise semantic BIM data in UHI analysis for a detailed simulation in building-scale. However, urban planners can employ the framework excluding the BIM model, resulting in lower resolution but the larger area, to assess the microclimate parameters in city-scale. This approach would provide a less complex framework but fewer details.

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APPENDIX

A. Dynamo and Grasshopper codes of the model simulations are available via GitHub
https://github.com/marjanmmk/BIM-GIS-Integration-framework-.git

B. The whole process of the framework is presented in a tutorial video
https://drive.google.com/file/d/14ELCpXA242Gaz_QHRuZvI5kl-oAlLIfp/view?usp=sharing

C. The questionnaire for the evaluation:

1. **The model effectively combines BIM and GIS data.**
   Disagree 1 2 3 4 5 Agree
2. **The framework properly involves all data that influence the urban heat island (weather parameters, urban infrastructure, greeneries, material, etc.).**
   Disagree 1 2 3 4 5 Agree
3. **The model effectively provides the required information for architects and urban planners to better use green facades.**
   Disagree 1 2 3 4 5 Agree
4. **The level of details of the results/outputs is sufficient to make (re)development decisions toward an optimized design/plan in terms of the urban heat island.**
   Disagree 1 2 3 4 5 Agree
5. **The framework can be used in practice toward a healthy city design.**
   Disagree 1 2 3 4 5 Agree
6. **The framework is applicable to different areas and case studies. (e.g. different climates)**
   Disagree 1 2 3 4 5 Agree
7. **Following the video, which part of the process you found challenging?**
   - Pre-processing data
   - BIM-GIS integration
   - Scripting in Grasshopper
   - ENVI-met settings
8. **Please list any deficiencies you have observed in the framework.**
9. **Please list the major benefits you have observed in the framework.**
10. **Please provide any other suggestions for the improvement of the framework.**