3D City Digital Twin Simulation to Mitigate Heat Risk of Urban Heat Islands

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Abstract

Consecutive high-temperature days, a phenomenon known as heatwaves, are becoming more frequent and intense due to anthropogenic climate change. Padua City, characterized by significant urban soil sealing, is particularly vulnerable to these changes and the exacerbation of Urban Heat Island effects. This study integrates Urban Digital Twin technology and Internet of Things concepts within a three-dimensional modelling environment to develop a Nature-Based Solutions scenario simulation tool. This tool is designed to address climate-manmade problems in Padua City. Using sensor-derived air temperature and relative humidity data, our approach provides detailed micro-climate information to identify heat-prone areas in Padua City. According to this information, the first pilot project test of scenario development was selected to assess how best to achieve a cooling effect through the use of green-blue infrastructure in order to combat the heat hazard in Padua City. Furthermore, this study addresses the urgency of developing Nature-Based Solutions in Padua City's planning to reduce the heat effect during heatwaves.

1. Introduction

Heat waves (HWs) have been increasing in both frequency and intensity over the last century due to anthropogenic climate change (Klingelho¨fer et al., 2023). Compared to other hazards, HWs cannot be readily seen and are only recognized by the perceived feelings, making it challenging for people to understand that they are facing a health risk of increased morbidity or mortality. High temperatures have been scientifically proven to impact human health and well-being, and can even create critical conditions for vulnerable groups (Deschenes, 2014). In addition, according to the Copernicus Climate Change Service (C3S) and the World Meteorological Organization (WMO), 2023 was the second warmest year on record for Europe and featured the highest number of days with extreme heat stress (Emerton et al., 2024).

The HWs situation is expected to become more severe in urban areas due to the Urban Heat Island (UHI) (Pappalardo et al., 2023). The UHI effect explains why urban areas are warmer than rural areas. Consequently, this effect highlights the climate impact on urban populations, underscoring the need to address this issue to advance Sustainable Development Goals (SDGs) 3, 11, and 13. Padua City in Italy, is one of the examples of an urban region in Europe facing extreme UHI conditions, one that experiences multiple HWs every year. Padua City, with a population of just over 200,000, is known for its vast urbanization and industrial activities. Recent work by Pappalardo et al. (2023) identified a number of UHI in Padua City based on satellite data. Acknowledging the predicament of high temperatures in the city led the Padua City to take serious measures to improve outdoor conditions. To allow a better understanding of the actual HWs situation, Padua City installed 109 outdoor sensors, placed them approximately two meters above the ground and distributed them throughout the city to monitor the city's air temperature and relative humidity.

The landscape configuration of Padua further amplifies the retention of heat within the city. According to a study by Fokaides et al. (2016), the expansive sealed areas have the potential to elevate surface temperatures significantly. In 2018, as reported by the Italian Institute for Environmental Protection and Research (ISPRA), approximately 49.4% of Padua's surface was completely sealed (Munafo`, 2018). Multiple studies have addressed the phenomenon of surface sealing in Padua City, including those by Pappalardo et al. (2023) and Pristeri et al. (2020). Their research reveals that the largest sealed area in Padua is situated within an industrial zone in the East of the city, encompassing approximately 6.13 km^2. In response to these findings, the City Development Plan has stated its intention to address this issue by 2025. Consequently, the industrial area of Padua city was chosen as the focus of this research.

In addition, to address the heat mitigation plan, Nature-Based solutions (NBS) has been explored as an effective intervention aimed at reducing temperatures (Zheng et al., 2023). However, despite its effectiveness, there is a big gap in NBS implementation (Lafortezza et al., 2018), which has also been an issue in Padua City. Building upon the aforementioned challenges, our research aim is to integrate scenario simulation utilizing real-time data through the Urban Digital Twin (UDT) approach in support of developing a mitigation strategy to reduce heat risk in Padua City. The City Digital Twin or also known as UDT is a

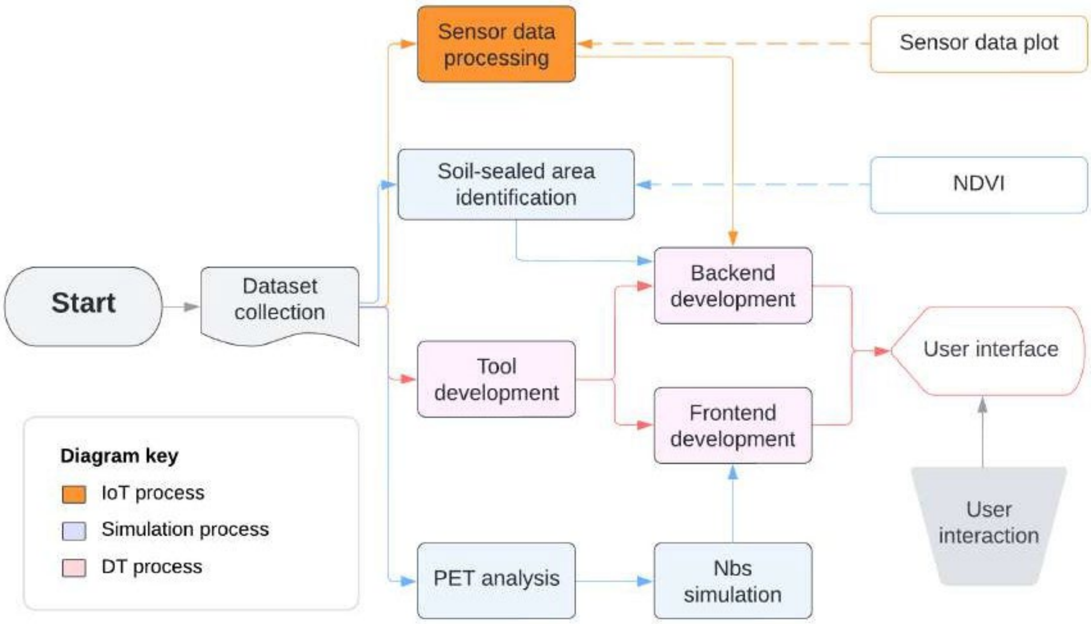


Figure 1. Methodology followed in this study.

data-driven computational model that can facilitate the planning and decision process through a comprehensive assessment of socio-economic and environmental impacts (Weil et al., 2023).

The concept of a UDT emerges as a pivotal extension of Digital Twin (DT) within the context of urban societies (Weil et al., 2023). The expansion of UDT in leveraging real-time data enhances the parallel function between DT and Internet of Things (IoT) in practice (idem). Sensor-Based-IoT (SBIoT) systems play a crucial role, enabling the monitoring of events of interest, such as HWs hazards (Kumar et al., 2023). This interaction underlines the typical acquisition of physical-world data through the UDT-IoT framework. Therefore, with the UDT potential explained above, this study adopts the UDT-SBIoT concept for the development of a scenario simulation tool.

Consequently, the insights gained from this study serve as foundational knowledge for Padua's decision-makers to design suitable green interventions by 2025. This study outlines the preliminary development of an NBS scenario simulation tool that integrates UDT and IoT sensors within three-dimensional (3D) urban building environments. The paper was conceptualised as a proof of concept to show how a critical HWs area defined based on physical sensor data can be modelled in a 3D UDT and how this can serve as a decision-making tool for Padua City.

2. Materials and Methods

The study area of this research was selected by the Padua City based on the sensor data and earlier satellite-based HWs analysis. In addition, two further criteria were considered: (i) the extent of soil sealing in the area, and (ii) the availability of space for future implementation. To achieve the aim of this study, the tool developed was integrated with the Physical Equivalent Temperature method (PET) from Koopmans et al. (2020) to provide the basis model quantification of the interaction between the meteorological condition and the interventions. In addition, Normalized Difference Vegetation Index (NDVI) was included in the methodology process (see Figure 1) to analyze the distribution between vegetation and built-up in the study area.

Therefore, the chosen area is located in an industrial zone of Padua City. The development of the UDT-IoT setting and analysis utilizing raster geospatial data and meteorological datasets provided by the Padua City. It consists of a 10 meter resolution of Digital Surface Model (DSM) and 1 meter resolution UAV images. These datasets were utilized to provide the building's height information and area identification. Thermal information was generated from LoRaWAN (Low power wide area range network) type sensor measurements throughout the city. These sensors acquire air temperature in degrees Celsius and relative humidity, recorded at 15-minute intervals. Additionally, vector information such as building footprints, road networks, waterline networks, and tree datasets was used from OpenStreetMap contributors (2017).

2.1 Conceptualization of The Tool System Design

The web app tool comprises a backend and frontend architecture (see Figure 3). Sensor data are processed and managed within the backend, while the frontend provides access to NBS intervention scenarios. The subsequent section elaborates on the architecture's structure and the software packages employed in this research.

2.2 Tool Architecture: Backend

Due to the restricted access to sensor datasets, this study utilizes a virtual private server (VPS) hosted through Contabo for its

Figure 2. Illustration of the developed tool.

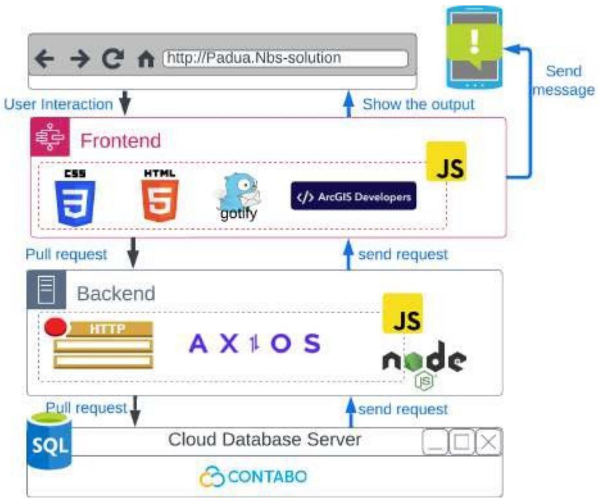


Figure 3. Architecture system design of the developed tool.

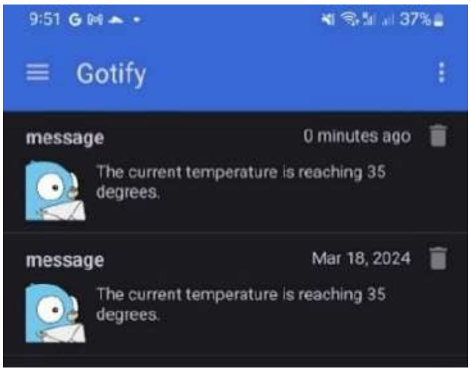


Figure 4. The overview of warning message interface received by the users.

application programming interface (API). The sensor measurements are stored in a cloud-based tabular database using Structured Query Language (SQL). Data retrieval is managed via a 'pull' function implemented through Hypertext Transfer Protocol (HTTP). This process requires client interaction to manage the state of the data request, categorizing it as pending, fulfilled, or rejected. Accordingly, the Axios library handles HTTP for fetching the sensor data from the API.

2.3 Tool Architecture: Frontend

The development of the web app system encompasses both backend and frontend components, as highlighted by Buitrago et al. (2016). The backend manages data storage, processing, and other server-side functions, while the frontend is responsible for presenting the visual components and facilitating user interaction. In this study, the front end utilizes HyperText Markup Language (HTML) to structure the web app, augmented by the JavaScript programming language, for enhanced functionality. Additionally, the system's flexibility is supported by a combination of a Geographic Information System (GIS) Representational State Transfer (REST) API and Software Development Kit (SDK). The simulation tool incorporates the 3D model to depict the surrounding environment. The developed 3D model in this study is based on geometric modelling to maintain the spatial components and ensure coordinate consistency (Ying et al., 2032). Additionally, this model integrates 3D GIS technology, which enhances the visualization and analysis capabilities essential for urban planning and environmental assessment. The development of the 3D model was based on Computer Generated Architecture (CGA) shape grammar, which facilitates the derivation of 3D architectural content. Further, the web app integrates the IoT system with a Gotify plugin to provide a scenario heat warning system. These heat warning scenario employs push notifications to alert users on their personal devices, as shown in Figure 4. This functionality is activated through user interactions with specific tasks. The visualization of sensor data is constrained to syntax commands that aggregate data on an hourly maximum basis. Moreover, a high-temperature warning system was developed in response to continuously received sensor data. The system utilizes the following command syntax: if the temperature exceeds 35°C, then an automatic notification is sent to mobile phones as a warning message.

2.4 Simulation Embedded in The Tool

This study implements a UDT simulation tool based on the PET framework, following by Koopmans et al. (2020) and Ca´rdenas et al. (2023) that have been tested for Wageningen City and Enschede City. As shown in equation 1, the calculation integrates meteorological data on air temperature, humidity, wind, and solar angle. Therefore, to explore PET potential, this study also follows the proof-of-concept (PoC) experiment and modelling guidelines from Ca´rdenas et al. (2023) to calculate the PET sun. Regarding the sunlight period, this study applies both PET sun and PET night depicted in equation 2 (Koopmans et al., 2020). The PET results have a dynamic relation with the simulation of NBS to provide PoC insight into the types of green-blue infrastructure that work optimally to reduce heat. The model simulation system that incorporates facade-level information, such as on building material or vegetation cover, is still under development.

$$\begin{aligned} \mathrm{PET}_{\mathrm{sun}} = & -13.26 + 1.25 T_a + 0.011 Q_s - 3.37 \ln(u_{1.2}) \\ & + 0.078 T_w + 0.0055 Q_s \ln(u_{1.2}) + 5.56 \sin(\phi) \\ & - 0.0103 Q_s \ln(u_{1.2}) \sin(\phi) + 0.0546 B_b + 1.94 S_{vf} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{PET}_{\mathrm{shade\ night}} = & -12.14 + 1.25 T_a - 1.47 \ln(u_{1.2}) + 0.060 T_w \\ & + 0.015 S_{vf} Q_d + 0.0060 (1 - S_{vf}) \sigma (T_a \\ & + 273.15)^4 \end{aligned} \tag{2}$$

where T_a = air temperature (°C) at 2m
Q_s = solar irradiation (W/m^2)
$u_{1.2}$ = wind speed at 1.2m height (m/s)
T_w = wet-bulb temperature
ϕ = solar elevation angle (degrees)
B_b = Bowen Ratio
S_{vf} = Sky-view factor

3. Results

3.1 Tool Development

The first version of the developed web tool is shown in Figure 2. There are several components displayed on the interface that allow interaction from the client side. There are several functionalities that enable the users to draw the NBS types, such as grass, trees, and green roofs, on the scene, which will be automatically saved on the cloud storage. The date functionality selection corresponds with the IoT sensor API system using the pull request and acts as input data for the simulation. After new objects are added or updated, the simulation for the impact of the new additions is simulated. There are several types of NBS information that can be shown on the interface (see Figure 2).

The UDT-based tool platform employs code-based development to enable a comprehensive design system that integrates real-time sensor data. This system facilitates DT continuous loop between the physical world and the virtual model, bridged by user commands. As explained in section 2.1, the tool's architecture is divided into a backend, where processes are hidden, and a frontend, where visible components are accessible to the public. Figure 1 provides a concise overview of the code snippets for each visible object on the web platform, including buildings, green-blue NBS, sensor distribution, and the PET simulation results. These objects enable direct interaction from the client side with the tool, where user inputs significantly influence the simulation's performance. In addition, the input alterations, such as adding or removing NBS features, will permanently affect the cloud storage data. A complete overview of the code snippets for the developed tool is available in the open-access repository [1]. To complete the UDT-IoT integration cycle, the tool includes a heat warning simulation that enables the system to send notification messages to personal mobile phones (see Figure 4). In order to provide a better perspective of the UDT-based developed tool, a simulation overview is accessible in a video animation[2].

3.2 Sensor Data Plot

The temperature data collected from the 109 sensors measurements from 31 May to 29 September 2023 are shown in Figure 5 (n=109). In this figure, grey lines represent data from the LoRaWAN sensor, and the highest temperature trends recorded by the sensors are highlighted with a red line illustrating fluctuations over the period. The peak temperature was 43.7°C on 23 August 2023, and the lowest was 18°C on 31 May 2023. The average air temperature recorded by the LoRaWAN sensors from June to September was 34.7°C. A notable temperature drop occurred between 26 and 28 August, falling dramatically from 41°C to 22°C, attributed to a sudden hail storm by local government reports. Over the summer, there were 45 days when temperatures exceeded 35°C, including several consecutive days where the temperature stayed above 35ºC. The humidity measurements from May to September showed relative humidity consistently above 58%, with some days reaching 100%. In Figure 6 shows the output of the NDVI processing. It shows a significant lack of greenery in the industrial zone of Padua City. In addition, the area is depicted to be covered in concrete that denotes built-up.

4. Discussion

The present study explored the potential of UDT and IoT integration in 3D building environments for heat hazard mitigation using NBS. The presented simulation tool serves as a foundation to investigate in detail the potential of different NBS, thus aiding the creation of a mitigation plan to tackle the extreme heat conditions in Padua City. Wangxin et al. (2022) assessed several NBS scenarios (vertical greening, traditional greening, high-albedo pavement, improvement of vegetation structure, and a combination of different types) for a heat mitigation plan in the old City of Beijing, China, an area that was identified as a UHI hotspot and that lacked green space. Wangxin et al. (2022) study quantified the effectiveness of NBS scenarios based on their impact on Ta and PET, showing that a comprehensive combination of all scenarios can decrease the Ta and PET approximately by 1°C. Sahani et al. (2023) identified a similar effectiveness of green-blue NBS in reducing local temperatures in built-up areas during the summer of 2022, where the combination of tested NBS (water bodies, woodlands, and grasslands) had the highest spatial cooling effect. However, the aforementioned studies did not capture the thermal effects of buildings, which

[1] https://github.com/AuliaImania/Padua/tree/main
[2] https://youtu.be/tcYQKSNRjQM

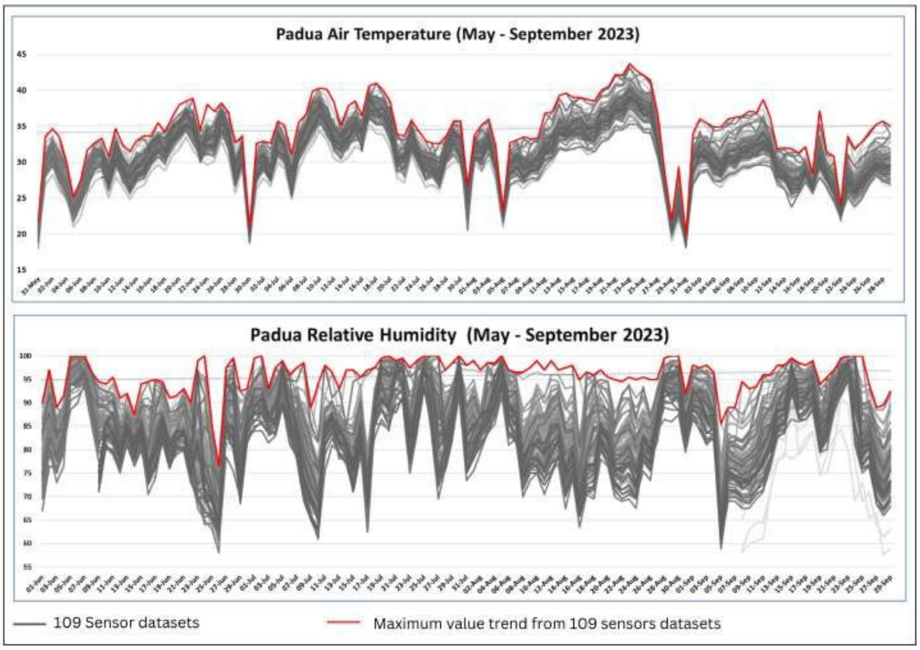


Figure 5. LoraWAN sensors measurements output plot of air temperature (above), and relative humidity (below) during May until September 2023.

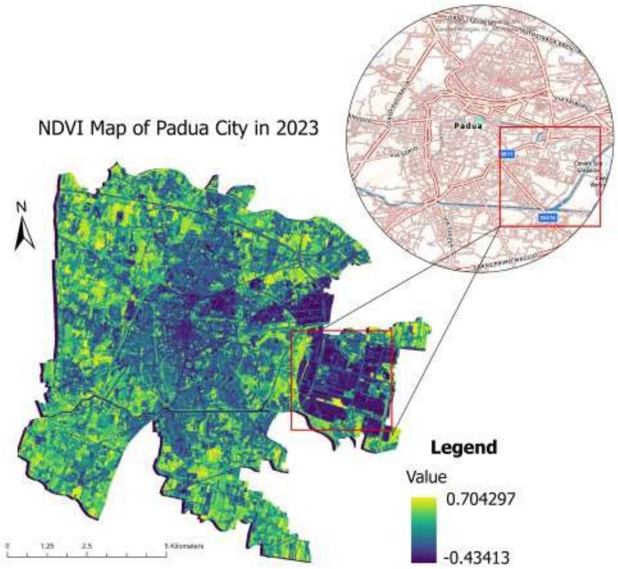


Figure 6. NDVI map of Padua City for the period of May to September 2023, derived from Sentinel-2 satellite imagery.

are known to exacerbate the heat flux coming from the building materials, and a building's heat waste (Kandya and Mohan, 2018; Shuangping et al., 2019). These conditions trigger the feedback loop where overheated buildings increase reliance on air conditioning to create indoor thermal comfort which causes the release of more anthropogenic waste heat outdoors, contributing to increased temperatures (Hayes et al., 2022; Shuangping et al., 2019).

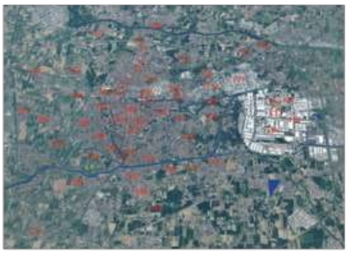
Another study by Qingyan et al. (2022) reported that industrial parks exacerbate UHI conditions by emitting large amounts of anthropogenic heat from industrial facilities, generating the phenomenon called intra-heat islands or industrial heat islands (IHI). Qingyan et al. (2022) also demonstrated significant results concerning high land surface temperatures (LST) associated with the IHI effect during spring and summer in industrial parks, while Pappalardo et al. (2023) provided similar findings for Padua City's industrial zone. In addition, Qingyan et al. (2022) confirmed that temperatures in industrial areas remain elevated overnight. Therefore, this research adapted the PET model quantification from Koopmans et al. (2020) that enables to explore conditions during night-time, understanding of which is vital for assessing the potentially unrecognized threat posed by the heat-trapping phenomenon. Following the PET formula of Koopmans et al. (2020) and Ca´rdenas et al. (2023), the PET model was hypothetically tested in a small-scale area for traditional NbS : the presence of additional trees (Qingyan et al., 2022). The simulation using the Ta and humidity data on

DT-IoT object	View	Code snippet

Buildings		`. . .`
		`const building = new SceneLayer`
		`({url: "http:tiles.arcgis.com/…"});`

Blue infrastructure (water)		`const water_symbol = new PolygonSymbol3D({`
		`symbolLayers: [ new WaterSymbol3DLayer`
		`({ waveDirection: 260,`
		`color:"#25427c",`
		`waveStrength: "moderate",`
		`waterbodySize: "medium"`
		`})],`
		`edges: new SolidEdges3D({`
		`size: 1,`
		`color: "#a2f9f5"}),`
		`ElevationInfo: {`
		`mode: "relative-to-ground"}});`
		
		`const water_renderer = new SimpleRenderer`
		`({symbol: water_symbol });`
		
		`const river = new FeatureLayer({`
		`url: "https://services1.arcgis.com/...`
		`",renderer: water_renderer});`

Green infrastructure (trees)		`...`
		`const trees = new FeatureLayer({`
		`url: "https://services1.arcgis.com/...`
		`",renderer:. . .});`

Sensors		`var sensorData = [];`
		`async function getData() {`
		
		`const inputDate =`
		`document.getElementById("Date").value;`
		
		`try{`
		`const response = await.axios.get`
		`('http://158.220.113.243:3000/query', {`
		`params: {filter_date: inputDate},});`
		
		`const data = response.data;`
		`return data;`
		`} catch (error) {`
		`console.log('Failed to fetch`
		`data: ' + error.message);`
		`const zero = []`
		`return zero; }};`

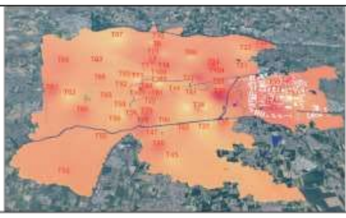
PET		`const PET = new RasterFunction({`
		`rasterFunction:`
		`"RasterCalculator",`
		`rasterFunctionArguments: {`
		`InputNames: [...],`
		`Expression: ...,`
		`ExtentType: 0,`
		`Rasters: ["$1",...],`
		`variableName: "Raster" }});`

Table 1. The code snippet overview of the visible components on the tool platform.

August 21, 2023, at 12 PM. The results showed a reduction in small scale local PET temperatures by approximately 0.1 °C, indicating a similar outcome from Qingyan et al. (2022) who demonstrated that tree planting could potentially decrease temperatures by 0.29°C.

The purpose of the developed tool is to support the decision-makers to create a heat mitigation plan in Padua City. An ongoing project called GREEN-UP[3], developed by the European Space Agency (ESA), shares a major similarity in concept with the tool developed in this study; both are designed to assess

[3] https://eo-labs.dhigroup.com/eo-clinic-nbs/antananarivo

the impact of scenarios involving NBS. However, the web-app outputs cannot be compared as the GREEN-UP tool has not yet been completed. Another NBS tool, created through the H2020 project, called UNaLab. This tool provides temperature information and defines NBS scenarios for three different years: 2015, 2030, and 2050 (Piersaverio et al., 2018). In contrast, the UNaLab tool does not offer the flexibility for users to create their own scenarios, unlike the tool developed in this research. However, access to the UNaLab web app is no longer available, precluding a detailed comparison. Several challenges were encountered to integrate the SBIoT system into the tool, as also reported by Kumar et al. (2023). These issues include the reliability of the sensor system, interruptions in gateway mobility affecting data access, and network connectivity issues related to internet access. Nevertheless, the DT loop practices in this study successfully leveraged real-time sensor data to capture pivotal activities (Weil et al., 2023).

Considering the economic dimension of green solutions for urban heat island mitigation, evidence points to a high potential for feasibility if social benefits are considered. Several extensive studies have already been carried out exploring the business case for green roofs, Berto et al. (2017) assessed the case of an industrial site in Trieste, Italy, considering extensive green roofs, and concluded that when in addition to technical characteristics social (public) benefits of ecosystem services are included (aesthetics, biodiversity, carbon reduction, air quality improvements in air quality, rainwater retention and sewage relief), the probability of economic feasibility remains uncertain but increases to 74%. This study did not include the effect of the decrease of local temperature, which brings substantial positive benefit to urban citizens and is estimated to be the strongest in industrial areas (Macintyre and Heaviside, 2019). Similar results are reported by Switzer et al. (2021) for a comparable Dutch case, where green roofs do not entirely earn themselves back even when the social (public) benefits of green roof ecosystems are considered. Importantly, both studies assume relatively low energy prices, which have now increased by 20-25% after the energy crisis in 2022. This difference in energy prices may also help the business case of green roofs as energy savings make up a major part of private benefits (Berto et al., 2017). Another study, conducting extensive modelling of vegetation effects and including a cost-benefit analysis of these measures for three Austrian cities, reports positive results indicating that total benefits are higher than total costs (Johnson et al., 2020). The Austrian case included combined measures of green roofs, trees and low vegetation, and was based on similar assumptions for economic feasibility analysis as Berto et al. (2017) and Switzer et al. (2021). Importantly,Johnson et al. (2020) included not only heat-related mortality but also productivity losses. In future, it is intended to explore the specific contributions of particular types of vegetation, and their combinations in the Padua case will be further explored in 3D model simulations.

Future research needs to consider enhancing the 3D model by adding facade information. Currently the 3D model is at LoD-1 which is deemed appropriate for neighborhood-level simulations. Future enhancements will involve integrating higher LoD 3D models to facilitate a more precise analysis of facade information. Future studies will delve deeper into the analysis of NBS, aiming to contribute scientifically to the selection of green-blue infrastructure. The selection of buildings to be modelled will be discussed with local government officials and other stakeholders. We aim to incorporate Building Information Modeling (BIM) to capture the thermal properties of building elements more accurately. Moreover, the work can incorporate preferences for NBS from Padua citizens, gathered through a Volunteered Geographic Information (VGI) survey to assess their thermal perceptions. The development of the simulation tool is an iterative process, incorporating tuning adjustments and functional enhancements to ensure continuous improvement.

5. Conclusions

In this study, the developed tool demonstrates the potential of UDT to replicate real-world conditions by integrating physical and non-physical variables. Employing a 3D digital twin-based approach, modelling and analysis of the impact of these variables simulates various scenarios and incorporates NBS to mitigate the UHI effect effectively. The research highlights the efficiency of NBS in reducing urban temperatures and their potential for economic feasibility, thereby contributing to more sustainable urban planning. This tool is designed as a proof of concept to enable stakeholders to make assertive decisions. It integrates with a direct feedback system that provides near-real-time results during discussion sessions. By leveraging IoT concept and PET model quantification, the tool can measure and compare the benefits of each scenario. Likewise, the tool enhances the use experience while designing the NBS scenario based on insight from the decision-makers. This input potentially bridges the gap between the scientists and policy-makers, which leads to realistic applicable scenarios. Despite its function of supporting Padua City in developing city plans to combat heat issues and create a sustainable environment, the tool is fully capable of incorporating local knowledge from multidisciplinary expertise and background.

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