Smart Green Planning for Urban Environments: The City Digital Twin of Imola

Mansoureh Gholami, Daniele Torreggiani, Alberto Barbaresi, and Patrizia Tassinari

Abstract Urban green spaces are significant in adjusting the urban microclimate. Street trees are the most influential type of urban vegetation in reducing heat stress. However, simulating trees' 3D models, wind flow, surface temperature, and radiation parameters in complex urban settings and producing high-resolution microclimate maps is often time-consuming and requires extensive computing processes. Therefore, efficient approaches are needed to visualize green scenarios for the future development of the cities. Smart green planning of Imola aims at developing a microclimate digital twin for the city that provides complementary and supportive roles in the collection and processing of micrometeorological data, automates microclimate modeling, and represents climatic interactions virtually. This chapter sets out to explore the smart green planning of Imola in two parts. The first part is focused on the potential and intentions of developing the urban microclimate digital twin for the city of Imola and its conceptual framework. The second part aims at testing and evaluating the applicability of the proposed microclimate digital twin by implementing it in the city of Imola. This digital twin can provide urban planners and policymakers with a precise and useful methodology for real-time simulation of the cooling effects of the trees and other green systems on urban-scale, pedestrian-level thermal comfort, and also a guarantee for the functionality of policies in different urban settings.

Keywords Digital twin · Smart green planning · Urban transformation · Microclimate · Real-time simulation · Imola

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1 Introduction

The Mediterranean countries are mostly vulnerable regions to climate change, extreme weather events such as heatwaves, cold snaps, heavy rainfall or snowfall, ice or hailstorms, droughts, extratropical or tropical cyclones, storm surges, and tornadoes (Cramer et al., 2018).

Cities are notably vulnerable to these climate changes and must have a key role in making adaptation policies that require action at the local level. The main aim of these adaptation plans must be to prevent further deterioration of the climate crisis and to slow down the increase in global temperature, as it is considered in the Paris Agreement to reach net-zero greenhouse gas (GHG) by 2050. To accomplish this, it is necessary to keep up-to-date knowledge of the deteriorative impacts of climate change (Gholami, 2022). Because climate change is already expanding to some level, responding to climate change involves a two-pronged approach:

- Mitigation: Reducing emissions and stabilizing the levels of heat-trapping greenhouse gases in the atmosphere.
- Adaptation: Adapting to climate change that is already in the pipeline. The mechanism for climate adaptation is defined as adjusting to actual or possible expected scenarios for future climate (NASA, 2022).

These mechanisms are not limited to the urban public environment but also include building complexes and individual buildings.

Global energy demand is set to increase 4.6% in 2021, more than offsetting the 4% contraction in 2020 that occurred due to the COVID-19 pandemic (Energy Agency, 2021). Building energy consumption is responsible for over one-third of global final energy consumption and 38% of total global energy-related GHG emissions.

The EU climate and energy policy sets the following targets for 2030 (EU, 2021):

- At least 40% cuts in greenhouse gas emissions (from 1990 levels)
- At least 32% share of renewable energy
- At least 32.5% improvement in energy efficiency

Europe, however, has made itself committed to raising the 2030 GHG emission reduction target to at least 55% in comparison to 1990. Thus, important measures are needed to reduce energy consumption and GHG emissions in urban areas. Without consistently pursuing reduction policies in urban areas, Europe will miss these targets.

1.1 State of the Art

Italy is in a region that is specifically vulnerable to global climate change. Climate data in Italy show an increase in extreme temperatures, which puts this country at risk of natural hazards. Global climate change is expected to increase vulnerability to climate-related events in subsequent years. Urbanization contributes to a considerable increase in human activities (Yang et al., 2017). The high-level concentration of human activities causes a decrease in green urban spaces and a shift in the microclimate of urban areas (Gholami et al., 2020a). Climate change and urbanization are unavoidable. Howard in the 1800s (Mills, 2008) and later Landsberg in the early 1900s (Landsberg, 1981) have been considered among the pioneers who have studied urban climate and demonstrated the difference between urban microclimate and the microclimate in surrounding suburbs and rural areas. This variation can be found in air temperature, humidity, solar radiation, wind speed and direction, air pollution level, and amount of precipitation (Fig. 1). Urban Heat Island (UHI) has been counted as a synthetic factor in using temperature in microclimate variation, and it is defined as a heating effect when air temperature rises in a developed (urbanized) area in comparison to the surrounding rural area (Taha, 2004). Urban spaces cut out vegetation from the land area by the development of building construction, roads, roofs, and other urban infrastructure throughout open lands, and these urban surfaces hold the heat of shortwave radiation and longwave radiation more than vegetation (Gholami et al., 2018). Thus, UHIs are partially due to a lack of greenery and inappropriate urban design.

UHI is defined by calculating the difference between average and maximum air temperature in rural and urban areas (Khare et al., 2021). There are two types of UHIs, air and surface heat islands, each of which is caused by a variety of dominant physical processes and has different temporal and spatial patterns, but they are largely caused by the transformation of the surrounding landscape into corrugated, mostly manufactured, and less vegetation-covered surfaces. Air UHI is the effect in the canopy layer or boundary layer. The UHI in the urban canopy can be measured at meteorological stations; however, for the UHI in the boundary layer, more special installments are needed in aircraft or tall towers (CUHK, 2008). On the other hand, surface UHIs measure the difference in radiant temperature between urban and

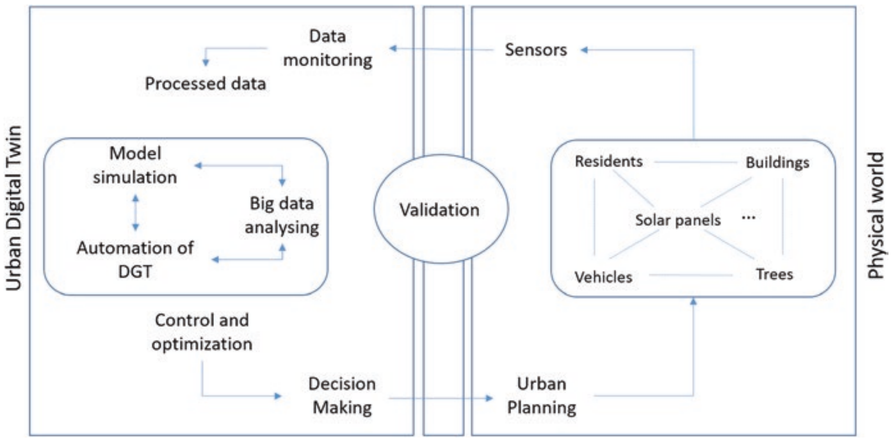

Fig. 1 Conceptual framework of an urban digital twin

suburban surfaces, and this UHI can be measured directly by satellite thermal temperature remote sensing data. In urban spaces, the mean radiant temperature depends on the building geometry, street layout green cover, and albedo of urban walls and ground (Wong et al., 2011).

Green spaces in an urban area can affect UHIs in various aspects of the surface energy balance (Gholami et al., 2020b). It can reduce radiation and air temperature and decelerate wind. Trees can decrease the mean radiant temperature and cause a reduction in the sky view factor (Khare et al., 2021). The mean radiant temperature (MRT) is the uniform temperature of an environment in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual environment (Li, 2016). Assessing the effect of trees on heat stress proved that the mean radiant temperature can be decreased by 77% (Milošević et al., 2017). Wang and Akbari showed that the highest range of MRT reduction can be achieved by enlarging the tree canopy (Wang & Akbari, 2016). Zheng et al. examined the lawn and shaded ground with shrubs and trees through a CFD model and demonstrated that the lawn has the lowest surface temperature in summer. However, trees are more effective in reducing the Tmrt (Zheng et al., 2016). A comprehensive review of all the published studies in different climate zones (Santamouris, 2013) has demonstrated the importance of green roofs for the air temperature at the pedestrian level by reducing Tmrt by 0.3–3.0 K by the condition that it has been applied on the city scale. A test carried out in Singapore demonstrated that the cooling effects of a green roof can be considered if the height of the building is less than 10 m (Wong et al., 2003).

1.2 Conceptual Framework Planning for an Urban Microclimate Digital Twin

Several models and methods have been developed for the evaluation of microclimate, energy balance, and air quality. However, the complexity of urban environments has limited the functionality of urban models to simulate all the interconnectivity and interdependencies in urban systems. To overcome this limitation, multilevel modeling methodologies have been increasingly employed to perform several single simulations and then combine the output as a comprehensive urban model. Digital twins are among the well-known multilevel models.

Performing any digital twin is in three separate domains, namely, the real world, digital world, and intermediate space, which should work together in a real-time frame (Wright & Davidson, 2020). A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process. A city digital twin is a series of interconnected digital twins representing certain aspects of the functioning of urban environments (Austin et al., 2020). Every digital twin receives a continuous flow of data collected by sensors in real time, analyzes the data, and presents the outcome in various virtual models (Cioara et al., 2021). Since the data are collected in real time, the ability of the digital twin relies on processing data flows. Digital twins perform change predictions and scenario modeling for what-if questions (Qi & Tao, 2018).

A microclimate digital twin provides complementary and supportive roles in the collection and processing of micrometeorological data, automates microclimate modeling, and virtually represents climatic interactions. A digital twin on the first step needs an urban climatic mapping method. Urban climatic mapping integrates parameters in urban planning and climate into mapping. This means that it takes meteorological data, land use, building footprints, topography, and green spaces into consideration to analyze thermal loads and climate comfort into various categories in a spatial thermal impact map (CUHK, 2008). Urban characteristics can create variation in the horizontal and vertical wind profiles, and this effect alters the climate conditions in urban canopy layers (Oke, 1989). As the frictional drag on airflow increases, wind speed and orientation can massively change in built-up areas in comparison to rural areas. This difference is originally referred to as the roughness of a region that plays the main role in affecting the local wind flow. Roughness points out any obstruction in cities such as buildings from, traffic networks, tree canopy outlines, density, and even banner boards in microclimate examination (Yang & Chen, 2020). The impact of urban characteristics on microclimate becomes more complicated when the terrain is not flat. For example, wind profiles and urban ventilation can change according to the topography. Thus, it is crucial to develop climate models based on urban planning characteristics.

An urban microclimate digital twin has three performance steps: information gathering, analyzing processes, and postperformance and assessing resolutions. The main aim of a digital twin is to create a parallel world to a real world (Cioara et al., 2021). The postperformance step is required when the uncertainty in the measurements and modeling is not completed. In this case, a validation of the real-time databases can overcome the uncertainty. This microclimate digital twin runs offline 3D urban simulations and then applies a real-time microclimate (Fig. 2). The method also proves how the digital twin can be expanded to include a wide variety

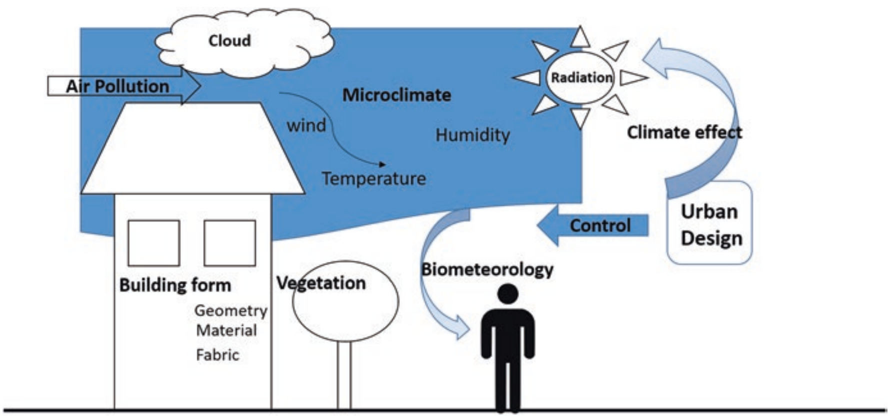

Fig. 2 Urban microclimate and involved parameters

of data resources and simulations on various scales and subjects. Moreover, a balance must also be created between urban management and urban engineering to maximize the benefits of trees in retrofitting strategies. The digital twin can provide urban planners and policymakers with a precise and useful methodology for simulating the effects of trees on urban-scale, pedestrian-level thermal comfort and help them guarantee the functionality of policies in different urban settings.

2 Methods

The main aim of this microclimate digital twin is to measure the mean radiation temperature and the Universal Thermal Climate Index (UTCI) based on a hybrid model. The Universal Thermal Climate Index (UTCI) was used for thermal comfort evaluation. The UTCI was introduced in 2011 by the International Society of Biometeorology (ISB) as a new thermal index for outdoor thermal comfort. It evaluates outdoor thermal conditions one-dimensionally in terms of air temperature, wind speed, humidity, and longwave and shortwave radiant heat fluxes.

The model is run through a Python 3.8.1 code that integrates three engines: EnergyPlus (U.S. Department of Energy, 2020), Rhino (McNeel, 2021), and OpenFOAM (Greenshields & Weller, 2022). Each parameter is modeled in different software. To ensure the accuracy of the modeling, the interconnectivity of the parameters is coded in a single comprehensive Python script, and input and output data are directly linked and validated in single steps and the ultimate results.

Figure 3 illustrates the interrelations and order of the steps.

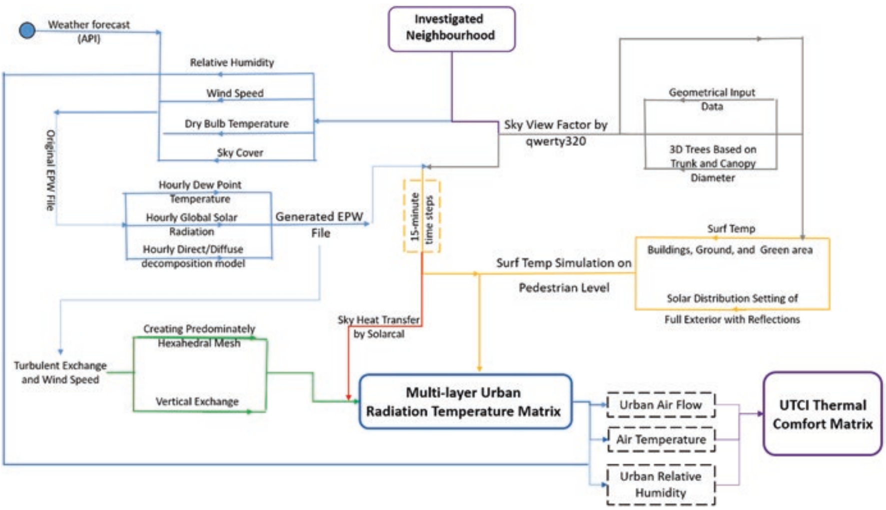

Fig. 3 Modeling methodology of the city digital twin

2.1 Automated Workflow Execution

One of the main challenges in developing the microclimate digital twin is a real-time weather data file for short-term forecasting. To accomplish this, a model is developed in Grasshopper that aims at regenerating the epw file based on forecasting data. The forecast weather data are acquired from API (OpenWeatherMap) in JSON format, which provides short-term forecasting weather data at various time scales. Four elements are required from the API file for the regeneration of the epw file: dry bulb temperature, relative humidity, wind speed, and sky cover. These elements were used to generate hourly dew point temperature, global solar radiation, and direct and diffuse decomposition models. Since Grasshopper cannot directly interact with EnergyPlus, the Honeybee tool was utilized to link open studio, energy plus, radiance, and daysim for an automated process to rewrite an epw file based on the existing epw file. The weather elements were replaced through the automated process in hourly format. This weather file will be used in the next steps for simulations.

3 Case Study

3.1 Smart Green Planning of Imola: Urban Microclimate Digital Twin of the City of Imola

The biosystems engineering group of the University of Bologna has initiated the project of developing an urban microclimate digital twin for the city of Imola to improve thermal comfort, livability, and sustainability in this city. In this phase of the project, developed within the "health, safety, and green systems" Ph.D. program of the district of Imola of the University of Bologna, the multidisciplinary team of the project has proposed a climate-sensitive digital twin that simulates possible green scenarios with the purpose of providing outdoor climate comfort.

Prof. Patrizia Tassinari, chair of the biosystems engineering group of the University of Bologna and coordinator of the Ph.D. program, mentions that the project will help urban planners and policymakers understand the impact of greener urban design and infrastructure on outdoor thermal comfort for the residents of the city of Imola.

Marco Panieri, the mayor of the city of Imola, brings up that this "digital twin" is the result of a scientific and technological study that shows how the Imola territory aims at cutting-edge goals, focusing on the knowledge and expertise developed within the university and continuing strengthening the connection among the university, the municipality, and the other local stakeholders, in the first place, the Cassa di risparmio di Imola Foundation, and Conami.

3.2 Objectives for Microclimate Digital Twin of the City of Imola

Imola is selected for the investigation of new greening policies in urban spaces. The outcome of this digital twin enables data scientists and infrastructure planners to validate and optimize the impact of new infrastructure before investing and deploying capital equipment (Gholami et al., 2022). By using historical databases, this tool helps planners simulate the impact of data-driven goals before they are implemented and helps operators monitor and maintain smart city services. This digital twin enables city planners to confidently and efficiently transform their energy systems by:

1. Identifying and optimizing spatial maps of existing, proposed, and planned infrastructure enhancements before investing in equipment;
2. Creating scenarios based on combined models to optimize service to the community; and
3. Predicting and effectively managing the green parameters in a given neighborhood, such as planting new trees in the city or managing rooftop green systems.

3.3 Urban and Climate Context of Imola

This chapter bases the study on the city of Imola, Italy. Italy is ranked fifth among European countries, with a population of 60 million in 2020. The district of Imola is a city in the Metropolitan City of Bologna, located on the river Santerno, in the Emilia-Romagna region of northern Italy (44° 21′ 11.0088″ N, 11° 42′ 52.9992″ E) (Fig. 4). It covers an area of 204 km^2 and has a population of approximately 70,000 inhabitants. According to Koppen's climate classification, Imola is in the zone of the humid subtropical climate and has a relatively continental and four-season climate. In Imola, the summers are warm and mostly clear, and the winters are very cold and partly cloudy. Over the year, the temperature typically varies from −0.5 to 31.11 °C and is rarely below −5 °C or above 35.5 °C. The city receives approximately 2230 hours of sunlight per year. July has an average maximum temperature of 30 °C. The coldest month is January with an average minimum temperature of −1 °C. The wettest month is November with 95 mm of rainfall. The sunniest month is August, with approximately 11 hours of sunshine. The driest month is July, with 43 mm of precipitation (Figs. 5, 6, 7, and 8). The selected neighborhood itself has an area of 900 m × 500 m, 9% of which is covered by street tree canopies. The neighborhood consists of detached two- to three-story single buildings with a dense pattern of tree planting in some parts (Fig. 9).

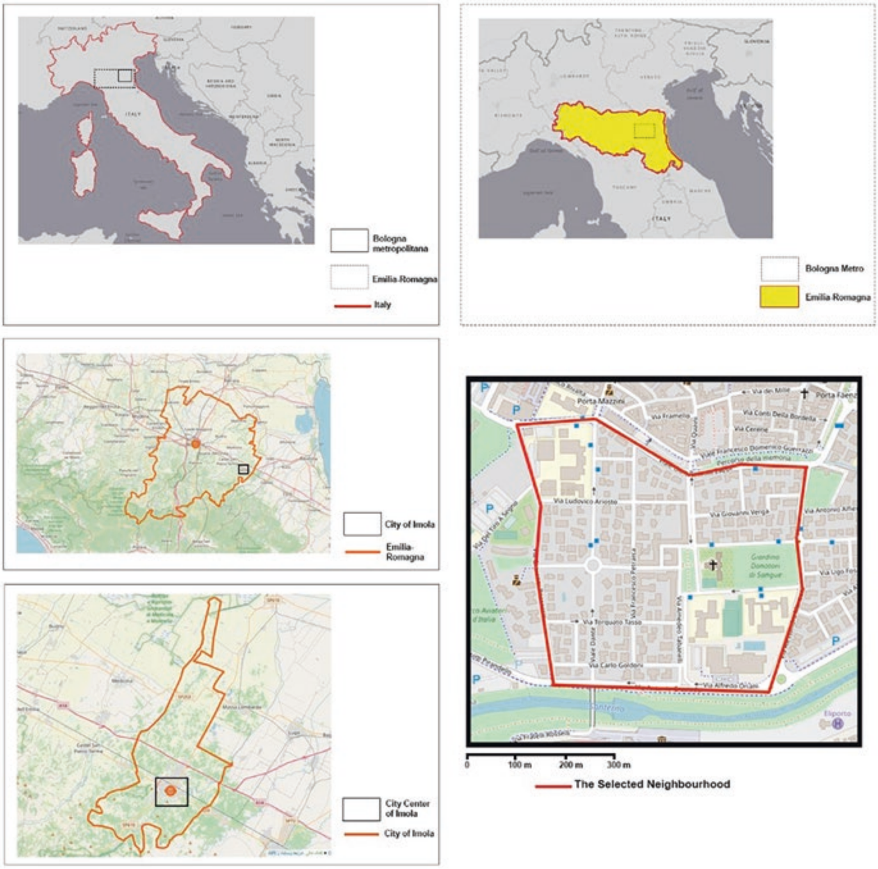

Fig. 4 Aerial view of the study area in Imola, Italy

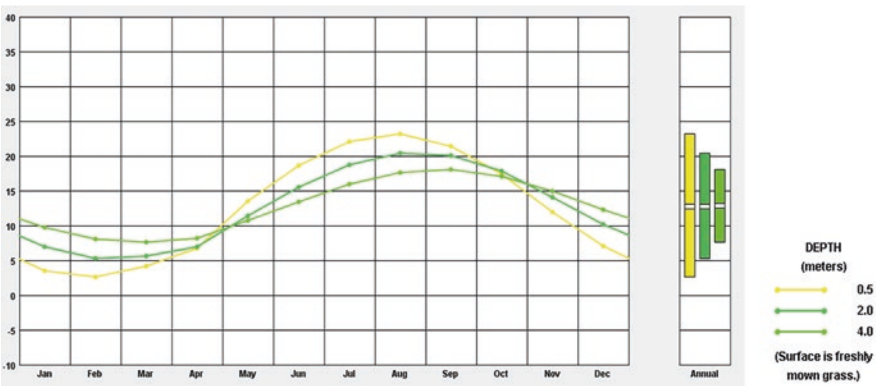

Fig. 5 Monthly average ground temperature in Imola

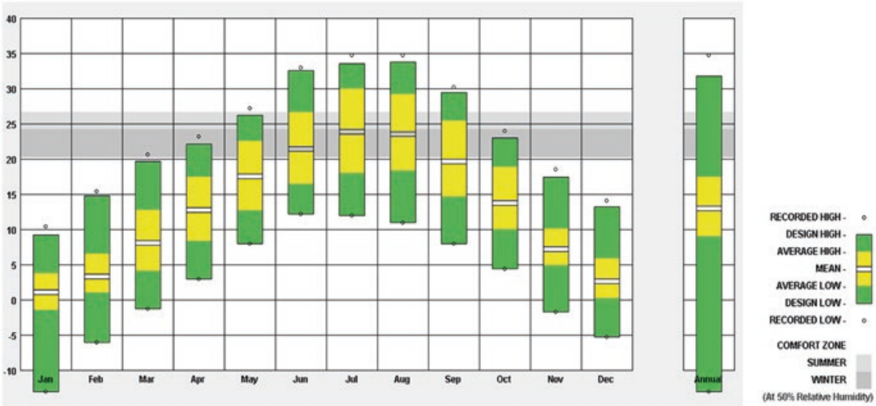

Fig. 6 Monthly average temperature in Imola

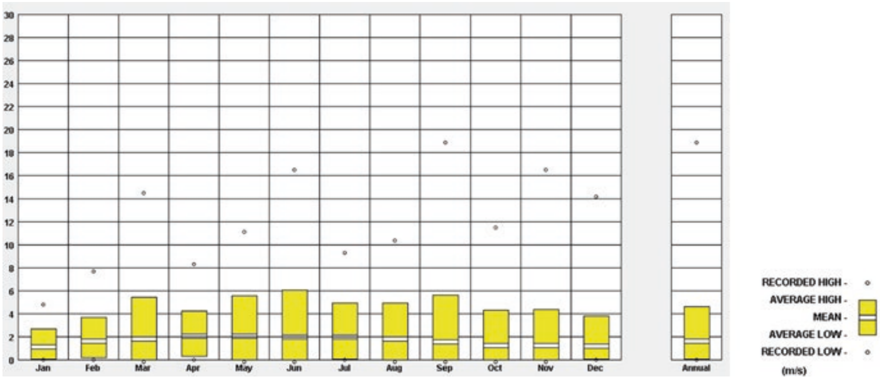

Fig. 7 Monthly average wind velocity in Imola

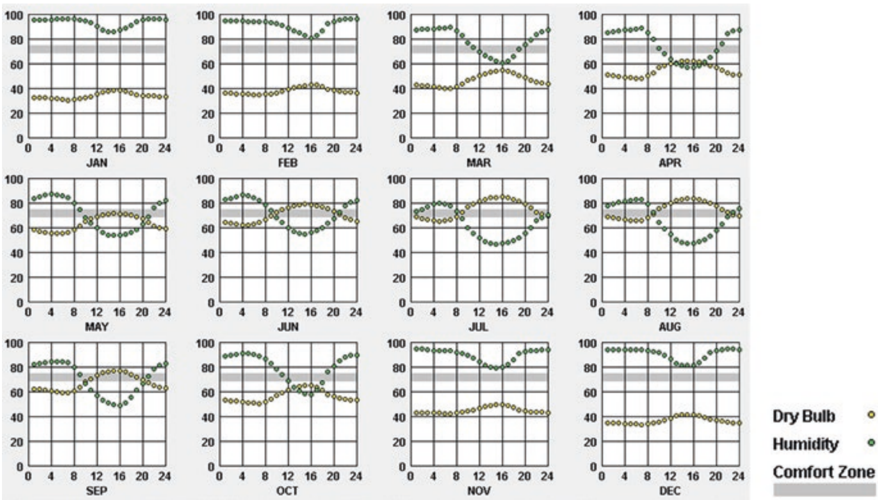

Fig. 8 Monthly dry bulb and humidity in the city of Imola

Fig. 9 Bird view of Imola, Italy (http://mappegis.regione.emilia-romagna.it/moka/download/sig/FOTO_IBC_HD/05DB_03_036.png; http://mappegis.regione.emilia-romagna.it/moka/download/sig/FOTO_IBC_HD/05DB_07_073.png

4 Results

Four different urban blocks inside the neighborhood are selected: (a) low-rise blocks with high canopy cover (LR-HCC), (b) mid-rise blocks with medium canopy cover (MR-MCC), (c) mid-rise blocks with low canopy cover (MR-LCC), and (d) high-rise blocks with high canopy cover (HR-HCC). After selecting the blocks and feeding the required data into the model, simulations are developed in the digital twin to generate a series of high-resolution mean radiant temperature (MRT) and Universal Thermal Climate Index (UTCI) maps at the pedestrian level. Moreover, a data matrix was created based on the hourly simulation of the hottest week of the year, August 3–9 (the study period). The maps and data were generated using a detailed 3D model of the geometric properties of buildings and canopies as well as several digital surface models (DSMs). As Fig. 3 illustrates, the process took into consideration the local microclimate, hourly turbulent exchange, surface temperature, and sky heat exchange. Therefore, the generated maps are highly accurate and clear for investigating tree parameters as well as optimal adaptation strategies in urban retrofitting.

4.1 Mean Radiant Temperature at the Street Level

The highest level of heat stress in the urban blocks was recorded at LR-HCC, which is a church in a designed landscape in a community-scale park. During the hottest day of the year, the mean radiant temperature exceeded 65 °C (Fig. 10). The canopy cover of the site is scarce due to the large distance between trees. Contrary to this site, the archetype HR-HCC has been shaded due to the high density of the canopies and buildings, and this shaded area has made this site the coolest part of the neighborhood during the hottest days of the year. The MRT in this block on the hottest day of the year was 45.5 °C, which is 20° lower than that in the archetype LR-LCC. As Fig. 11 shows, the archetype MR-LCC is a good example of the building shade effect in Imola. The dense fabric of the site helps create cool and comfortable pedestrian spaces.

4.2 The Universal Thermal Climate Index (UTCI) at the Street Level

This measurement system employs the correlations observed in human adaptive outdoor thermal behavior to predict the clothing of subjects of average age, height, and weight (Jendritzky et al., 2014). Heat stress occurs when the body fails to keep the internal temperature status at a certain level. Table 1 shows the categorization of thermal stress based on UTCI ranges. There are different types of UTCI, including heat and cold stress. In this chapter, we only consider heat stress.

The peak of the temperature on the 9th of August created a large gap in the level of UTCI in different urban blocks in Imola, but as the temperature decreased, this gap also decreased. Heat stress, on the other hand, was at an all-time high in Imola. The archetypal LR-HCC suffered the greatest UTCI level, as shown in Fig. 12, with

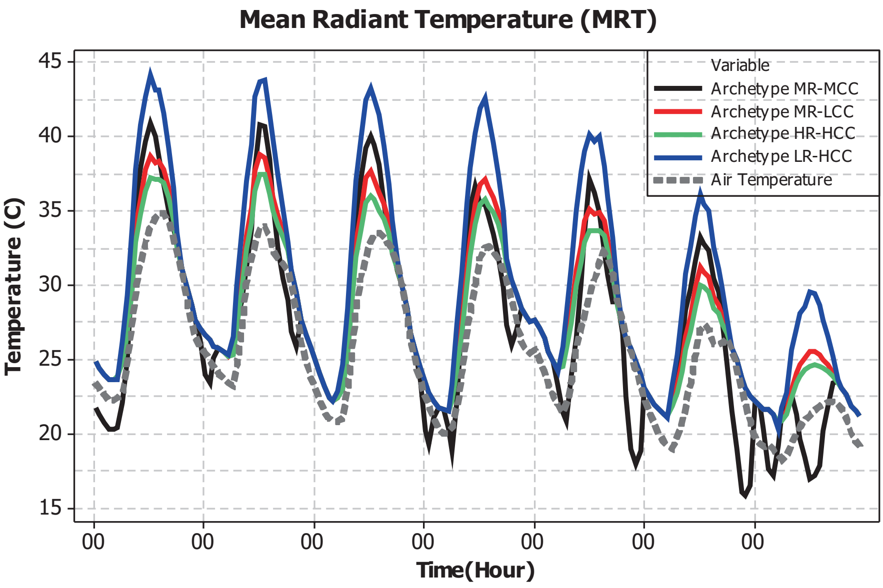

Fig. 10 Mean radiant temperature in the four archetypes in Imola

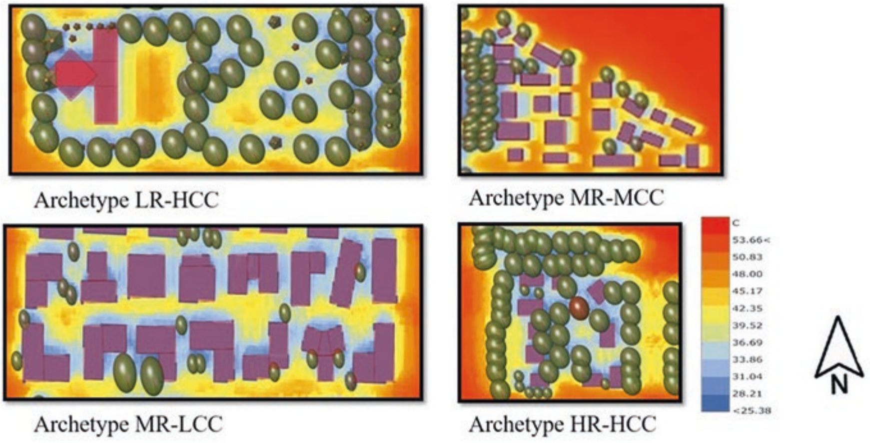

Fig. 11 Spatial variations in MRT at the microscale in the city of Imola

Table 1 The UTCI assessment scale: the UTCI categorized in terms of thermal stress

UTCI(C) range	Stress category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress

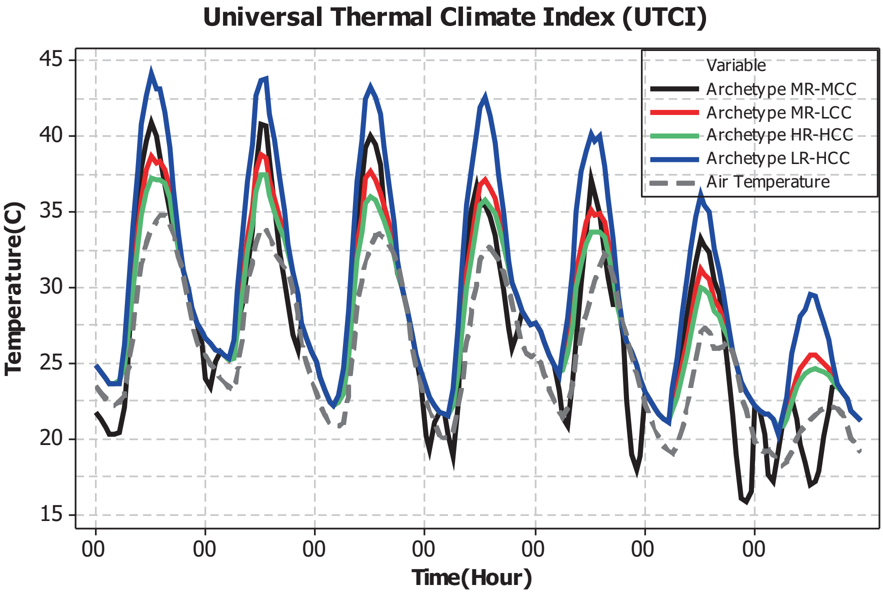

Fig. 12 Universal thermal climate index (UTCI) in the city of Bologna (above) and Imola

a temperature of 43.4 °C, indicating extremely significant heat stress. Meanwhile, the HR-HCC had less heat stress, with a mean UTCI of 37.5 °C at midday on August 4. It is worth mentioning that sunny parcels bordered by buildings were 1–2 °C warmer than wide sunny spaces. The reflection of solar and longwave radiation onto parcels close to vertical surfaces might be the cause. Similarly, shaded parcels next to trees had a 0.5–1.5 °C cooler temperature than shaded parcels close to buildings.

5 Discussion

The proposed model in this chapter employs Ladybug and Honeybee; however, to date, various simulation engines have been presented in different contexts. Ladybug and Honeybee are capable of analyzing complex 3D models. The model is based on surface temperature and generated sky view factor by the Rhino platform. Envimet is one of the most-employed engines over the last decade for the calculation of Tmrt. It uses 3D models based on the equation of Bruse. Ground evaporation and the transpiration of urban vegetation are also calculated. Rayman is another engine that simplifies the environment and calculates the MRT based on Stephen Boltzman's radiation law. Any model can be challenged by the complexity of urban environments, and the validation of the model and input data is necessary.

5.1 Performance Validation of the Digital Twin of Imola

The model was validated through field measurements in the city of Tempe, USA, on June 9th, 2018. The field measurements were conducted in a clear sky in the city for model validation. Four sample locations were selected for collecting human-bio meteorological data on June 9th, 2018. Sensors measure georeferenced 6-directional longwave (L) and shortwave (K) radiation flux densities with three Hukseflux 4-Component Net Radiometers, Ta, Ts, v, and RH in 2-s intervals at pedestrian height. Every sample site is archived through hemispherical 180° photos taken at 1.1 m height with a Canon EOS 6D and Canon EF 8–15-mm f/4 Fisheye USM Ultra-Wide Zoom lens. Table 2 indicates the minimum and maximum and average mean radiant temperature measured and modeled from 8 am to 8 pm. The results have been calibrated based on these four points in the area.

5.2 Application of the Cooling Scenario

The study used a strategy scenario that involves putting trees in specified spots as well as increasing the number of trees in public spaces to evaluate the model's performance in analyzing the impacts of increased tree coverage on communities.

Table 2 Measurements and model outputs of mean radiant temperature

Point code		Min Tmrt	Max Tmrt	Average Tmrt	Standard deviation
1	Measurement	30.4800	69.4017	43.8754	13.66891
	Model	37.2510	44.5320	39.7083	4.871698
2	Measurement	32.0426	40.3306	35.2940	3.229757
	Model	38.9000	43.3000	40.0000	3.579011
3	Measurement	24.8197	61.8556	48.6251	20.65881
	Model	25.0000	72.0000	55.6667	26.57693
4	Measurement	31.6427	48.7733	40.5803	8.589577
	Model	26.1000	33.9000	30.2000	3.915354

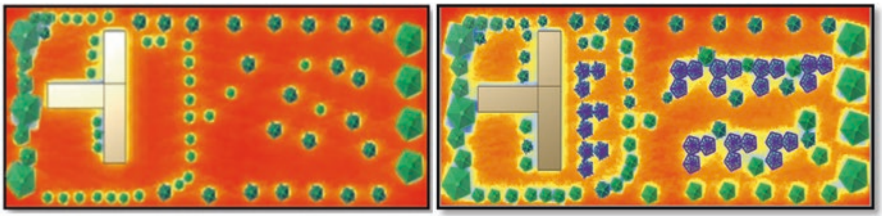

Fig. 13 Spatial variations in the UTCI of the cooling scenario for archetype LR-LCC

Numerous experiments have examined how shade caused by urban surfaces influences the spatial variance of radiant temperature (Thorsson et al., 2011). On a small scale, the number of trees and the spatial location of extra trees are both essential factors in lowering the MRT. To decide the priority of parcels to receive new trees, the first stage in putting trees in optimum areas is to create an accurate map of each block's climate comfort based on the UTCI (Fig. 13).

In examining the situations, two findings from previous research were taken into account: First, trees are more beneficial at lowering MRT in clusters than individually (Streiling & Matzarakis, 2003); and second, trees are more effective at reducing MRT in clusters than they are individually (Streiling & Matzarakis, 2003). The tree addition cooling scenario was put up in the block with the highest MRT in the modeled neighborhood in Imola. At each site, 10 clusters of trees with a canopy width of 7 m and a height of 10 m were placed (additional trees are highlighted in blue in Fig. 8). The present layout of the sites was not modified in any capacity, ensuring that the findings are applicable to the creation of appropriate retrofitting solutions. During the hottest hours of the year, the cooling strategy can reduce the radiant temperature by 9 °C and increase neighborhood climate comfort by up to 35%.

6 Conclusion

Today's urbanization has resulted in worldwide environmental and economic challenges that have a detrimental influence on cities and, as a result, urban planning procedures. Urban planning and design have been deeply involved in reducing carbon emissions in recent decades. One method of reaching low-carbon towns is through the upgrading technique of restructuring urban trees. Street trees are now more than ever valuable for our urban environments given how extreme heat in cities has reached concerning levels in recent decades. Overall, the number of trees must increase to prevent this effect, and urban design principles are essential for optimizing the distribution and placement of trees. Digital twins are one of the most recent technological innovations in urban planning. The goal of this study is to provide a digital twin concept that includes a real-time climate model in complicated 3D city simulations.

The suggested digital twin for the city of Imola simplifies complicated ideas and critical stages for developing a real-time urban microclimate model, and it incorporates a hybrid model that uses a unique method for MRT modeling. The output of the digital twin is visualized through thermal maps, and the future scenarios for the smart green planning of Imola are evaluated. The results are validated through a measured dataset, and the reliability of the real-time microclimate forecasting is indicated. The proposed microclimate digital twin in Imola can act as a platform to enhance green infrastructure and engage the community. A powerful community engagement tool can educate citizens and enhance the awareness of locals by coupling real city conditions with a digital twin platform. It is an incentive program for changing the materials of the buildings or planting trees on the streets.

We believe that this digital twin platform can be used to expand the possibilities for predictive maintenance, infrastructure expansion, and clean energy and green planning. Creating a digital twin library of existing and proposed infrastructure elements enables stakeholders to make action plans, transform cities and improve the quality of life for locals in urban spaces for a more sustainable world.

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